*J. Org. Chem.* **1999,** *64,* 2188−2193

*Articles*

# 2-Pyridyl and 2-Pyrimidyl Cations: Stable *o*-Hetarynium Ions in the Gas Phase[†]

Fábio C. Gozzo and Marcos N. Eberlin*

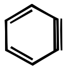
*State University of Campinas—UNICAMP, Institute of Chemistry,*
*CP 6154, 13083-970 Campinas, SP Brazil*

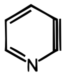
*Received April 1, 1998*

As indicated by high-level CBS-Q ab initio calculations, extensive overlap occurs in the 2-pyridyl and 2-pyrimidyl cations between the fully occupied sp$^2$ orbital of nitrogen and the adjacent, coplanar, and empty sp$^2$ orbital of the C2-carbon. Such effective orbital overlap results in *o*-aryne-like structures with substantially shorter N−C$^+$ bond lengths and N−C$^+$ bond orders of 1.9−2.1. Therefore, the 2-pyridyl and 2-pyrimidyl cations are best represented, and can be regarded as, *o*-hetarynium ions, being more stable than their positional, nonconjugated isomers by as much as 18−28 kcal/mol. The 4-pyrimidyl cation also displays characteristic *o*-hetarynium ion structure with substantial orbital overlap. However, the ion easily isomerizes by charge-induced ring opening, as indicated by both the calculations and the ion's lack of *o*-hetarynium-like reactivity. A high energy barrier of 62.8 kcal/mol hampers isomerization by H-ring walking of the 3-pyridyl cation to the far more stable 2-pyridyl cation. For the related 2-furanyl, 2-thiophenyl, and 2-pyrrolyl cations, little or none of the extra orbital overlap occurs; hence, they display energies close, and structures similar, to those of their 3-isomers. Collision-induced dissociation of collisionally quenched precursor ions performed via triple-stage QqQqQ mass spectrometric (MS$^3$) experiments confirms the greater stability of the 2-pyridyl and 2-pyrimidyl cations.

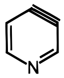
## Introduction

*o*-Benzyne (**1**), a key intermediate in many reactions of aromatic compounds, is the simplest and most common aryne.[1] The discovery of *o*-benzyne[2] raised the interesting questions of whether heteroarynes (hetarynes) exist and of how they could be made available for chemical manipulation.[3] Several studies have unambiguously established that hetarynes do indeed exist; two neutral *o*-azabenzynes, i.e., 2,3-pyridyne (**2**) and 3,4-pyridyne (**3**), have been detected and trapped by many characteristic reactions as reactive intermediates, particularly in nucleophilic substitutions on heteroaromatic halides.[3]


(1)

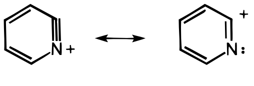


(2)



(3)

Replacing a dehydrogenated carbon in *o*-benzyne (**1**) by a nitrogen atom results in the cationic 1-aza-*o*-benzyne **4a**, that is, the mesomeric 2-pyridyl cation **4a′**/**4a″**. Ion **4a**, which is therefore isoeletronic with *o*-benzyne, is a common species that participates as a reactive intermediate in several condensed-phase reactions.[4]



(4a')
(4a")

Both **4a′** and **4a″** are aromatic six-$\pi$-electron structures, but Kaufffmann[3a] used the relatively higher stability of *o*-benzyne (**1**), compared to that of the phenyl cation (**5**; protonated *o*-benzyne) to predict the major contribution of the mesomeric form **4a′**. In **4a′**, as opposed to **4a″**, all atoms bear a complete octet of electrons, an electronic configuration that is widely observed to confer stability. Further, in **4a**, the fully occupied sp$^2$ nitrogen orbital and the empty sp$^2$ carbon orbital are adjacent and coplanar; hence, orbital overlap is facilitated (see structures below) resulting in a delocalized MO that likely enhances the N−C$^+$ bond order, thus favoring structure **4a′**.

The positional and nonconjugated isomers **4b** and **4c** are isoelectronic with *m*- and *p*-benzyne, respectively; hence, they can be also regarded as *m*- and *p*-hetarynium ions. No effective orbital overlap is expected, however, for **4b** and **4c,** which should therefore display major aromatic carbocation-like structures and chemical behaviors similar to that of the phenyl cation (**5**).

---

[†] Dedicated to the memory of Prof. Robert R. Squires in recognition of his incisive contributions to gas-phase ion chemistry.

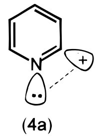
(1) (a) Heaney, H. *Chem. Rev.* **1962**, *62*, 81. (b) Hoffman, R. W. *Dehydrobenzyne and Cycloalkynes;* Academic Press: New York, 1967. (c) Borden, W. T. *Diradicals*; Wiley: New York, 1982. (d) Nash, J. J.; Squires, R. R. *J. Am. Chem. Soc.* **1996**, *118*, 11872 and references therein.

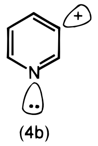
(2) For an early case in which the existence of *o*-benzyne was demonstrated, see: Roberts, J. D.; Semenow, D. A.; Simmons, H. E., Jr.; Carlsmith, L. A. *J. Am. Chem. Soc.* **1956**, *78*, 601.

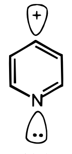
(3) (a) Kauffmann, T. *Angew. Chem., Int. Ed. Engl.* **1965**, *4*, 543. (b) Den Hertog, H. J.; Van Der Plas, H. C. *Heterocycl. Chem.* **1965**, *4*, 121. (c) Kauffmann, T.; Wirthwein, R. *Angew. Chem., Int. Ed. Engl.* **1971**, *10*, 20.

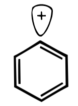
(4) (a) Ohkura, K.; Seki, K.-I.; Terashima, M.; Kanaoka, Y. *Tetrahedron Lett.* **1989**, *30*, 3433. (b) Kauffmann, T.; Marhan, H. *Chem. Ber.* **1963**, *96*, 2519. (c) Bunnett, J. F.; Singh, P. *J. Org. Chem.* **1981**, *46*, 4567.

10.1021/jo980599+ CCC: $18.00

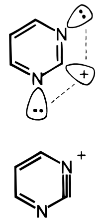

(4a)

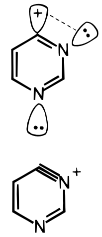

(4b)

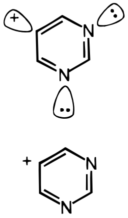

(4c)


(5)

Effective orbital overlap is also anticipated for the 1,3- (**6a**) and 1,5-diazabenzynium (**6b**) ions; hence, these ions may also display pronounced *o*-hetarynium ion behavior and structure. Again, the extra orbital overlap is not possible for **6c**, and this nonconjugated isomer is expected to display aromatic carbocation-like structure and chemical behavior.


(6a)

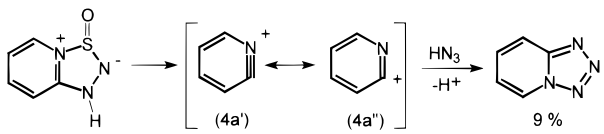

(6b)


(6c)

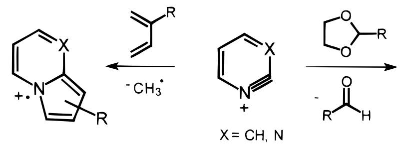
Although long antecipated,[5] so far no conclusive experimental or theoretical evidence for the *o*-aryne-like nature of **4a** has been provided. Kauffmann and Marhan[4b] intercepted **4a** by 1,3-cycloaddition with HN$_3$, isolating tetrazolopyridine (Scheme 1) that was taken as indicative of **4a′**. The yield was, however, very low (9%). Bunnett and Singh[4c] tested the arynelike chemical behavior of **4a** by generating the ion in the presence of anthracene and furan, two dienes that react promptly by Diels−Alder cycloaddition with *o*-benzyne.[6] Ion **4a** failed, however, to participate in the expected cycloaddition reactions.

In the gas phase, the isomeric ions **4a**−**c** and **6a**−**c** are easily formed by dissociative electron ionization of appropriate precursors such as, for instance, monohalogenated pyridines and pyrimidines. Recently, we showed that the 2-pyridyl (**4a**) and 2-pyrimidyl cations (**6a**) display unique and structurally diagnostic chemical behavior in the gas phase.[7] Both **4a** and **6a** react extensively with conjugated dienes and cyclic acetals by two novel annulation reactions (Scheme 2), whereas their isomers show typical aromatic carbocation reactivity; that is, they react mainly by proton transfer and H-abstraction, as does the phenyl cation (**5**). However, both annulation reactions most likely follow stepwise mechanisms[7] of cyclization that cannot be taken either as indicative or as opposing evidence for *o*-hetarynium-like behavior of **4a** and **6a**.

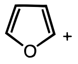
**Scheme 1**

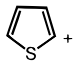


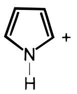
**Scheme 2**

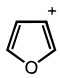


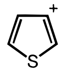
In the present study, high-level complete basis set (CBS-Q)[8] ab initio calculations are used to investigate whether **4a**, **6a**, and **6b** display characteristic aryne-like (*o*-hetarynium) structures in the gas phase and to estimate the extent of resonance stabilization relative to their *meta* and *para* isomers. The CBS-Q calculations are also used to estimate the energy barrier for H-ring walking that could interconvert **4b** and **4a** and the relative energies and structures of related five-membered heteroaromatic cations; that is, the isomeric furanyl (**6a** and **6b**), thiophenyl (**7a** and **7b**), and pyrrolyl (**8a** and **8b**) cations. Pentaquadrupole (QqQqQ) mass spectrometry[9] is also used to address the stabilities of **4a** and **5a** (relative to the respective **4b**,**c** and **5c)**, via their ease of formation in MS$^3$ experiments in which ions were collisionally quenched before collision-induced dissociation.

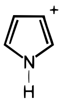

(7a)


(8a)


(9a)


(7b)


(8b)


(9b)

## Methods

Molecular orbital ab initio calculations were run on GAUSSIAN94[10] at the CBS-Q level. The CBS-Q model[8] estimates electronic energies with high accuracy (0.8 kcal/mol standard deviation);[11] it combines the results of several different calculations as an approximation to a single, very high level computation which is yet much too expensive to be practical. The model first optimizes the geometry at the MP2/6-31G(d) level of theory and calculates the zero-point vibrational energy (ZPE) at the HF/6-31G level. It then calculates a base energy using a large basis set, MP2/6-311+G(3d2f,2df,2p), and performs a CBS extrapolation to correct the energy through second order. It also performs two additional calculations: MP4(SDQ)/6-31+G(d(f),d,f), to approximate higher order correlation effects, and QCISD(T)/6-31+G, for still higher order effects. The model also has empirical corrections for spin

---

(5) (a) Lewis, E. S.; Copper, J. E. *J. Am. Chem. Soc.* **1962**, *84*, 3847. (b) Kauffmann, T.; Boettcher, F.-P. *Chem. Ber.* **1962**, *95*, 949.

(6) (a) Wittig, G.; Pohmer, L. *Angew. Chem.* **1955**, *67*, 348. (b) Friedman, L.; Logullo, F. M. *J. Org. Chem.* **1969**, *34*, 3089.

(7) (a) Carvalho, M.; Sparrapam, R.; Mendes, M. A.; Kascheres, C.; Eberlin, M. N. *Chem. Eur. J.* **1998**, *4*, 1161. (b) Moraes, L. A. B.; Gozzo, F. C.; Eberlin, M. N. *J. Org. Chem.* **1997**, *62*, 5096. (c) Sparrapan, R.; Mendes, M. A.; Gozzo, F. C.; Carvalho, M.; Eberlin, M. N. Submitted for publication.

(8) Ochterski, J. W.; Peterson, G. A.; Montgomery, J. A., Jr. *J. Chem. Phys.* **1996**, *104*, 2598.

(9) (a) Moraes, L. A. B.; Pimpim, R. S.; Eberlin, M. N. *J. Org. Chem.* **1996**, *61*, 8726. (b) Eberlin, M. N.; Sorrilha, A. E. P. M.; Gozzo, F. C.; Sparrapan, R. *J. Am. Chem. Soc.*, **1997**, *119*, 3550. (c) Sparrapan, R.; Mendes, M. A.; Ferreira, I. P. P.; Eberlin, M. N.; Santos, C.; Nogueira, J. C. *J. Phys. Chem. A* **1998**, *102*, 5189. (d) Eberlin, M. N. *Mass Spectrom. Rev.* **1997**, *16*, 113. (e) Mendes, M. A.; Moraes, L. A. B.; Sparrapan, R.; Eberlin, M. N.; Kostiainen, R.; Kotiaho, T. *J. Am. Chem. Soc.* **1998**, *120*, 7869.

(10) Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Gill, P. M. W.; Johnson, B. G.; Robb, M. A.; Cheeseman, J. R.; Keith, T.; Petersson, G. A.; Montgomery, J. A.; Raghavachari, K.; Al-Laham, M. A.; Zakrzewski, V. G.; Ortiz, J. V.; Foresman, J. B.; Peng, C. Y.; Ayala, P. Y.; Chen, W.; Wong, M. W.; Andres, J. L.; Replogle, E. S.; Gomperts, R.; Martin, R. L.; Fox, D. J.; Binkley, J. S.; Defrees, D. J.; Baker, J.; Stewart, J. P.; Head-Gordon, M.; Gonzalez, C.; Pople, J. A. GAUSSIAN94, Revision B.3; Gaussian, Inc., Pittsburgh, PA, 1995.

(11) Foresman, J. B.; Frisch, A. E. *Exploring Chemistry with Electronic Structure Methods;* Gaussian: Pittsburgh, PA, 1993.

**Table 1. Total and Relative Energies from *ab Initio* CBS-Q Calculations**

| ion | energy (hartree) | rel energy (kcal/mol) |
|---|---|---|
| **4a** | −246.873 83 | 0 |
| **4b** | −246.845 36 | 17.9 |
| **4c** | −246.837 30 | 22.9 |
| **TS**$_{\mathbf{4a-4b}}$ | −246.745 25 | 62.8 |
| **6a** | −262.904 87 | 9.1 |
| **6b** | −262.907 16 | 7.6 |
| **6c** | −262.863 06 | 35.2 |
| **6d**[a] | −262.919 30 | 0 |
| **7a** | −228.600 87 | 0 |
| **7b** | −228.598 74 | 1.3 |
| **8a** | −551.244 13 | 8.7 |
| **8b** | −551.258 10 | 0 |
| **9a** | −208.767 74 | 2.3 |
| **9b** | −208.771 54 | 0 |

[a] **6d** is an acyclic isomer resulting from charge-induced ring-opening of **6b**; see Scheme 3.

contamination and a size-consistent higher-order correction.[11] Orbitals were visualized using SPARTAN 4.1.2.[12]

The MS$^3$ experiments were performed using an Extrel (Pittsburgh, PA) pentaquadrupole mass spectrometer, which is described in detail elsewhere.[13] The instrument, denoted as Q1q2Q3q4Q5, consists of three mass-analyzing quadrupoles (Q1, Q3, Q5), which are used to either mass-select or mass-analyze ions, and two reaction quadrupoles (q2, q4), in which either low-energy ion/molecule reactions or collision-induced dissociations (CID) are performed. For the MS$^3$ experiments, the precursor ions were formed by dissociative 70 eV electron ionization (EI) of 2-chloropyridine, 3-chloropyridine, 4-chloropyridine, 2-chloropyrimidine, or 5-bromopyrimidine. First, Q1 is used to mass-select the precursor ion for near 0 eV collisional quenching with cyclohexane in q2. Subsequently, the surviving precursor ion is mass-selected by Q3 for 15 eV CID with argon in q4, while scanning Q5 to record the product spectrum. The target gas pressures used in q2 and q4 correspond to a typical beam attenuation of 50−70%, viz., to multiple collision conditions. The collision energies were calculated as the voltage difference between the ion source and the collision quadrupole.

## Results and Discussion

***Ab Initio* Calculations**: **Pyridyl and Pyrimidyl Cations**. Table 1 compares the CBS-Q *ab initio* relative energies of the isomeric ions, whereas Figure 1 summarizes their optimized structures. Major contribution of *o*-aryne-like structures of **4a**, **6a**, and **6b** would be suggested by the calculations if they provide both optimized structures with considerably shorter N−C$^+$ bond lengths (and therefore greater N−C$^+$ bond orders) and electronic energies substantially lower than those of the nonconjugated isomers.

Indeed, the extra electronic stability anticipated for **4a**, **6a**, and **6b** is notable at the CBS-Q level. Ion **4a** is as much as 17.9 and 22.9 kcal/mol more stable than **4b** and **4c**, respectively. Therefore, the extent of the extra resonance stabilization in **4a** well exceeds the opposite destabilizing electron-withdrawing effect resulting from placing the electronegative nitrogen atom adjacent to the positive charge site.

Ions **6a** and **6b** are stabilized by the extra resonance even more pronouncedly. The ions display quite similar electronic energies, which lie 26.4 (**6a**) and 27.8 kcal/mol (**6b**) below that of the nonconjugated isomer **6c**. Therefore, in **6a**, placing a second nitrogen atom adjacent to the carbon positive charge site results in no extra stabilization. This finding suggests that any extra orbital overlap stabilization conferred by the second N in **6a** is canceled by its destabilizing electron-withdrawing effect.

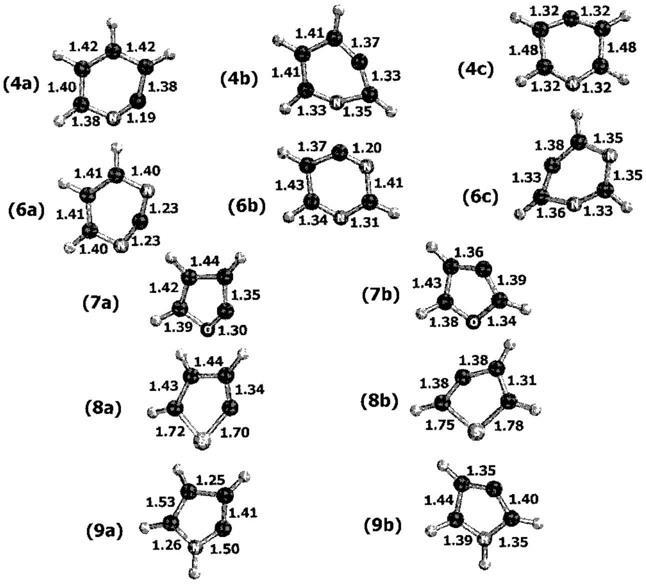


**Figure 1.** CBS-Q optimized structures for the ions investigated. Only the major bond lengths (Å) are specified.

The “uncharged” N−C bonds in **4a**, **6a**, and **6b** (Figure 1) are just slightly longer (1.38−1.41 Å) than the C−N bonds in neutral pyridine (1.34 Å). However, the corresponding “charged” N−C$^+$ bonds are considerably shorter (1.19−1.23 Å), with lengths very close to those expected for a $N{\equiv}C$ triple bond (1.17 Å). Therefore, the N−C$^+$ bonds of **4a**, **6a**, and **6b** are about 0.11−0.15 Å shorter than normal aromatic C−N bonds. Such an effect of bond shortening resulting from orbital overlap is much more pronounced than that observed for *o*-benzyne, in which the $C{\equiv}C$ bond is 0.05 Å shorter than normal C−C aromatic bonds.[14]

The effective orbital overlap also deforms considerably the rings of **4a**, **6a**, and **6b** (Figure 1); that is, it results in N−C$^+$−C(N) bond angles (**4a** (137.2°), **6a** (154.6°), and **6b** (132.2°)) that are much greater than those of the normal N−C−N angles of 120° in neutral pyridine.

Bond orders for N−C$^+$ as estimated via electron localization calculations further characterize the *o*-hetarynium ion structures of **4a**, **6a**, and **6b**; whereas aromatic N−C bond orders are typically near 1.5, substantially higher bond orders are obtained for the N−C$^+$ bonds of **4a** (2.04), **6a** (1.81), and **6b** (2.06).

The orbital overlap in **4a**, **6a**, and **6b** is also evident when examining their MO’s, by comparing them to those of neutral pyridine. In the 12th highest MO of neutral pyridine (Figure 2), the inner and outer atomic pyridine orbital lobes generate a continuous and symmetrical molecular orbital that contributes significantly to establish the ring $\sigma$ bonds. However, in the corresponding MO of the *o*-hetarynium ions **4a** and **6a** (Figure 2), the very effective overlap between the outer lobes of the atomic orbital of nitrogen and those of the adjacent C$^+$ removes the symmetry, forming a rather compact molecular orbital. Electron density in this orbital is therefore high

---

(12) Hehre, W. J.; Yu, J.; Klunzinger, P. E. *A Guide to Molecular Mechanics and Molecular Orbital Calculations in SPARTAN*; Wavefunction: Irvine, CA, 1997.

(13) Juliano, V. F.; Gozzo, F. C.; Eberlin, M. N.; Kascheres, C.; Lago, C. L. *Anal. Chem.* **1996**, *68*, 1328.

(14) Laing, J. W.; Berry, R. S. *J. Am. Chem. Soc.* **1976**, *98*, 660.

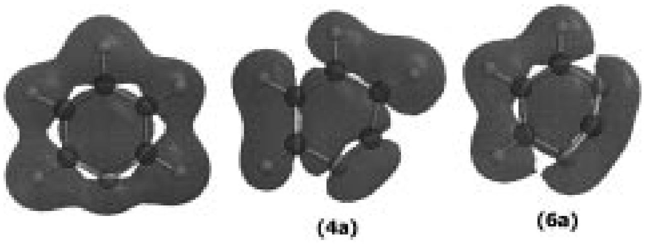


**Figure 2.** Twelfth highest MO's of neutral pyridine and the *o*-hetarynium ions **4a** and **6a**.

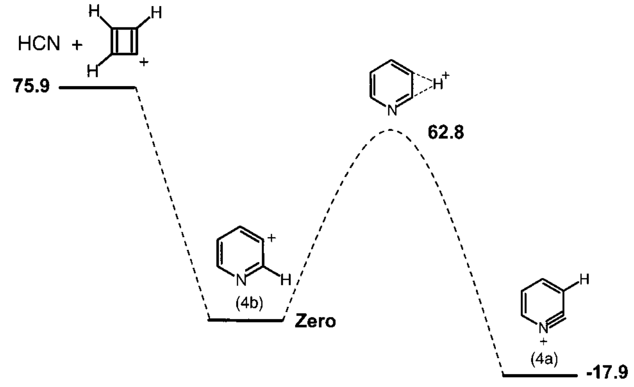


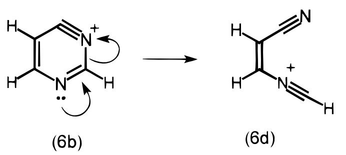
**Figure 3.** *Ab initio* CBS-Q potential energy surface diagram for H-ring walking isomerization and dissociation by HCN loss of **4b**. Energies are given in kcal/mol. Most data were taken from Table 1. CBS-Q energies for HCN and the $C_4H_3^+$ fragment are respectively (in hartrees) −93.286 18 and −153.438 16.

around the N−C atoms, and an additional and energy-stabilizing $\sigma$ bond is established. Similar orbitals are displayed by **6b** (not shown).

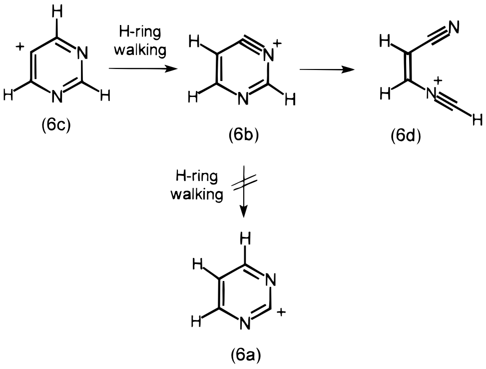
Although **6b** also displays a characteristic *o*-hetarynium ion structure, with an electronic energy close to that of **6a** (Table 1), in reactions with both conjugated dienes[7b] and cyclic acetals,[7a] **6b** fails to undergo the annulation reactions in which **6a** participates so pronouncedly (Scheme 2). Under CID conditions, **6b** also dissociates uniquely, more promptly, and exclusively by HCN loss.[7a] Ion **6b** is unique in that the location of its charge site can induce ring-opening to the acyclic isomer **6d** (Scheme 3). Similar charge-induced ring openings of both **6a** and **6c** are not likely, since such processes would form much more energetic vinyl cations or nitrenium ions, or both.[7a] CBS-Q calculations (Table 1) show that ring opening of **6b** is exothermic by −7.2 kcal/mol, leading to an acyclic isomer (**6d**) that is the most stable among the four $C_4H_3N_2^+$ isomers investigated.

**H-Ring Walking**. The greater stability of the *o*-hetarynium ions raises the question of whether the thermodynamically favored isomerization by H-ring walking[15] to the *ortho* isomer occurs for the *meta* and *para* isomers. To evaluate the kinetic constraint of such isomerizations, the energy of the transition state for **4a/4b** interconversions ($\mathbf{TS_{4a-4b}}$) was calculated (Table 1). $\mathbf{TS_{4a-4b}}$ was found to lie 62.8 kcal/mol above **4b**; hence, a quite high energy barrier hampers H-ring walking from **4b** to **4a** (Figure 3). The dissociation threshold of **4b** by HCN loss[7a] is, however, 75.9 kcal/mol; that is, 13.1 kcal/mol higher in energy than the barrier for H-ring walking (Figure 3). Therefore, H-ring walking in **4a** may occur to some extent for vibrationally excited ions. Reactions with both conjugated dienes[7a] and 2-methyl-1,3-dioxolane[7b] have suggested minor isomerization of both **4b** and **4c** to **4a.**

**Scheme 3**

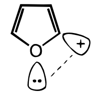


**Scheme 4**

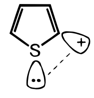


A substantial energy barrier is also likely to hamper H-ring walking from **6c** to **6b**; further, H-ring walking from **6b** to **6a** is both blocked by the 1,3-nitrogens and prevented by the facile ring opening of **6b** to **6d** (Scheme 4). In reactions of isomeric ions **6** with conjugated dienes[7a] and 2-methyl-1,3-dioxolane,[7b] both **6c** and **6b** show chemical reactivities that excluded any contribution of **6a**; that is, no H-ring walking to **6a** occurs.

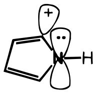
**Furanyl, Thiophenyl, and Pyrrolyl Cations**. For the 2-furanyl (**7a**) and 2-thiophenyl (**8a**) cations, the $sp^2$ orbital of oxygen or sulfur carrying the unshared electron pair may overlap with the coplanar and empty $sp^2$ carbon orbital:



(7a)



(8a)



(9a)

Hence, **7a** and **8a** could also display some *o*-arynelike character. For the 2-pyrrolyl cation (**9a**), however, no effective orbital overlap is expected; the unshared electron pair of nitrogen occupies a p orbital that participates in the $\pi$-aromatic cloud and that is perpendicular to the empty $sp^2$ carbon orbital.

For **7a** (Figure 1), the optimized structure indicates that orbital overlap occurs to some extent; the $O-C^+$ bond (1.30 Å) is slightly shorter than the O−C bond (1.38 Å). Orbital overlap results, however, in little electronic stabilization, as **7a** is only 1.3 kcal/mol more stable than **7b** (Table 1). For **7a**, the strong electron-withdrawing destabilizing effect of the very electronegative oxygen atom most likely cancels the extra stability conferred by the not so effective orbital overlap.

For **8a** (Figure 1), the similar $S-C^+/S-C$ bond lengths suggest no substantial orbital overlap. For **9a**, the $N-C^+$ bond length (1.50 Å) is considerably longer than that of the N−C bond (1.26 Å), which results from no extra

---

(15) Gallup, G. A.; Steinheider, D.; Gross, M. L. *Int. J. Mass Spectrom. Ion Proc.* **1976**, *22*, 185.

orbital overlap with the dominance of the electron-withdrawing, bond-destabilizing effect of the electronegative nitrogen atom. With no substantial extra orbital overlap, the 2-thiophenyl (**8a**) and 2-pyrrolyl cations (**9a**) are slightly *less* stable than their respective 3-isomers **8b** and **9b** (Table 1).

**MS$^n$ Experimental Data**. **MS**. The greater stability of **4a** affects the mass spectra of isomeric monosubstituted pyridines.[16] For instance, in the 70 eV EI mass spectra of the three isomeric 2-, 3-, and 4-chloropyridines,[16] the *m*/*z* 78 fragment (**4a**) is much more abundant for 2-chloropyridine. Similarly, the mass spectrum of 2-chloropyrimidine displays **6a** (*m*/*z* 78) as the most abundant fragment, but that of 5-chloropyrimidine displays no fragment with *m*/*z* 78 (**6c**).

**MS$^2$**. The higher stability of **4a** also influences, and is revealed by, double-stage (tandem) mass spectra.[17] The MS$^2$ low-energy CID spectrum of ionized 2-methylpyridine[17a] displays the *m*/*z* 78 fragment (**4a**) with a relative abundance of about 36%, whereas in the CID spectra of 3- and 4-methylpyridine, the fragment ions **4b** and **4c** are very minor (5−2%). Low-energy CID of ionized 2-ethylpyridine forms a unique fragment ion of *m*/*z* 78 (**4a**), which distinguishes 2-ethylpyridine from both the 3- and 4-isomers.[17b]

**MS$^3$ (Ion Quenching/Collision-Induced Dissociation Experiments)**. The greater thermodynamic stability of the *o*-hetarynium ions is further demonstrated by MS$^3$ ion quenching/CID experiments (Figures 4 and 5). The isomeric precursor ions were generated by 70 eV EI and mass-selected by the first mass-analyzing quadrupole (Q1). In an effort to minimize internal energy effects, near 0 eV collisions with cyclohexane in q2 were used to quench the nascent ions. Subsequently, the surviving ions were mass-selected by Q3 for 15 eV collisions with argon in q4, while Q5 was scanned to record the triple-stage mass spectra.

Both ionized 4-chloropyridine (Figure 4a) and 3-chloropyridine (Figure 4b) dissociate to the respective **4b** and **4c** of *m*/*z* 78 to medium and *very similar* extents. However, ionized 2-chloropyridine dissociates more promptly to **4a** (Figure 4c).

Ionized and collisionally quenched 2-chloropyrimidine dissociates extensively and exclusively to **6a** of *m*/*z* 79 upon 15 eV collisions with argon (Figure 5a). However, for ionized 5-bromopyrimidine (Figure 5b), fragment ions of *m*/*z* 131 and 104, formed by two consecutive HCN losses, effectively compete with the Br-loss fragment of *m*/*z* 79, that is, **6c**.

For the MS$^3$ results to be valid in comparing relative stabilities of fragment ions, it must be assumed that the energies of the isomeric precursor ions are not substantially affected by the different locations of the halogen substituent. This assumption is reasonable as ab initio calculations provide energies for the three isomeric ionized chloropyridines that vary just within a 3.2 kcal/mol range.[18] The MS$^3$ results also gain relevance when considering that all the precursor ions were formed, quenched, and dissociated under *the same tanden-in-space* QqQqQ experimental conditions.[9d]

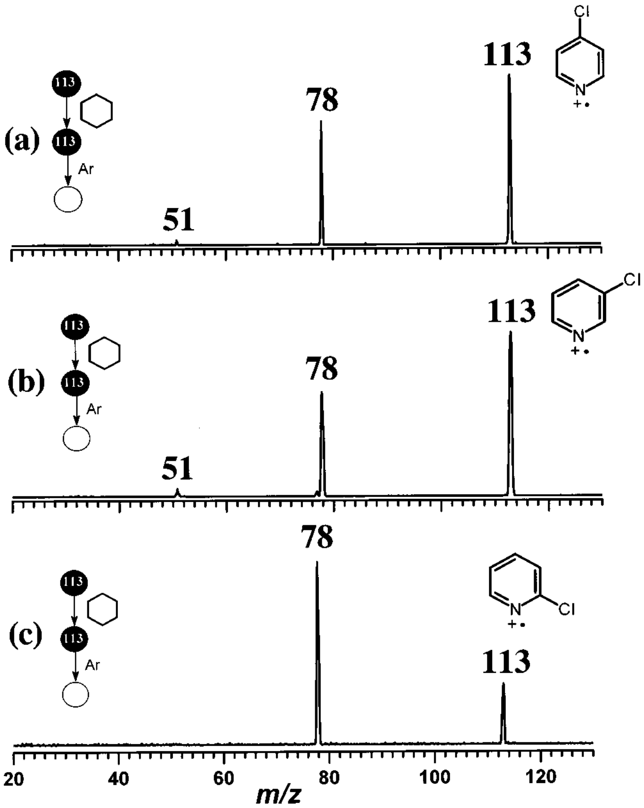


**Figure 4.** Triple-stage (MS$^3$) sequential product spectra of ionized (a) 4-chloropyridine, (b) 3-chloropyridine, and (c) 2-chloropyridine. In the terminology used to describe the type of MS$^n$ experiment and scan mode employed, a filled circle represents a fixed (or selected) mass, and an open circle, a variable (or scanned) mass, whereas the neutral reagent or collision gas that causes the mass transitions is shown between the circles. For more details on this terminology, see ref 19.

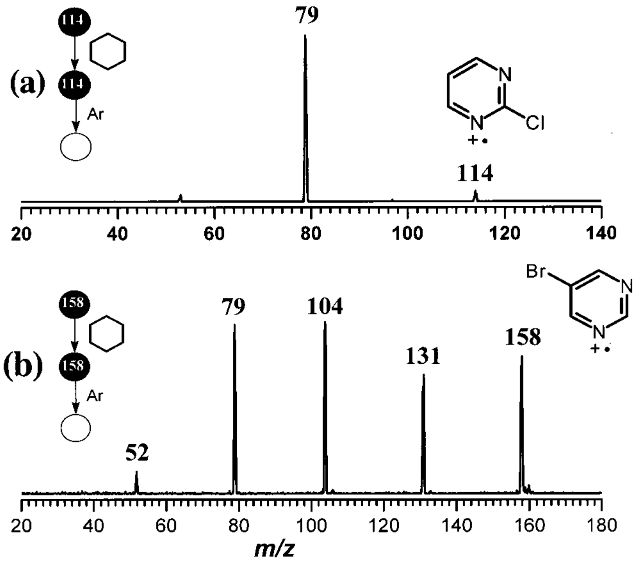


**Figure 5.** Triple-stage (MS$^3$) sequential product spectra of ionized (a) 2-chloropyrimidine and (b) 5-bromopyrimidine.

## Conclusion

The 2-pyridyl (**4a**) and 2-pyrimidyl (**6a**) cations are stable species in the gas-phase, in which they both

---

(16) McLafferty, F. W.; Stauffer, D. D. *The Wiley/NBS Registry of Mass Spectral Data*; Wiley: New York, 1989.

(17) (a) Gozzo, F. C.; Eberlin, M. N. *J. Am. Soc. Mass Spectrom.* **1995**, *6*, 554. (b) Sorrilha, A. E. P. M.; Gozzo, F. C.; Pimpim, R. S.; Eberlin, M. N. *J. Am. Soc. Mass Spectrom.* **1996**, *7*, 1126.

(18) G2MP2 energies (in hartrees) are as follows: ionized 2-chloropyridine, −705.301 67; ionized 3-chloropyridine, −705.304 62; ionized 4-chloropyridine, −705.306 93.

(19) Schwartz, J. C.; Wade, A. P.; Enke, C. G.; Cooks, R. G. *Anal. Chem.* **1990**, *62*, 1809.

display pronounced *o*-hetarynium ion structures. The fully occupied $sp^2$ nitrogen orbital of both **4a** and **6a** overlaps very efficiently with the adjacent, coplanar, and empty $sp^2$ $C^+$ carbon orbital. Such effective orbital overlap results in extensive charge delocalization, enhances considerably the $N-C^+$ bond order, drastically shortens the $N-C^+$ bond length, and stabilizes the *o*-hetarynium ions **4a** and **6a** by as much as 18−28 kcal/mol as compared to their positional nonconjugated isomers. The 4-pyrimidyl cation (**6b**) also displays the characteristic *o*-hetarynium ion structure, and substantial resonance stabilization, but both the calculations and its chemical behavior suggest that the ion easily isomerizes by charge-induced ring opening to form the more stable acyclic isomer **6d**.

**Acknowledgment.** This work was supported by the Research Support Foundation of the State of São Paulo (FAPESP) and the Brazilian National Research Council (CNPq).

JO980599+