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Ab Initio Calculations and Mass Spectrometric Determination of the Gas-Phase Proton Affinities of 4,4′-Disubstituted 2,2′-Bipyridines

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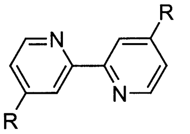
The gas-phase proton affinities of 4,4′-di(R)-2,2′-bipyridines (R: H, Br, Cl, NO_2, Me) were determined by mass spectrometric measurements and by ab initio calculations at the HF/6-31G** and MP2/6-31G** levels of theory. The energy barriers for rotation about the central C−C bond were also studied computationally. Two minima were found for both unprotonated and protonated species, the global minima being at the trans planar and cis planar conformations, respectively. Local minima for the unprotonated compounds were at the cis nonplanar conformation and for the protonated compounds at the trans nonplanar. Two different proton affinity values were calculated for each compound by employing different conformations for the protonated species. The computational values were in good agreement with the experimental proton affinities. Substituents affect the proton affinity according to their ability to withdraw or to donate electrons, halogen and nitro-substituted bipyridines having a lower proton affinity and methyl-substituted bipyridine having a higher proton affinity than 2,2′-bipyridine itself.

Introduction

Polypyridines, especially 2,2′-bipyridine (2,2′-bpy), are widely used as ligands in metal complexes. The ability to form stable chelates and to coordinate with various metals makes 2,2′-bpy a suitable ligand for many applications. By substituting the 2,2′-bpy ring, it is possible to tune the properties of the ring system and thus to modify the properties of the complex. The substituents at the ring position 4,4′ are useful for this purpose. In complexes, the 2,2′-bpy appears most commonly in the cis conformation, so the substituents at the ring position 4,4′ do not establish any significant steric hindrance. The effects of the 4,4′-substituents on the electronic and photochemical properties of ruthenium complexes have been studied previously.[1] To evaluate the substituent effects on the availability of the nitrogen lone pair, we were interested in the proton affinities (PA) of the substituted 2,2′-bpy compounds. To our knowledge, there is no extensive PA data available for the 4,4′-substituted 2,2′-bpy compounds shown in Figure 1. However, studies exist of the PA of 2,2′-bpy, including a spectroscopic estimate,[2] AM1 calculations,[3] ab initio calculations,[4] and mass spectrometric studies.[5] The previous mass spectrometric study provides a relative proton affinity of 2,2′-bpy compared to some other pyridine ring systems.[5]

There are some conformational aspects that concern the proton affinity of 2,2′-bpy. The 2,2′-bpy is in a trans planar conformation in solid state,[6] and there is evidence of a near-planar trans conformation in solution.[7] Previous ab initio calculations in the gas phase have given the trans planar conformation as the global minimum structure. However, there is a local minimum at the cis nonplanar structure.[4,8] The rotational barrier of 2,2′-bpy has been studied recently in detail using density functional methods.[9] Ab initio calculations made by Howard show that there is the possibility of the protonated form existing in two conformations, in a trans nonplanar conformation (local minimum) and in a cis planar (global minimum) one.[4] Raman scattering studies suggest that this is also the case in solution.[10] Semiempirical calculations have provided somewhat different results.[11,12] The



1-5

1 R: H
2 R: Br
3 R: Cl
4 R: Me
5 R: NO_2

FIGURE 1. Studied compounds.

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effect of conformation on the proton affinity of 2,2′-bpy has been studied using AM1 calculations[3] but ignoring the possibility that the unprotonated and protonated species could exist in different conformations.

The present study provides the gas-phase proton affinities for 2,2′-bpy and also for various 4,4′-disubstituted 2,2′-bpy's (Figure 1) determined by mass spectrometric measurements and by ab initio calculations at the HF/6-31G** and MP2/6-31G** levels. An energy barrier for rotation about the central C−C bond was also calculated for each compound. The study provides information about the intrinsic effect of the substituents on the proton affinities and on the conformations. The comparison of the mass spectrometric values with the computational values at different levels of theory provides valuable information about the accuracy of the calculations.

Methods

The mass spectrometry experiments were performed on a Bruker BioApex 47e Fourier transform ion cyclotron resonance (FTICR) mass spectrometer (Bruker Daltonics, Billerica, MA). This device is equipped with an Infinity cell, a 4.7 T 160 mm bore superconducting magnet (Magnex Scientific Ltd., Abingdon, U.K.), and an external electrospray ion source (Analytica of Branford, Inc., Branford, CT). Normal operating conditions were as follows: the sample was introduced through a syringe infusion pump at a flow rate 50 μL h^{-1}, and heated nitrogen (225 °C) was used as a counter-current drying gas. The ion source voltages were at a constant +3.5 kV to the cylinder, end plate, and capillary. The scan accumulation and data processing were performed using the Bruker XMASS software version 5.0.6. Each spectrum measured consisted of an average of 16 scans. The instrument was calibrated externally using a water/acetonitrile solution of sodium trifluoroacetate, as introduced by Moini et al.[13]

For ion−molecule reactions, neutral reagents were introduced into the cell using a precision variable leak valve (Varian, Palo Alto, CA) until a pressure of 5.0×10^{-8} Torr was observed. Argon was introduced into the cell through a pulsed valve for cooling the protonated bipyridines formed under the electrospray. After a delay of 1 s, the cooled ions were isolated using the correlated harmonic excitation field (CHEF) procedure.[14] The isolated ions were allowed to react with the neutral reagent for 20 s before the product ions were detected. All of the data was background corrected. This procedure involved the reaction of an isolated nonexisting ion near the *m*/*z* value of the ion of interest under the original reaction conditions. The product ions observed during the reaction arise from the reactions of ions other than the ion of interest and were subtracted from the product distribution observed for the reaction of the ion of interest. The neutral bases that were used, 2,2′-bipyridine **1** and 4,4′-dimethyl-2,2′-bipyridine **4**, were obtained from commercial suppliers, and they were used as received. 4,4′-Dibromo-2,2′-bipyridine **2**, 4,4′-dichloro-2,2′-bipyridine **3**, and 4,4′-dinitro-2,2′-bipyridine **5** were prepared according to the literature procedures.[15,16]

The calculations were carried out using the GAUSSIAN 98 program.[17] The geometry optimizations and harmonic frequency calculations were performed at both the MP2 and HF levels employing the 6-31G** basis set. Zero-point energy (ZPE) corrections were scaled with a semiempirical correction factor.[18] The basis set superposition error (BSSE) correction[19] was estimated from a single-point calculation by adding ghost functions in place of hydrogen in the optimized protonated structures. The energies for rotational barriers were calculated at the MP2/6-31G** level.

TABLE 1. Bracketing Experiments To Determine Proton Affinities[a,b]

test base	PA (kJ/mol)	**1**	**2**	**3**	**4**	**5**
triethylamine	981.8	+	+	+	−	+
N,*N*-dimethylisopropylamine	970.6	+				
2,3-lutidine	958.9	−	+	+		+
piperidine	954.0	−	+	+		+
diethylamine	952.4	−	−	−		+
2-methylaniline	890.9					+
N-methylacetamide	888.5					−
aniline	882.5					−

[a] Proton affinity values are from ref 21. [b] Symbols indicate whether proton transfer to the test base was observed (+) or not (−).

Results and Discussion

The experimental PAs of bipyridines **1**−**5** (Tables 2 and 3) were measured by means of the proton transfer bracketing method (Table 1) allowing the protonated bipyridines to react with selected neutral bases with known proton affinities in the cell of a Fourier transform ion cyclotron resonance mass spectrometer. As a result of the absence of suitable sufficiently volatile neutral reagents, only approximate estimates of the proton affinity values could be established. It should also be noticed that, in reality, bracketing experiments produce ΔG values that can be regarded as representing the proton affinity values (ΔH) if the entropy term is insignificant ($\Delta G = \Delta H - T\Delta S$). However, when the conformation changes upon protonation, as was the present case, the $T\Delta S$ term may affect the PA by underestimating the actual value.[20]

The energy barriers for rotation about the central C−C-bond were calculated for all of the protonated and unprotonated compounds presented in Figure 1. The energies were calculated by varying stepwise the dihedral angle (N−C−C−N) by 10° (**1**) or 20° (**2**−**5**) steps from 0° to 180°, while the rest of the molecule was allowed to be optimized freely. The results for the unprotonated and protonated compounds are presented in Figures 2 and 3, respectively. For the unprotonated species **1**−**5**, the global minimum is at the dihedral angle (χ) 180°, the trans planar conformation, and a local minimum at around 45°. The results are in agreement with previous

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TABLE 2. **Computational Trans-Cis Proton Affinities, the Experimental Values (kJ/mol), and Computational Δ*S* Values (J/mol K)**

	1	2	3	4	5
ZPE[a] HF	36.0	35.4	35.4	35.8	34.8
ZPE[b] MP2	35.4	34.6	34.5	34.8	33.5
BSSE HF	1.4	1.4	1.4	1.5	1.3
BSSE MP2	12.6	12.4	12.4	12.7	12.1
PA HF	997.6	962.1	959.0	1018.1	894.4
PA MP2	976.7	946.5	946.1	994.6	900.3
ΔS MP2[c]	−3.2	3.8	4.6	−0.9	−7.4
PA_{exp}[d]	958.9−970.6	952.4−954.0	952.4−954.0	>981.8	888.5−890.9

[a] Scaled with an empirical correction factor of 0.9181.[18] [b] Scaled with an empirical correction factor of 0.9608.[18] [c] The computational estimations of ΔS values were carried out without taking into account possible internal rotations in the system. [d] Mass spectrometric values.

TABLE 3. **Computational Trans-Trans Proton Affinities, the Experimental Values (kJ/mol), and Computational Δ*S* Values (J/mol K)**

	1	2	3	4	5
ZPE[a] HF	35.5	34.7	34.9	35.4	34.3
ZPE[b] MP2	36.6	35.6	35.7	36.1	34.8
BSSE HF	1.6	1.5	1.4	1.6	1.2
BSSE MP2	13.3	13.0	13.0	13.4	12.4
PA HF	969.5	934.9	932.0	990.6	868.4
PA MP2	945.1	916.2	915.7	963.9	870.0
ΔS MP2[c]	−3.6	3.7	3.7	−1.7	−7.9
PA_{exp}[d]	958.9−970.6	952.4−954.0	952.4−954.0	>981.8	888.5−890.9

[a] Scaled with an empirical correction factor of 0.9181.[18] [b] Scaled with an empirical correction factor of 0.9608.[18] [c] The computational estimations of ΔS values were carried out without taking into account possible internal rotations in the system. [d] Mass spectrometric values.

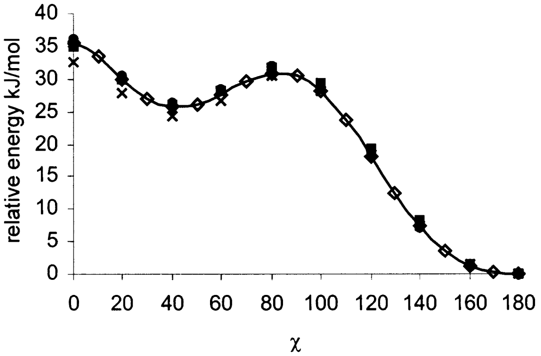

FIGURE 2. Relative energies for unprotonated compounds plotted against the dihedral angle (N−C−C−N). R: H, ◇; NO_2, ×; Cl, ▲; Br, ■; Me ●.

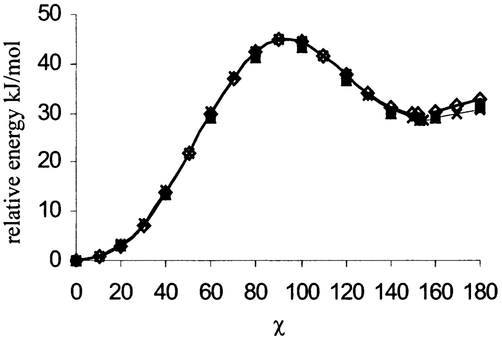

FIGURE 3. Relative energies for protonated compounds plotted against the dihedral angle (N−C−C−N). R: H, ◇; NO_2, ×; Cl, ▲; Br, ■; Me, ●.

ab initio studies for 2,2′-bpy.[4,8] A gas-phase electron diffraction study of 2,2′-bpy also supports these results.[22] In Howard's computational study, the optimizations were performed at the HF/6-31G** level, followed by single-point calculations at the MP2/6-31G** level.[4] Since 2,2′-bpy appears in nonplanar trans conformation in solution,[7] it was suggested that the difference between the conformations in the gas phase and in solution to arise either from the absence of an electron correlation during the optimization or from the interactions with the solvent in the case of solution.[4] The present study indicates, by including the electron correlation in optimizations, that the solvent effect is the more probable explanation. The substituents at the 4,4′-position have no significant effect on the rotational barrier. This seems reasonable since there is no evident reason why any of the substituents would have either a destabilizing effect on the planar conformation or cause additional stabilization for some other conformation. A search conducted on the Cambridge Structural Database afforded the solid-phase structures for compounds **4** and **5**. The compounds are in the planar trans conformation ($\chi = 180°$) in the solid state.

For the protonated species, the global minimum is at the cis planar structure ($\chi = 0°$) and a local minimum can be found at around 150°. In the local minimum structure, the dihedral angle is 155 ± 2.5° for all compounds. The results agree with the previous ab initio study.[4] A search was conducted on the Cambridge Structural Database for solid-phase structures for the protonated 4,4′-substituted 2,2′-bpy's, all of the structures found in which the rotation around the central C−C-bond

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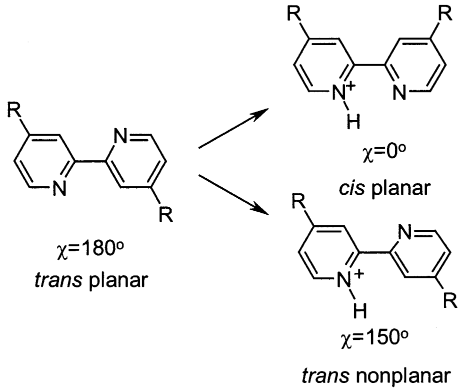

FIGURE 4.

had been possible were at the cis planar or the cis near-planar ($\chi = 0-25°$) conformation. The planar cis structure is favored by the interaction between the nitrogen lone pair and the proton in the adjacent ring. It has also been proposed that planar structures could be further stabilized by π-delocalization between the pyridyl rings.[4] An unfavorable interaction in the cis planar conformation arises mainly from the repulsion between the hydrogens H_3 and $H_{3'}$.

Two PA values were calculated for each compound by using different conformations for the protonated species. One value was calculated by employing the local minimum structure trans nonplanar, and the other was calculated by employing the global minimum, the cis planar structure (Figure 4). The geometry used for unprotonated species was the trans planar structure. The calculated proton affinities, together with the ZPE and BSSE corrections, are presented in Tables 2 and 3. When the results from the HF and MP2 calculations are compared, the difference is dependent on the substituent. For **1**−**4**, the MP2 values are smaller and for **5** slightly larger than the HF PAs. The ZPE correction is of the same magnitude for both levels. The ZPE corrections differ by only ca. 1 kJ/mol, and hence, the HF values provide a good approximation of the ZPE correction for MP2 calculations. A difference can be found in the BSSE corrections, which for the HF calculations are ca. 1.5 kJ/mol and for the MP calculations ca. 13 kJ/mol. Comparison with the results for 2,2′-bpy calculated by Howard[4] shows that the inclusion of the electron correlation in the optimizations has only a small effect on the PA (ca. 1.4 kJ/mol, with different scaling factors for the ZPE correction). Even though the absolute values in the HF and MP2 calculations are different, the relative magnitudes of the PAs throughout the substituent series remain the same.

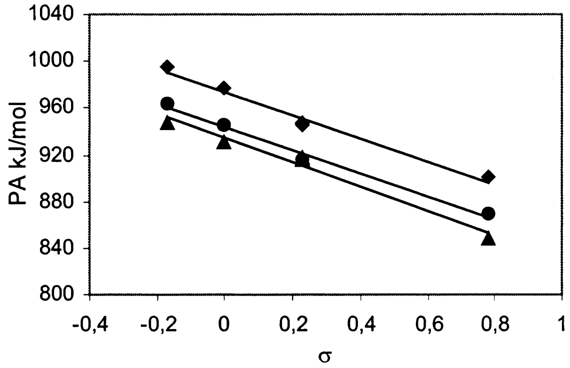

FIGURE 5. Hammett plot: experimental PAs for 4-substituted pyridines,[21] ▲; MP2/6-31G** PAs trans → cis, ◆; trans → trans, ●.

Computational MP2 trans-trans PA values (Table 3) are lower than the corresponding experimental values for all of the compounds studied. The trans-cis PAs (Table 2) are larger than the experimental ones in the case of **1** and **5**. For the halogen-substituted compounds **2** and **3**, the computational values are slightly smaller than the experimental ones. Overall, the computational PAs provided a good estimate of the experimental PAs. It has been suggested on the basis of a comparison made of the computational and experimental values for pyridine that calculations at the MP2/6-31G**//HF/6-31G** level overestimate the PA values.[4] From this, it would appear that the trans-cis values may be more reliable. Nevertheless, from the present results it can be seen that, when different substituents are concerned, an overestimate cannot always be taken for granted. The rotational barrier for protonated compounds from the trans nonplanar structure (local minimum) to the cis planar (global minimum) is approximately 15 kJ/mol, which is reasonably small to be overcome, at least in the gas phase. Raman scattering studies suggest that both conformations exist in solution, depending on the pH.[10] Pyridine ($pK_a = 5.23$) is a stronger base in solution than 2,2′-bpy ($pK_a = 4.35$) but has a lower proton affinity (930 kJ/mol)[21] in the gas phase than 2,2′-bpy (Table 2). This difference in basicities may be caused by different conformational behavior of 2,2′-bpy in the gas phase and in solution. As expected, substituents affected the PA according to their ability to withdraw (NO_2, Br, and Cl) or to donate (CH_3) electrons. The electronic effects of the substituents in the para position can be seen by plotting computational PA values against Hammett substituent constants (σ).[23] Hammett plots are presented in Figure 5 together with the experimental PA values[21] for the corresponding 4-substituted pyridine compounds A linear correlation was found in all cases showing a systematic change in the PA values with the change of electron-donating/accepting nature of the substituent.

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Supporting Information Available: Cartesian coordinates and energies for all calculated compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

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