

Theoretical study of guanine–Cu and uracil–Cu (neutral, anionic, and cationic). Is it possible to carry out a photoelectron spectroscopy experiment?

Ana Martínez^{a)}

Instituto de Investigaciones en Materiales, Universidad Nacional Autónoma de México (UNAM), Circuito Exterior S/N, Ciudad Universitaria, 04510 Coyoacán, México Distrito Federal, México

(Received 16 March 2005; accepted 25 April 2005; published online 20 July 2005)

The structure and bonding of guanine–Cu and uracil–Cu (neutral, anionic, and cationic) are discussed on the basis of the calculated structures and energies. The interaction of the metal atom with guanine and uracil has been analyzed using the B3LYP density-functional approach. The removal of one electron from the neutral complexes produces the stabilization of one of the isomers, while the addition of one electron leads to a system where the metal atom is weakly bounded to guanine or uracil, according to the metal-bases bond distance that is long (2.29–2.90). For guanine–Cu and uracil–Cu, the vertical ionization energy of the anion is close to the dissociation energy of one hydrogen atom from guanine–Cu or uracil–Cu. In these cases, it could be possible to produce the detachment of one electron from the anion and also the removal of one hydrogen atom. This is important since the photoelectron spectroscopy of atomic or mixed-atomic cluster anions has proven to be a very effective tool in the study of small systems. For the analysis of copper atoms with DNA bases such as guanine and uracil, it is expected that the photoelectron spectra of the anion-bases complexes strongly resemble the spectrum of Cu^{-1} , just shifted to higher electron binding energies due to the product stabilization. Hopefully, this information will be useful for the experimental groups. © 2005 American Institute of Physics. [DOI: 10.1063/1.1935507]

INTRODUCTION

Studies of metal-DNA base complexes provide valuable thermodynamic and structural information relevant to our knowledge of metal effects on biological processes involving DNA.^{1–13} The interest in DNA is not only due to its role in biology but also to the advent of molecular electronics that has stimulated interest in the possibility of using this molecule in functional electronic devices and in molecular computing.¹² Metal centers complexed with DNA may function as electron acceptors and donors and have been successfully used to study the charge transport through strands of DNA. This may make DNA useful as a molecular wire in molecular scale electronic devices. Different structural and electronic factors may intercede electron transfer processes, and model complexes have been arranged to explore this effect.

The structure and function of DNA are, in general, dependent on metal ions. These ions can interact with many sites in DNA.^{3,7–18} For cationic systems, the best metal-binding site of the guanine seems to be N7, due to the large dipole moment of guanine (>7 D) and its orientation.^{3,7,8} Regarding the interaction of uracil with metal cations, the orientation and magnitude (>5 D) of the dipole moment orientate the metal-binding site of the uracil^{9,10} to O4. Most of the theoretical studies of metal-DNA interactions have focused on guanine and uracil complexes in which metal cat-

ions are bound to N7 or O4, respectively. Little is known about the energetic or properties of other isomers of metal–guanine and metal–uracil complexes in which the metal bounds to sites other than N7 or O4. It is not clear whether an analogous affinity for N7 or O4 applies to neutral as well. On the other hand, biologically important negatively charged molecules have been extensively studied, both experimentally^{19–21} and theoretically.^{22–26} Electron trapping on nucleic acid bases has been an important topic in radiation biology for several decades. The recent experiments of Sanche and co-workers suggest that electrons with energies in the range of 1–20 eV can induce DNA damage.^{27,28} The authors suggested that excess electrons trapped in temporary anionic states initiate chemical reactions leading to a single- and double-strand breaks. The excess of electrons can be provided by metal atoms and ions interacting with the DNA bases.

Photoelectron spectroscopy (PES) of atomic and mixed-atomic cluster anions has proven to be a very effective tool in the study of small clusters mainly for two reasons.^{21,29–34} First, photodetachment of an anion spectroscopically access the ground and low-lying electronic states of the neutral, many of which are not detectable with conventional absorption spectroscopy. Second, anions are inherently mass selectable, so clusters and molecules can be separated out by mass prior to any spectroscopic investigation. One question that can be answered with this theoretical study is if it is possible to use this powerful tool in the study of the interaction of DNA bases with copper atoms.

^{a)}Electronic mail: martina@matilda.iimatercu.unam.mx

Evidently, metal atoms and ions play an important role in stabilizing as well as destabilizing DNA bases, base pairs, and the DNA double helix. To understand the role of the metal ions in the biophysics of DNA, it is necessary first to carry out a detailed interaction study of ions with isolated bases. This is the aim of the present work. In this paper, stable structures of guanine–Cu and uracil–Cu (neutral, anionic, and cationic) are discussed. Optimized geometries, ionization energies, electron affinities, Mulliken atomic charges, and molecular orbitals are reported. The dissociation energy of one hydrogen atom from guanine–Cu or uracil–Cu is also presented. As discussed below, in these systems it could be possible to produce the detachment of one electron from the anion and also the dissociation of one hydrogen atom.

COMPUTATIONAL DETAILS

All calculations have been carried out using the program GAUSSIAN 03.³⁵ Full geometry optimization without symmetry constraints was performed using two different density-functional approximations: Becke–Perdew86 (Ref. 36) and hybrid three-parameter B3LYP.³⁷ Three different basis sets were used: 6-31G*, 6-311+G(2d,p),³⁸ and LANL2DZ.³⁹ Optimized minima were verified with harmonic frequency analysis. In search of the global minimum, several initial geometries were considered. We cannot exclude the possibility that global minima were missed but the diversity of initial geometries that were examined is sufficient to inspire confidence that the global minimum has been identified. The visualization of the results was done with the CERIUS package⁴⁰ and the MOLEKEL.⁴¹

In order to determine the position of the Cu atom complexing the guanine and uracil molecules, several initial geometries were used. For guanine–Cu, the Cu atom bonded to N7 or N3, inserted into the N1–H bond, or bridging the N3 and N9 positions was considered. With uracil, the Cu was connected to all the atoms. Several tautomeric forms of the guanine were used for the optimization with B3LYP and the three different basis sets. The effect of the basis is not significant. The energy difference between the three most stable structures is less than 3 kcal/mol for all the calculations. The stability order obtained with the larger basis is the same as those obtained with LANL2DZ. With the smallest basis, the stability order is a bit different. Considering that we are on the limits of accuracy of the calculations, it is possible to say that the effect of the basis on the results is really small. In order to evaluate the effect of the functional, for uracil–Cu two different density-functional approaches (BP86 and B3LYP) and two different basis sets (6-31+G* and LANL2DZ) were used. The energetic order is the same in both cases. The same calculations were performed for the cation and the anion molecules. The results obtained with B3LYP/LANL2DZ method are practically the same as those obtained with other methods. Hence, the effect of the basis set and the density functional is not significant. For this reason and in order to simplify the presentation, the focus of the discussion will be on the B3LYP/LANL2DZ results.

There is no universally accepted method of calculating

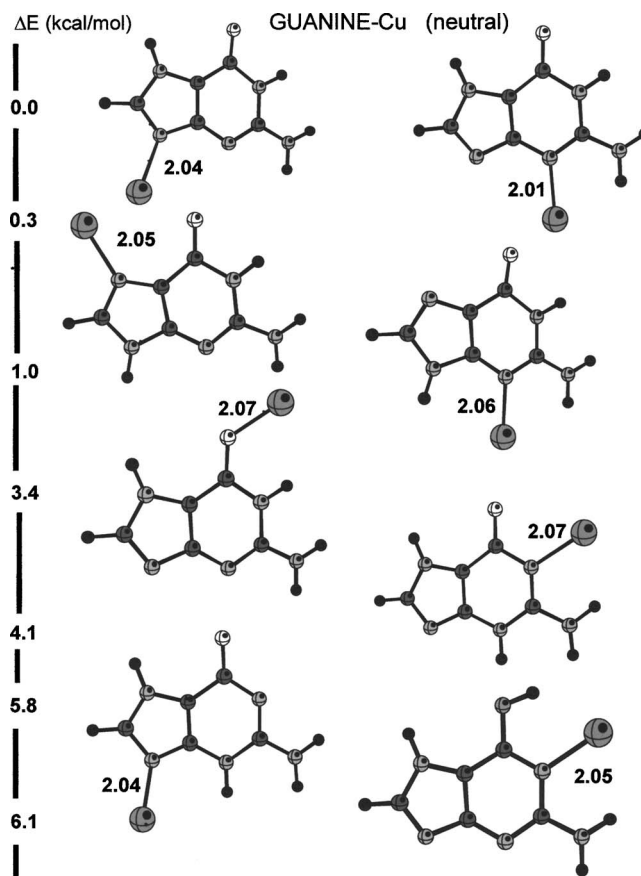


FIG. 1. Optimized guanine–Cu complexes. Initial geometries with different bond positions for the Cu atoms were used. Relative energies to the most stable structure in kcal/mol. Bond distances are reported in angstroms. All the calculations were done with B3LYP/LANL2DZ.

atomic charges, and no experimental technique is available to measure them directly. In a previous work, de Oliveira *et al.*⁴² reported an investigation testing the quality of Mulliken and Bader charges. They found a good agreement between both methods for a qualitative description of the atomic charges. For this reason, in this paper the Mulliken atomic charges are used to discuss the qualitative behavior of the charge-transfer process.

RESULTS AND DISCUSSION

Guanine–Cu (neutral, anion, and cation)

Optimized structures of guanine–Cu (neutral) are reported in Fig. 1. There are eight stable structures, with an energy difference of less than 7 kcal/mol. The structures are not planar, the Cu atom being out of the plane. The calculation of several isomers of the isolate guanine was also done. The optimization of guanine places the 9H form of guanine below the others, but the 7H form is only 0.22 kcal/mol higher. This result agrees with previous MBPT(2) reported by Dolgounitcheva *et al.*²⁵ where that energy difference is 0.21 kcal/mol. When the copper atom binds to guanine, the most stable isomer is the 7H form. The two most stable structures are with this isomer and are degenerated. As can be seen in the figure, one has a Cu–N9 bond and the other presents a Cu–N3 bond. For this isomer of the guanine, there

is another structure with a Cu-O bond that lies 3.4 kcal/mol higher. This energy difference is very small and it is on the limits of accuracy of the calculation. For the 7H form of guanine it is possible to conclude that N3, N9, and O are suitable for the metal to bind, with practically no difference on the stability between them. Figure 1 also shows two stable structures with the 9H form of guanine. The copper atom in this isomer can be bonded to N3 or to N7, with practically the same stability. Copper atom affects the stability of the tautomeric forms of the guanine. The energy difference between the two more stable structures of Fig. 1 is approximately the same as the energy difference between the tautomeric forms of the isolated guanine, but the ground state with copper is with the 7H isomer. For the next structures, the N3 has one hydrogen atom and the metal atom is bonded to N1 or to N9. Both structures present almost the same stability, with an energy difference of 1.7 kcal/mol among them. At 6.1 kcal/mol there is a structure with the copper atom bonded to the *cis*-amino-oxy 7H guanine isomer. The calculations of other isomers with the oxy-guanine forms were performed, and all of them present very similar stabilities. To simplify, we did not include the other optimized structures with the oxy-guanine in the figure, neither other structures that are less stable, such as the systems with the copper atom bonded to the oxygen or to the carbon atom of the five-membered ring (this structure lies 10.8 kcal/mol higher). It is possible to conclude that the Cu-N bond is preferred over the Cu-O bond in this molecule, but there are several isomers that could be present in an experiment, since the largest energy difference is less than 7 kcal/mol.

Figure 2 shows the optimized structures for the cationic guanine-Cu. All systems are singlets, while the neutrals are doublets. It is well known that the preferred sites for nucleobase-ion interaction are the N7 and the O6 positions of guanine (most often simultaneously binding to both sites). Guanine possess a large dipole moment, and its orientation supports the N7/O coordination. As can be seen, the most stable structure is separated by 10.1 kcal/mol from the second stable structure. In the ground state, copper is connected to N7 and O. This structure was reported before¹⁵ and agrees with the idea that these positions act as the active sites for the interaction of metal cations with nucleic acids in the various biological systems. In Table I, Mulliken atomic charges of selected atoms of guanine-Cu (cation) are reported. For comparison, the values of the neutral compound are included. As can be seen, the metal atom on the cation is the most positive atom. When ionization takes place, the electron is removed from the copper atom since the ionization energy of copper^{43(a)} (7.72 eV) is lower than the ionization energy of guanine^{43(b),44} (8.49 eV). Atomic charges indicate that the oxygen atom is negative and copper is positive in all the cationic isomers, as expected from the electronegativities of oxygen and copper. The metal atom becomes positive and there is an electrostatic interaction with the oxygen atom of guanine that is negative. Furthermore, the dipole moment guides the bond of the metal cation towards the N7 position of the guanine and only one stable structure is preferred over

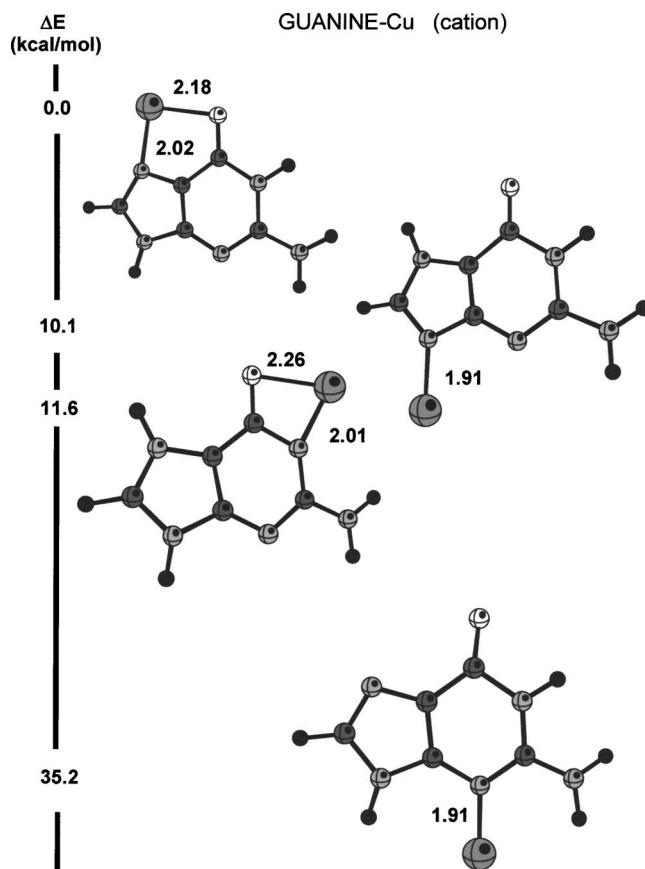
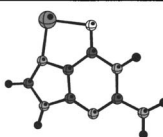
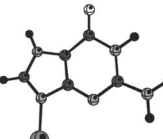
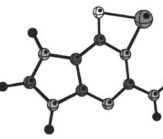


FIG. 2. Optimized guanine-Cu cationic complexes. Initial geometries with different bond positions for the Cu atoms were used. Relative energies to the most stable structure in kcal/mol. Bond distances are reported in angstroms. All the calculations were done with B3LYP/LANL2DZ.

TABLE I. Mulliken atomic charges of selected atom for the most stable isomer of guanine-Cu cationic. For comparison, Mulliken atomic charges of the neutral compound are also shown.

[guanine-Cu] ⁺¹	Mulliken Atomic Charges (e. u.)	
	Cation	Neutral
	O	-0.3
	N7	-0.2
	N9	-0.4
	Cu	-0.2
	O	-0.3
	N7	-0.4
	N9	-0.3
	Cu	-0.1
	O	-0.3
	N7	-0.3
	N9	-0.4
	Cu	-0.1

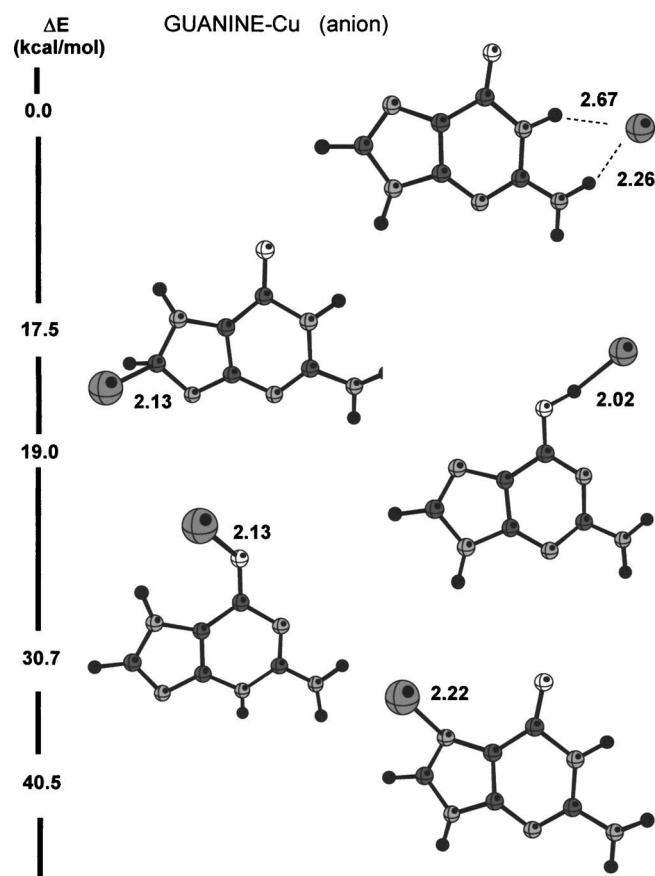


FIG. 3. Optimized guanine-Cu anionic complexes. Initial geometries with different bond positions for the Cu atoms were used. Relative energies to the most stable structure in kcal/mol. Bond distances are reported in angstroms. All the calculations were done with B3LYP/LANL2DZ.

the others. The copper is positive and the overall charge of guanine is negative. Hence, the bond between Cu^+ and guanine^- appears to have an ionic character.

Figure 3 reports the optimized structures of the anionic compounds. These systems are singlets. Triplets spin states were also calculated, but they are less stable. The most stable structure shows Cu-H long bonds, and hence it is possible to say that the metal atom is weakly bonded to guanine. The most stable structure with copper and guanine covalently bonded is 17.5 kcal/mol less stable. Table II contains the Mulliken atomic charges of selected atoms on the anionic compounds. As can be noticed, in this case the extra electron is localized on the copper due to the fact that the electron affinity of the metal atom is larger than that of guanine. For this reason, in the ground state the Cu is close to the hydrogen atoms that present a positive charge, and far from N7 and O that have negative charges. The third structure in Fig. 3 shows the Cu atom close to the hydrogen atom in an oximino isomer of guanine, which also has a partial positive charge.

In a previous work we reported the structures and reactivity of guanine-Al compounds.⁸ The results for Al suggest that the Al atom binds to the O and N. This implies that the Al-guanine bonding mainly involves an interaction with the lone pairs. The most significant result that was reported⁸ is that the most stable isomer is one where both of the nitrogen

TABLE II. Mulliken atomic charges of selected atom for the most stable isomer of guanine-Cu anionic. For comparison, Mulliken atomic charges of the neutral compound are also shown.

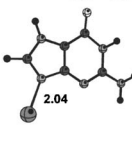
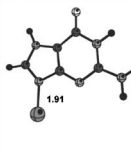
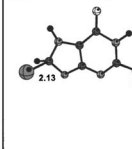
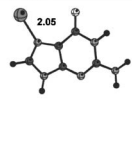
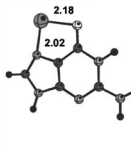
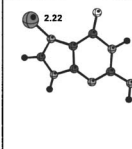
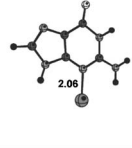
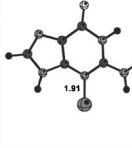
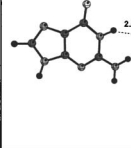
[guanine-Cu] ⁻¹	Mulliken Atomic Charges		
	Anion	Neutral	
	O	-0.3	-0.3
	N7	-0.1	-0.2
	N9	-0.4	-0.4
	Cu	-0.9	-0.2
	Anion	Neutral	
	O	-0.4	-0.3
	N7	-0.4	-0.4
	N9	-0.1	-0.3
	Cu	-0.5	-0.1
	Anion	Neutral	
	O	-0.3	-0.3
	N7	-0.2	-0.3
	N9	-0.4	-0.4
	Cu	-0.7	-0.2

atoms in the five-membered ring of guanine are bound to H. To our knowledge, there was no prior experimental or theoretical observation of such isomers of guanine. The more stable isomer of Al-guanine was found to be a complex of an Al atom with a previously unobserved, experimentally or theoretically, isomer of guanine and thus represented a significant discovery. With copper we also find a structure where both of the nitrogen atoms in the five-membered ring of guanine bound to H, but this structure (not shown) is 13.0 kcal/mol less stable than the others in Fig. 1. For the cation, it is 11.6 kcal/mol less stable (see Fig. 2) and for the anion, it lies more than 40 kcal/mol higher (not shown).

Table III reports the ionization energies and electron affinities (vertical and adiabatic) for the three most stable isomers of neutral guanine-Cu. For comparison, the structures of cationic and anionic species are also shown. Vertical and adiabatic ionization energies and electron affinities are different, due to the varied geometries of the neutral, cation, and anion systems. The first two isomers present similar ionization energies (4.8 and 4.4 eV), while the other shows a higher value (5.9 eV). The much higher ionization energy is characteristic of a species with a stronger oxidative potential. The adiabatic electron affinity is lower for the first two neutral isomers than for the third one, where for the anion the Cu is weakly bonded to the guanine. For the second isomer, the electron affinity is negative, meaning that the ionization leads to a less stable system. Clearly, the chemical properties of the isomers differ significantly.

Comparing the structures and bond distances of the neutral (Fig. 1) with the cationic (Fig. 2) it is possible to see that

TABLE III. Vertical and adiabatic ionization potential and electron affinity (in eV) of selected stable isomers of guanine-Cu neutral.

Ionization Energy		Electron Affinity		Neutral	Cation	Anion
Add	Ver	Add	Ver			
4.8	5.0	0.7	0.3			
				2.04	1.91	2.13
4.4	4.9	-0.3	-0.7			
				2.05	2.18 2.02	2.22
5.9	6.1	1.5	0.2			
				2.06	1.91	2.67 2.26

the geometries are not the same. The biggest difference is on the Cu-N bond distance. For the cationic species, this bond length is shorter than for the neutral. The stability order of the cationic systems is different, since the most stable cation corresponds to the third neutral structure. The most stable neutral structure corresponds to the second cationic geometry. The fourth neutral structure is the last one for the cation, and the fifth neutral is the third of the cationic system. These structures share an important characteristics, namely, that when one electron is removed the N-Cu bond distance decreases and the copper atom forms a bridge with oxygen and nitrogen (when O and N are close enough to do so). The formation of O-Cu-N bridges suggests that this geometry is characteristic of cationic Cu-DNA complexes, but it is not for neutral or anionic molecules. Neutral copper bonds equally (with the same stability) to guanine in three different nitrogen atoms and the Cu-O bond is also stable. For the anionic molecule, copper atom is weakly bonded to guanine.

Paying attention to the anions, when the metal is bonded to the guanine molecule the metal-N or metal-O bond distances are larger for the anion than for the neutral. The extra electron is localized in the highest occupied molecular orbital (HOMO) of the neutral, that is, an antibonding- π orbital between Cu and the nonmetal atoms, as can be seen in Fig. 4.

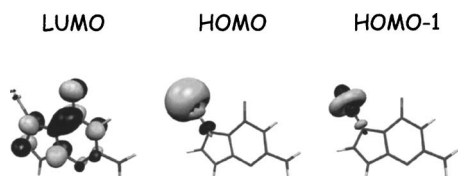


FIG. 4. Molecular orbitals of one isomer of guanine-Cu, as an example. Other molecular-orbitals pictures are similar.

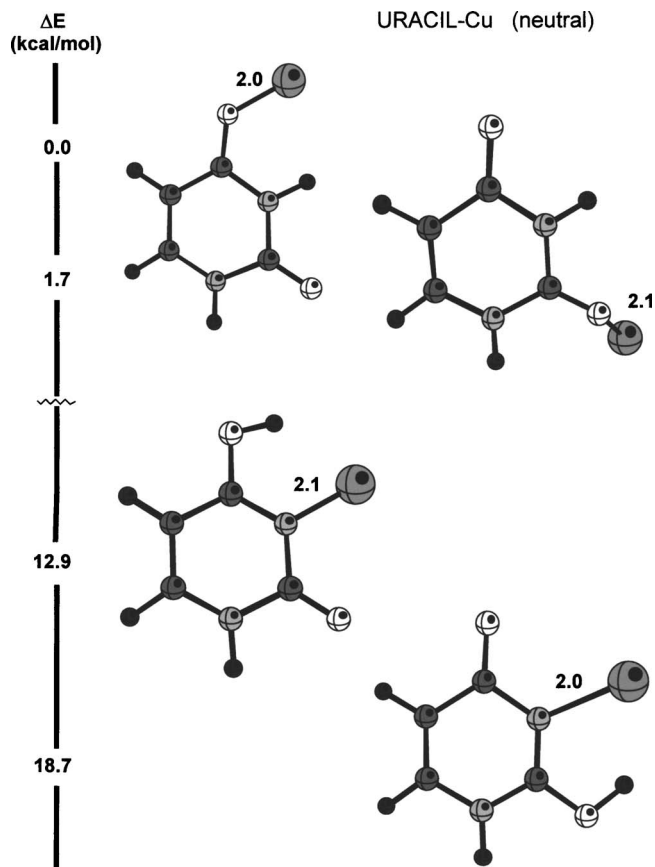


FIG. 5. Optimized uracil-Cu complexes. Initial geometries with different bond positions for the Cu atoms were used. Relative energies to the most stable structure in kcal/mol. Bond distances are reported in angstroms. All the calculations were done with B3LYP/LANL2DZ.

For the anion, the copper atom is weakly bonded to guanine. There is an electrostatic repulsion between the copper anion and guanine, since the extra electron is placed on copper and guanine molecule has a large dipole moment.

Uracil-Cu (neutral, anion, and cation)

Optimized structures of uracil-Cu (neutral) are reported in Fig. 5. There are four stable structures, with an energy difference of less than 20 kcal/mol. The structures are not planar, with the Cu atom being out of the plane. For brevity we did not include in this figure the other optimized structures that are less stable. The calculation of several isomers of the isolate uracil was also performed. The free uracil tautomers are separated by 18.3 and 24.9 kcal/mol from the most stable. These tautomers correspond to the arrangements of the uracil that are forming the third and fourth isomers of uracil-Cu (Fig. 5). For uracil, the metal atom does not interfere with the stability order of the different uracil tautomeric forms, i.e., the most stable complexes are formed starting from the most stable tautomers. When the copper atom binds to uracil, the most stable isomer contains the metal atom bonded to an oxygen atom. The energy difference between the two most stable structures is very small (1.7 kcal/mol) and hence they can be considered degenerated. The copper atom in this isomer can be bonded to O3 or to O4, with practically the same stability. It is possible to conclude that,

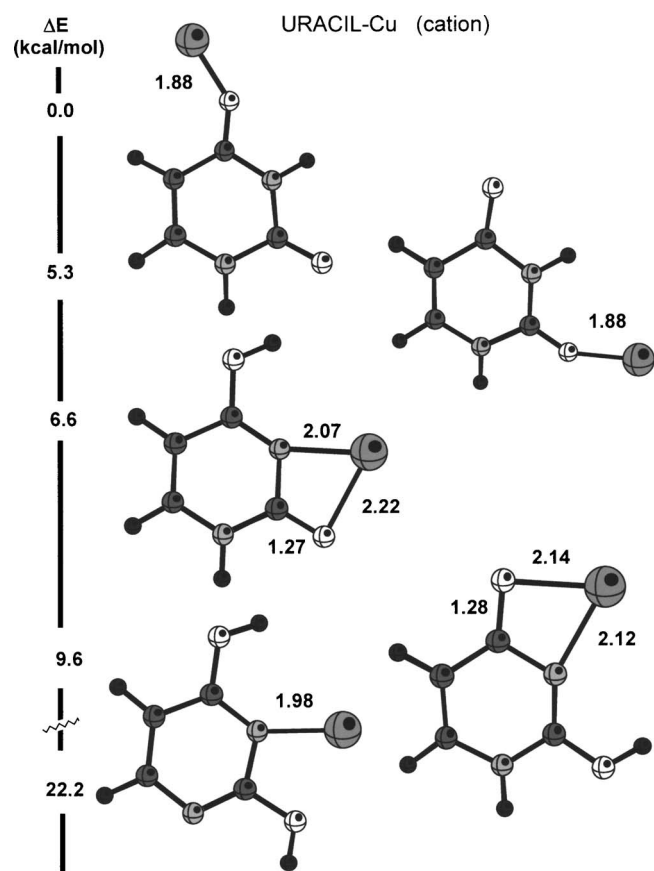


FIG. 6. Optimized uracil-Cu cationic complexes. Initial geometries with different bond positions for the Cu atoms were used. Relative energies to the most stable structure in kcal/mol. Bond distances are reported in angstroms. All the calculations were done with B3LYP/LANL2DZ.

for uracil, Cu-O bond is preferred over Cu-N bond, and there are two isomers that could be present in an experiment, since their energy difference is less than 10 kcal/mol.

Figure 6 reports the optimized structures for the cationic uracil-Cu. All systems are singlets, while the neutrals are doublets. As can be seen, the most stable structure is separated by 5.3 kcal/mol from the second stable structure. In the most stable structures, copper is connected to the oxygen atom. Another two stable structures lie at 6.6 and 9.6 kcal/mol, and show a N-Cu-O bridge. All these isomers could be present in an experiment, since the energy difference between them is less than 10 kcal/mol. In Table IV, Mulliken atomic charges of selected atoms of uracil-Cu (cation) are reported. For comparison, the values of the neutral compound are included. The metal atom on the cation is the most positive atom. When ionization takes place, an electron is removed from the copper atom since the ionization energy of copper^{43(a)} (7.72 eV) is lower than for uracil⁴⁴ (9.54 eV). The atomic charges indicate that the oxygen atom is negative and copper atom is positive for all the cationic isomers, as expected from the electronegativities of oxygen and copper. The metal atom becomes positive and there is an electrostatic interaction with the oxygen atom of uracil that is negative. The overall charge of uracil is negative and hence, the bond between Cu⁺ and uracil⁻ appears to have an ionic character.

Figure 7 reports the optimized structures of the anionic compounds. These systems are singlets. The triplets spin

TABLE IV. Mulliken atomic charges of selected atom for the most stable isomer of uracil-Cu cationic. For comparison, Mulliken atomic charges of the neutral compound are also shown.

[uracil-Cu] ⁺¹	Mulliken Atomic Charges (e. u.)	
	Cation	Neutral
	O4 -0.5	-0.4
	O3 -0.2	-0.3
	N9 -0.4	-0.4
	Cu 0.7	-0.1
	Cation	Neutral
	O4 -0.2	-0.3
	O3 -0.5	-0.4
	N9 -0.4	-0.3
	Cu 0.7	-0.1
	Cation	Neutral
	O4 -0.4	-0.4
	O3 -0.3	-0.3
	N9 -0.4	-0.4
	Cu 0.6	-0.1

states were also calculated, but they are less stable. In the most stable structure, there is a weak bond between the metal atom and the hydrogen atoms of the uracil. With the copper covalently bonded to uracil, the most stable structure is 20.1 kcal/mol less stable. Table V contains the Mulliken atomic charges of selected atoms on the anionic compounds. As it can be noticed, in this case the extra electron is localized on the copper due to the fact that its electron affinity is larger than that of uracil. For this reason, Cu is close to the hydrogen atoms that present a positive charge, and far from the oxygen atoms that have negative charge. The third structure of Fig. 7 shows the Cu atom close to the hydrogen atom in an oxo-amino isomer of uracil, which also has a partial positive charge.

Table VI reports the ionization energies and electron affinities (vertical and adiabatic) for the three most stable isomers of uracil-Cu complexes (neutral). Vertical and adiabatic ionization energies are similar due to the similar geometries of the neutral and cation systems. The three most stable isomers present similar ionization energies (vertical values between 5.7 and 6.1 eV; adiabatic values in the range of 5.3–5.7 eV). Vertical and adiabatic electron affinities are different given the varied geometries of neutral and anion compounds. The highest adiabatic electron affinity corresponds to the most stable neutral isomer since when one electron is removed, these isomers become 20.1 kcal/mol less stable than the most stable anionic compound.

Comparing the structures and bond distances of the neutral (Fig. 5) and the cationic (Fig. 6) systems, it is clear that the geometries are practically the same, the biggest differ-

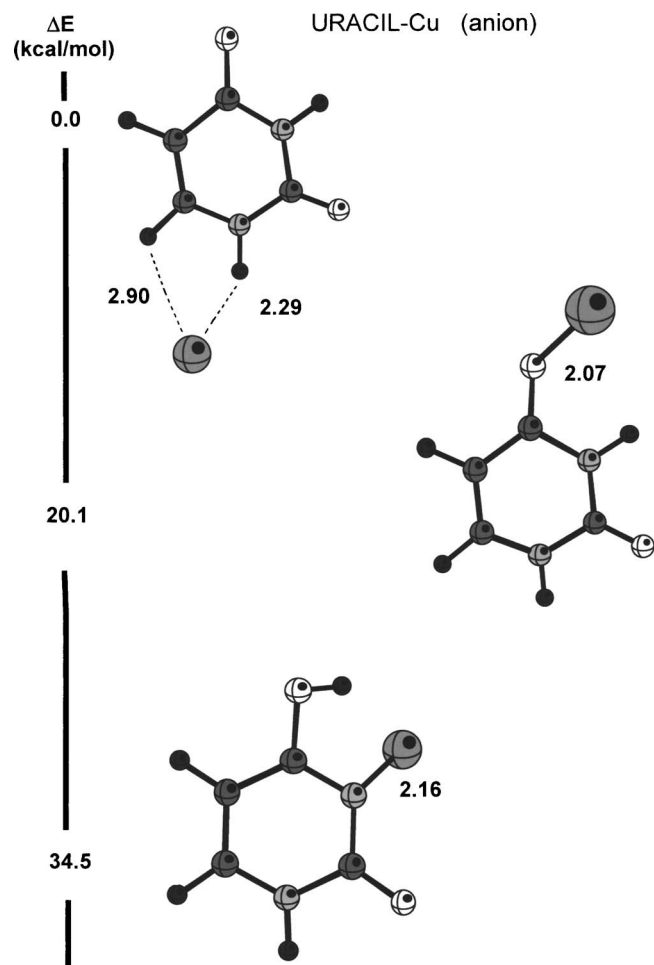


FIG. 7. Optimized uracil-Cu anionic complexes. Initial geometries with different bond positions for the Cu atoms were used. Relative energies to the most stable structure in kcal/mol. Bond distances are reported in angstroms. All the calculations were done with B3LYP/LANL2DZ.

ence being the Cu-O bond distance. For the cationic species, this bond length is shorter than for the neutral. The stability order of the cationic systems is the same as for the neutral. In all cases, when one electron is removed the O-Cu bond distance decreases and the copper atom forms a bridge with oxygen and nitrogen (when O and N are close enough to do so). Neutral copper bonds equally (with the same stability) to uracil in two different oxygen atoms. As with guanine, for the cation the formation of O-Cu-N bridges is also a characteristic geometry, and the Cu-O bond is also stable. For the anion, the copper atom forms weak bonds with the hydrogen atoms of uracil.

For the anions, when the metal is bonded to uracil the metal-O bonds are similar for the anion and the neutral species. The extra electron is localized in an antibonding- π orbital between Cu and the nonmetal atoms. The copper anion is weakly bonded to uracil due to the electrostatic repulsion between the negative metal and uracil; this, in turn, is due to the extra electron being placed on the copper and the uracil molecule having a large dipole moment.

ELECTRON DETACHMENT VERSUS DEHYDROGENATION

With the previous results, it is possible to conclude that the anionic compounds present a weak interaction between

TABLE V. Mulliken atomic charges of selected atom for the most stable isomer of uracil-Cu anionic. For comparison, Mulliken atomic charges of the neutral compound are also shown.

[uracil-Cu] ⁻¹	Mulliken Atomic Charges (e. u.)	
	Anion	Neutral
	O4 -0.3	-0.4
	O3 -0.3	-0.3
	N9 -0.4	-0.4
	Cu -0.9	-0.1
	O4 -0.4	-0.3
	O3 -0.4	-0.4
	N9 -0.4	-0.3
	Cu -0.6	-0.1

the metal atom and two hydrogen atoms of the bases. The vertical ionization energies are 2.2 and 2.1 eV, for the most stable guanine-Cu anion and uracil-Cu anion, respectively. The electron binding energy of Cu⁻¹ is 1.2 eV. The photoelectron spectra of these complexes would strongly resemble the spectrum of Cu⁻¹, but shifted to higher electron binding energies due to some stabilization that arises from the weak bond between the metal and the hydrogen atoms of guanine or uracil.

TABLE VI. Vertical and adiabatic ionization potential and electron affinity (in eV) of selected stable isomers of uracil-Cu neutral.

Ionization Energy		Electron Affinity		Neutral	Cation	Anion
Add	Ver	Add	Ver			
5.5	5.8	0.7	0.5			
5.7	6.1	1.7	0.4			
5.3	5.7	0.7	0.3			

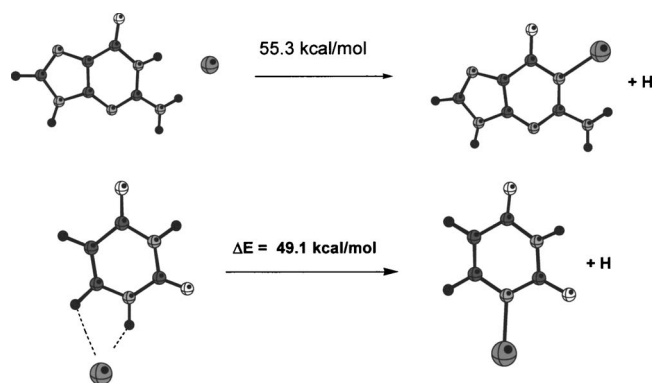


FIG. 8. Dehydrogenation reaction of guanine-Cu and uracil-Cu anionic.

It could be possible to form a covalent strong bond between the copper anion and guanine or uracil, if one hydrogen atom of the DNA bases is exchanged with the Cu. In order to study these reactions, the calculation of the dehydrogenated products was performed. Figure 8 reports these reactions for the most stable anionic structures of guanine-Cu and uracil-Cu. In these systems, the copper atom is negative while the DNA bases are almost neutral, and the Cu atom is weakly bonded to the DNA bases. When one hydrogen atom is removed, the metal binds covalently to guanine or uracil. The dehydrogenation energies are 55.3 and 49.1 kcal/mol for guanine-Cu and uracil-Cu, respectively, i.e., the systems need this energy in order to remove one hydrogen atom from guanine or uracil, and to form a metal-bases covalent bond. As expected, for the dehydrogenated compound the negative charge on the copper atom is smaller than on the bases-Cu (anion) systems.

The vertical ionization energies for the most stable guanine-Cu anion and uracil-Cu anion (50.8 and 48.4 kcal/mol, respectively) are close to the detachment energy of one hydrogen atom [55.3 and 49.1 kcal/mol, for guanine-Cu and uracil-Cu, respectively (Fig. 8)]. These values indicate that, for these systems, there could be a *tight competition* between the H dissociation and the electron aloofness. In these cases, it could be possible to produce the detachment of one electron from the anion and also the removal of one hydrogen atom. For comparison, the dehydrogenation of the neutral guanine and uracil was also calculated. For guanine we used guanine-9H instead of guanine-7H. The energy difference between these two tautomeric forms is less than 0.2 kcal/mol in accordance with Dolgounitcheva *et al.*²⁵ and with our own calculations, and hence the conclusions will not be modified with another tautomeric form of guanine. The dissociation energy is 108.4 kcal/mol. For the dissociation of one hydrogen atom from the uracil, 110.7 kcal/mol are required. With the metal the dissociation energy is lower, i.e., the copper anion forms a bond and weakens the N-H interaction in guanine and uracil. In this way, it is possible to have a stronger metal-guanine and metal-uracil bond.

According to the results previously discussed, the anionic complexes without one hydrogen atom are feasible products, and will probably be detected in an experiment. For this reason, it is important to obtain the vertical and

TABLE VII. Vertical and adiabatic electron detachment energy of the anionic dehydrogenate guanine-Cu and uracil-Cu.

	Vertical electron detachment energy (eV)	Adiabatic electron detachment energy (eV)
Guanine-Cu-H anion	1.7	1.3
Uracil-Cu-H anion	1.9	1.6

adiabatic electron detachment energies of these complexes. The values are reported in Table VII. Hopefully, this information will be useful for the experimental groups.

CONCLUSIONS

Eight stable structures for guanine-Cu and four for uracil-Cu were found, with similar stability. The formation of O-Cu-N bridges suggests that this geometry is characteristic of cationic Cu-DNA complexes, but it is not for neutral or anionic molecules. Neutral copper bonds equally (with the same stability) to guanine in three different nitrogen atoms and the Cu-O bond is also stable. With uracil, the metal atom bonds with the same stability to the nitrogen atoms. Anionic complexes show a weak bond between the metal atom and two hydrogen atoms of the bases. The compound between Cu⁺ and DNA anionic basis (guanine and uracil) appears to have an ionic bond character, similar to Al-guanine that was reported before.⁸ Vertical and adiabatic ionization energies for the neutral and anionic compounds of guanine are very different, due to the diverse geometries. For uracil, these values are similar since the geometries of all the systems are comparable. For both systems, the vertical ionization energy of the anion is close to the dissociation energy of one hydrogen atom from guanine-Cu or uracil-Cu. In these cases, it could be possible to produce the detachment of one electron from the anion and also the removal of one hydrogen atom.

ACKNOWLEDGMENTS

This work was supported by DGAPA (Grant No. N124602). The author acknowledges Marco-Vinicio Vázquez for his help with figures and tables, Sara Jiménez Cortés and María Teresa Vázquez for technical support, and DGSCA/UNAM (México) for providing computer time.

¹J. D. Watson and F. H. C. Crick, *Nature (London)* **171**, 737 (1953).

²F. Pichjerra, D. Hotheinrich, E. Zangrando, B. Lipperte, and L. J. Ranaccio, *JBIC, J. Biol. Inorg. Chem.* **1**, 319 (1996).

³J. Sponer, J. E. Sponer, L. Gorb, J. Leszczynski, and B. Lippert, *J. Phys. Chem. A* **103**, 11406 (1999).

⁴J. Muller, R. K. O. Sigel, and B. Lippert, *J. Inorg. Biochem.* **79**, 261 (2000).

⁵Y. A. Berlin, A. L. Burin, and M. A. Ratner, *Superlattices Microstruct.* **28**, 241 (2000).

⁶C. J. Murphy, M. R. Arkin, Y. Jenkins, N. D. Ghatlia, S. H. Bossmann, N. J. Turro, and J. K. Barton, *Science* **262**, 1025 (1993).

⁷J. Sponer, M. Sabat, L. Gorb, J. Leszczynski, B. Lippert, and P. J. Hobza, *J. Phys. Chem. B* **104**, 7535 (2000), and references therein.

⁸D. Pedersen, B. Simard, A. Martínez, and A. Moussatova, *J. Phys. Chem. A* **107**, 6464 (2003); A. Moussatova, M. V. Vázquez, A. Martínez, O. Dolgounitcheva, V. G. Zakrzewski, J. V. Ortiz, D. Pedersen, and B. Simard, *ibid.* **107**, 9415 (2004); M. V. Vázquez, A. Moussatova, A. Martínez, O. Dolgounitcheva, V. G. Zakrzewski, and J. V. Ortiz, *ibid.* **108**, 5845 (2004).

⁹M. T. Rodgers and P. Armentrout, *J. Am. Chem. Soc.* **122**, 8548 (2000).

- ¹⁰N. Russo, M. Toscano, and A. Grand, *J. Am. Chem. Soc.* **123**, 10272 (2001).
- ¹¹M. Noguera, J. Bertran, and M. Sodupe, *J. Phys. Chem. A* **108**, 333 (2004).
- ¹²*Metal Ions in Biological Systems: Interactions of Metal Ions with Nucleotides, Nucleic Acids and Their Constituents*, edited by A. Sigel and H. Sigel (Marcel Dekker, New York, 1996), Vol. 32.
- ¹³B. Lippert, *Coord. Chem. Rev.* **200**, 487 (2000).
- ¹⁴R. B. Martin, *Acc. Chem. Res.* **18**, 32 (1985).
- ¹⁵J. V. Burda, J. Sponer, and P. Hobza, *J. Phys. Chem.* **100**, 7250 (1996); J. V. Burda, J. Sponer, J. Leszczynski, and P. Hobza, *J. Phys. Chem. B* **101**, 9670 (1997).
- ¹⁶G. L. Eichhorn, *Adv. Inorg. Biochem.* **3**, 1 (1981).
- ¹⁷W. Saenger, *Principles of Nucleic Acid Structure* (Springer, New York, 1984).
- ¹⁸H. Sigel, *Chem. Soc. Rev.* **22**, 255 (1993).
- ¹⁹C. Desfrancois, S. Carles, and J. P. Schermann, *Chem. Rev. (Washington, D.C.)* **100**, 3943 (2000).
- ²⁰S. Xu, J. M. Nilles, and K. H. Bowen, Jr., *J. Chem. Phys.* **119**, 10696 (2003).
- ²¹I. Dabkowska, J. Rak, M. Gutowski, J. M. Nilles, S. T. Stokes, and K. H. Bowen, Jr., *J. Chem. Phys.* **120**, 6064 (2004).
- ²²N. A. Oyler and L. Adamowicz, *J. Phys. Chem.* **97**, 11122 (1993).
- ²³O. Dolgounitcheva, V. G. Zakrzewski, and J. V. Ortiz, *J. Phys. Chem. A* **103**, 7912 (1999).
- ²⁴M. Gutowski, J. Rak, J. Simons, and M. Gutowski, *J. Am. Chem. Soc.* **123**, 11073 (2001), and references therein.
- ²⁵O. Dolgounitcheva, V. G. Zakrzewski, and J. V. Ortiz, *J. Am. Chem. Soc.* **122**, 12304 (2000).
- ²⁶O. Dolgounitcheva, V. G. Zakrzewski, and J. V. Ortiz, *Chem. Phys. Lett.* **307**, 220 (1999).
- ²⁷L. Sanche, *Mass Spectrom. Rev.* **21**, 349 (2002).
- ²⁸B. Boudaiffa, P. Cloutier, D. Hunting, M. A. Huels, and L. Sanche, *Science* **287**, 1658 (2000).
- ²⁹V. C. Moravec, S. A. Klopccic, and C. C. Jarrold, *J. Chem. Phys.* **110**, 5079 (1999).
- ³⁰U. Das, K. Raghavachari, and C. C. Jarrold, *J. Chem. Phys.* **122**, 014313 (2005).
- ³¹O. C. Thomas, W. Zheng, and K. H. Bowen, Jr., *J. Chem. Phys.* **114**, 5514 (2001).
- ³²M. Gerhards, O. C. Thomas, J. M. Nilles, W. J. Zheng, and K. H. Bowen, Jr., *J. Chem. Phys.* **116**, 10247 (2002).
- ³³J. H. Hendricks, S. A. Lyapustina, H. L. de Clercq, J. T. Snodgrass, and K. H. Bowen, *J. Chem. Phys.* **104**, 7788 (1996).
- ³⁴J. H. Hendricks, S. A. Lyapustina, H. L. de Clercq, and K. H. Bowen, *J. Chem. Phys.* **108**, 8 (1998).
- ³⁵M. J. Frisch, G. W. Trucks, H. B. Schlegel *et al.*, GAUSSIAN 03, Revision B.05, Gaussian, Inc., Pittsburgh, PA, 2003.
- ³⁶A. D. Becke, *Phys. Rev. A* **38**, 3098 (1988); J. P. Perdew, *Phys. Rev. B* **33**, 8822 (1986).
- ³⁷A. D. Becke, *J. Chem. Phys.* **98**, 5648 (1993); C. Lee, W. Yang, and R. G. Parr, *Phys. Rev. B* **37**, 785 (1988); B. Mielich, A. Savin, H. Stoll, and H. Preuss, *Chem. Phys. Lett.* **157**, 200 (1989).
- ³⁸R. Krishnan, J. S. Binkley, R. Seeger, and J. A. Pople, *J. Chem. Phys.* **72**, 650 (1980); T. Clark, J. Chandrasekhar, G. W. Spitznagel, and P. v. R. Schleyer, *J. Comput. Chem.* **4**, 294 (1983); M. J. Frisch, J. A. Pople, and J. S. Binkley, *J. Chem. Phys.* **80**, 3265 (1984); A. D. McLean and G. S. Chandler, *ibid.* **72**, 5639 (1980).
- ³⁹P. J. Hay and W. R. Wadt, *J. Chem. Phys.* **82**, 270 (1985); W. R. Wadt and P. J. Hay, *ibid.* **82**, 284 (1985); P. J. Hay and W. R. Wadt, *ibid.* **82**, 299 (1985).
- ⁴⁰CERIUS2™ Forcefield-Based Simulations, Molecular Simulations, Inc., San Diego, 1997.
- ⁴¹P. Flükiger, H. P. Lüthi, S. Portmann, and J. Weber, MOLEKEL 4.2, Swiss Center for Scientific Computing, Manno, Switzerland, 2000.
- ⁴²A. E. de Oliveira, P. H. Guadagnini, R. L. A. Haiduke, and R. E. Bruns, *J. Phys. Chem. A* **103**, 4918 (1999).
- ⁴³(a) C. E. Moore, *Ionization Potentials and Ionization Limits Derived from the Analysis of Optical Spectra* (National Bureau of Standards, Washington, DC, 1970), NSRDS-NBS 34; (b) J. Lin, C. Yu, S. Peng, I. Akiyama, K. Li, L. K. Lee, and P. R. LeBreton, *J. Am. Chem. Soc.* **102**, 4627 (1980); (c) H. Hotop and W. C. Lineberger, *J. Phys. Chem. Ref. Data* **14**, 731 (1985).
- ⁴⁴O. Dolgounitcheva, V. G. Zakrzewski, and J. V. Ortiz, *Int. J. Quantum Chem.* **80**, 831 (2000).