An Ab Initio Study of Substituent Effects on the Excited States of Purine Derivatives

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Several excited singlet electronic states of purine nucleobases and related derivatives have been calculated using high-level multireference perturbation theory methods. Purine derivatives with one or two amino or carbonyl groups substituted at positions C^2 and/or C^6 of the purine ring have been included in the study. The effect of the substituents on excited-state energies and wave functions is examined. Some trends have been observed, such as the fact that substitution at the C^2 position decreases the energy of the first $\pi \rightarrow \pi^*$ state considerably. Although basic qualitative features of the effects can be explained with the simple frontier molecular orbital theory, ab initio calculations are required to describe the effects quantitatively.

1. Introduction

The excited states of DNA and RNA molecules have been studied extensively because of the biological importance of these systems.[1,2] The primary chromophores are the purine and pyrimidine bases which upon absorption of UV light are excited into higher electronic levels. Transient ionization and time-resolved photoelectron studies in the gas phase have shown that the excited states of the DNA/RNA molecules have lifetimes of the order of picoseconds.[2] Fluorescent and phosphorescent yields are also very low, on the order of 10^{-4} at room temperatures in aqueous solutions, indicating that the primary means of excited-state deactivation is by internal conversion. Studies have shown that DNA/RNA nucleobases decay nonradiatively to the ground state through energetically accessible conical intersections. On the other hand, small changes in the structure of the natural bases lead to molecules that have very different photophysical properties, and particularly increased fluorescence. Understanding the relation between structure and photophysical properties in these molecules is important since it can lead to the ability to design chromophores with photophysical properties tuned as we desire. These photophysical properties include absorption maxima, fluorescence maxima, excited-state lifetimes, and fluorescence quantum yields.

Previously, we examined how structure can affect absorption maxima in substituted pyrimidine bases.[3] Specifically, studies on the substituent effects on the excitation energies of 2-pyrimidinone (the ring structrure of cytosine without the amino group) revealed that the energy of the first bright excited state correlated strongly with the nature, position, and orientation of the substituent.[3] The excitation energies of cytosine for the first three singlet excited states are blue-shifted compared to the excitation energies of 2-pyrimidinone.[4] Furthermore, it was found that any electron-donating substituent at the C^4 position of 2-pyrimidinone has a similar effect of blue-shifting the excitation energies, whereas any electron-withdrawing group has the opposite effect. These calculated trends agreed with experimental observations whenever available.

The present work seeks to extend our understanding of how substituents affect excitation energies to the purine bases. The natural nucleobases adenine and guanine are purine bases with substituents at positions C^2 and/or C^6 (see Figure 1 for numbering). Here, we will examine all the possible combinations of substituting amino and/or carbonyl groups at these two positions. Figure 1 lists the derivatives discussed including purine (P), the reference system. Purine derivatives with substitution at position C^2 are 2-aminopurine (2A) and 2-oxopurine (2CO), derivatives with substitution at C^6 are adenine (6A) and hypoxanthine (6CO), and the doubly substituted purines discussed here are 2,6-diaminopurine (2,6A), xanthine (2,6CO), guanine (Gua), and isoguanine (iGua). These molecules often have more than one stable tautomer, especially in the gas phase, but we will discuss only the tautomers equivalent to the tautomers of natural nucleobases in DNA, i.e., 9H-purines, since we are interested in comparisons between the different substituents where the purine ring remains unchanged.

2. Methods

The geometries for all species presented in this report were obtained by geometry optimizations of the ground state at the MP2/cc-pvdz level with C_s symmetry constraints. Excitation energies were obtained using complete active space self consistent field (CASSCF) followed by multireference perturbation theory (MRMP2).[5] A state-averaged CASSCF procedure averaged over the first four A′ (ground and three excited states) and three A″ states was used to obtain the molecular orbitals. The complete active set of orbitals (CAS) for each molecule included in most cases all π and lone pair orbitals. Purine has nine π orbitals and three lone pairs, giving an active space of 16 electrons in 12 orbitals (denoted (16,12)). For the substituted purines an additional occupied orbital from the substituent was included in the actice space, giving rise to a (18,13) active space. The same active space was used for the doubly substituted purines as well. Depending on the size of the active space, between 2000 and about 70000 reference configurations were generated and used at the CASSCF calculations. Oscillator strengths were calculated at the CASSCF level. Partial charges for the ground and excited states were also calculated using the CASSCF wave functions and the CHELPG (CHarges from ELectrostatic Potentials using a Grid based method) algorithm as implemented in GAMESS,[6] to facilitate the assignment of the character of states. The software package GAMESS[7] was used for all CASSCF and MRMP2 calculations, whereas Gaussian[8] was used for the MP2 calculations.

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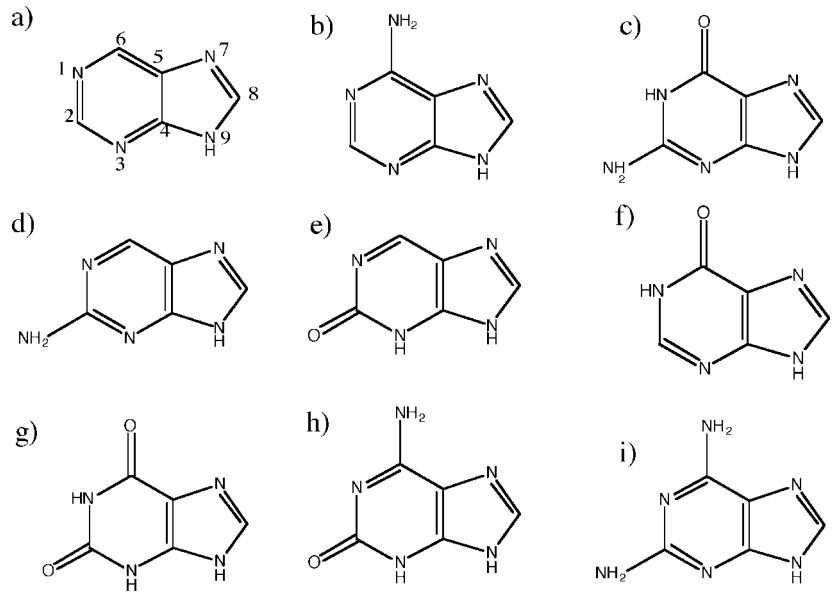

Figure 1. Structures of the purine derivatives discussed in this paper and their labeling: (a) purine, (b) adenine, (c) guanine, (d) 2-aminopurine, (e) 2-oxopurine, (f) hypoxanthine, (g) xanthine, (h) isoguanine, and (i) 2,6-diaminopurine.

TABLE 1: MRMP2 Vertical Excitation Energies in eV of the First Three ^{1}A′ and Three ^{1}A″ Excited States in Purine and Its Derivatives[a]

molecule	2 ^{1}A′	3 ^{1}A′	4 ^{1}A′	1 ^{1}A″	2 ^{1}A″	3 ^{1}A″
P	4.801 (0.031)	5.268 (0.070)	6.394 (0.038)	4.041	5.070	5.219
6A	4.900 (0.004)	4.931 (0.230)	6.304 (0.009)	4.687	5.495	5.824
6CO	4.606 (0.183)	5.391 (0.098)	5.667 (0.128)	4.241	4.769	5.352
2A	4.176 (0.099)	5.011 (0.128)	6.062 (0.025)	4.229	5.430	5.728
2CO	3.810 (0.241)	5.431 (0.090)	6.271 (0.092)	4.243	5.030	6.122
2,6A	4.582 (0.042)	4.904 (0.000)	6.111 (0.002)	5.128	5.864	6.130
2,6CO	5.090 (0.104)	5.481 (0.194)	5.826 (0.015)	5.048	6.719	7.322
Gua	4.602 (0.187)	5.366 (0.107)	6.001 (0.018)	5.467	5.958	6.499
iGua	4.362 (0.141)	5.234 (0.041)	5.552 (0.358)	4.999	5.383	6.272

[a] Oscillator strengths for the A′ states at the CASSCF level are given in parentheses.

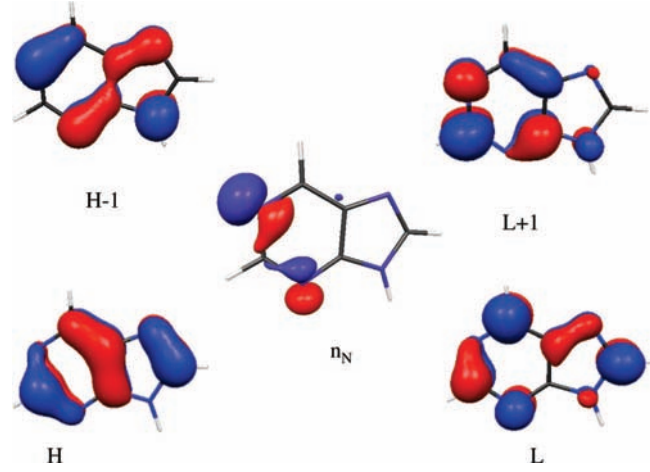

Figure 2. Orbitals of purine participating in the main excited states configurations. Orbitals are obtained from an average-of-states CASSCF as discussed in the text.

3. Results and Discussion

Vertical excitation energies were calculated for all molecules, where the geometry of the ground state was obtained by optimizations restricted to planar symmetry. In most cases the true equilibrium point is planar anyway, and use of planar symmetry simplifies the calculations and the analysis of the trends in the results. In molecules with an amino group the equilibrium ground-state geometry is predicted by high-level ab initio calculations to deviate from planarity with the nitrogen atom on the amino group being pyramidalized. Even in this case, however, previous calculations have shown that the effect of the nonplanar distortions on the excitation energies is very small. The first three A′ and first three A″ singlet excited-state energies for all molecules calculated at the MRMP2 level are presented in Table 1. Excited states involve either excitation from a π to a π^* orbital ($\pi \rightarrow \pi^*$) or excitation from a lone pair localized on a nitrogen or oxygen atom to a π^* orbital ($n \rightarrow \pi^*$). Since we have restricted the geometries to be C_s, the $\pi \rightarrow \pi^*$ excited states have A' symmetry whereas the $n \rightarrow \pi^*$ have A″ symmetry. Rydberg states are not considered here.

We first discuss the excited states in purine, which is the reference system in this work, and then we proceed to the other molecules which have substituents in positions C^2 and/or C^6. The numbering scheme of atoms is shown in Figure 1.

3.1. Purine. The energies of the first three ^{1}A′ and three ^{1}A″ excited states in purine calculated at the MRMP2 level, and the oscillator strengths of the ^{1}A′ states calculated at the CASSCF level are given in Table 1. The ordering of the excited states is 1 ^{1}A″($n \rightarrow \pi^*$), 2 ^{1}A′($\pi \rightarrow \pi^*$), 2 ^{1}A″($n \rightarrow \pi^*$), 3 ^{1}A″($n \rightarrow \pi^*$), 3 ^{1}A′($\pi \rightarrow \pi^*$), so the lowest excited state is a dark $n \rightarrow \pi^*$ at 4.04 eV followed by a bright $\pi \rightarrow \pi^*$ state at 4.80 eV. The next bright $\pi \rightarrow \pi^*$ states have energies of 5.27 and 6.39 eV. All three A′ states have comparable oscillator strengths with 3 ^{1}A′ having the largest one ($f = 0.07$).

The main orbitals involved in the lowest excited-state wave functions are shown in Figure 2. Both the first two $\pi \rightarrow \pi^*$ states include configurations of the type H → L, H − 1 → L, and H → L + 1 (H denotes highest occupied molecular orbital,

TABLE 2: Contributions of Configuration State Functions (CSF) in the 2 ^{1}A′ and 3 ^{1}A′ Excited States of Purine and Its Derivatives[a]

molecule	CSF	2 ^{1}A′ (%)	3 ^{1}A′ (%)
P	H → L	18	32
	H → L + 1	19	
	H − 1 → L	29	20
	H − 2 → L		11
6A	H → L		69
	H → L + 1	34	
	H − 1 → L	36	
	H − 1 → L + 1		7
6CO	H → L	59	8
	H → L + 1	8	30
	H → L + 2		16
2A	H → L	50	17
	H − 1 → L	11	32
	H − 1 → L + 1	6	
	H → L + 1	7	24
2CO	H → L	68	
	H → L + 1		49
	H − 1 → L		9
2,6A	H → L	18	53
	H → L + 1	34	14
	H − 1 → L	17	7
2,6CO	H → L	56	13
	H → L + 1	6	50
	H − 1 → L		9
	H − 1 → L + 1	7	
Gua	H → L	55	12
	H → L + 1	11	41
	H − 1 → L		17
iGua	H → L	64	
	H → L + 1		42
	H − 1 → L	5	18

[a] The squares of the coefficients taken from the CASSCF wave functions are shown. Only weights greater than 5% are shown.

HOMO, and L denotes lowest unoccupied molecular orbital, LUMO). Table 2 shows the weights of different configurations participating in the excited-state wave functions. 2 ^{1}A′ consists of about equal contributions of H → L, H − 1 → L, and H → L + 1 configurations. This mixing is common in other purine bases, but it is most pronounced in purine. 2,6-Diaminopurine and adenine are the other two bases that exhibit such a heavy mixing for 2 ^{1}A′ as will be discussed in more detail below. The next excited bright state in purine, 3 ^{1}A′, is also mixed but includes more H → L contribution than 2 ^{1}A′ does. This mixing of more than one configuration makes analysis of the substituent effects more difficult than that in the pyrimidine bases. The A″ states involve excitations mainly from the n_N orbital shown in Figure 2. 1 ^{1}A″ is mainly n_N → L whereas 2 ^{1}A″ is mainly n_N → L + 1.

The excited states of purine had been calculated previously using the CASPT2 method.[9] These calculations gave the ordering of states as 1 ^{1}A″ (3.76 eV), 2 ^{1}A′ (4.66 eV), 2 ^{1}A″ (4.72 eV), 3 ^{1}A″ (4.85 eV), and 3 ^{1}A′ (5.09 eV), similar to our calculations, with the lowest state predicted to be an $n \rightarrow \pi^*$. The energies of the A′ states in that study differ by 0.1−0.2 eV from ours.

TABLE 3: Comparison of MRMP2 and Experimental Excitation Energies in eV of the First Two $\pi \rightarrow \pi^*$ (2 ^{1}A′, 3 ^{1}A′) States in Purine and Its Derivatives

molecule	MRMP2 $2^1A'$, $3^1A'$	Exp. $2^1A'$, $3^1A'$
P	4.8, 5.3	4.7, 5.2[10−12,43]
6A	4.9, 4.9	4.6, 4.9[23]
6CO	4.6, 5.4	4.4, 5.2[11]
2A	4.2, 5.0	4.1, 5.1[39]
2CO	3.8, 5.4	3.9, 5.2[43]
2,6A	4.6, 4.9	4.4, 5.0[41,11,43]
2,6CO	5.1, 5.5	4.6[48]
Gua	4.6, 5.4	4.5, 5.0[56]
iGua	4.4, 5.2	4.3, 5.2[62]

Experimental absorption maxima of purine have been recorded in various conditions and results have been summarized previously.[10−12] The energies for the first two absorption peaks are shown in Table 3 and compared with the theoretical values. The experimental absorption maxima in methylcyclohexane for these states are 4.72 and 5.12 eV.[11] Our results agree within 0.2 eV with the experimental values. In agreement with theory the first singlet excited state is determined experimentally to be an $n \rightarrow \pi^*$.[12]

3.2. 6-Substituted Purine Bases. ***3.2.1. Adenine.*** An amino group substituted at the C^6 position of purine gives the natural nucleobase adenine (6A). The present MRMP2 results with a (18,13) active space predict the first excited state to be an $n \rightarrow \pi^*$, as in purine. The energy of that state is higher than that of purine, 4.69 eV compared to 4.04 eV for purine. Two $\pi \rightarrow \pi^*$ states follow about 0.2 eV higher, with energies of 4.90 and 4.93 eV, respectively. 3 ^{1}A′ is much brighter than 2 ^{1}A′, in agreement with previous results.

2 ^{1}A′ involves about equal contributions of configurations with excitations H → L + 1 and H − 1 → L, whereas 3 ^{1}A′ is primarily a H → L excitation (see Table 2). In Platt's nomenclature[13] 3 ^{1}A′ is an L_a state whereas 2 ^{1}A′ is an L_b state. In summary, adenine is similar to purine in the fact that the first $\pi \rightarrow \pi^*$ state involves more than one main configuration and the H → L is not the main component.

Excited states of 6A have been studied extensively with a variety of theoretical methods, and the results obtained vary widely.[14−21] The L_a state is especially difficult to describe computationally and its energy depends greatly on dynamical correlation. So, if one compares CASSCF and CASPT2 values using the same active space and basis sets, at the CASSCF level the energy of L_a is 6.5 eV, and when dynamical correlation is included at the MRMP2 level it drops to 4.9 eV. By comparison the L_b state with inclusion of dynamical correlation drops from 5.3 to 4.9 eV, only by 0.4 eV.

Experimentally, the gas-phase UV/vis absorption spectrum of 6A has a maximum at 4.92 eV, which is red-shifted in aqueous solution to 4.77 eV.[22] This band contains at least two electronic transitions with maxima at about 4.6 and 4.9 eV, with the first transition being weaker than the second.[14,23] A second band appears at higher energies, around 6 eV. These results agree qualitatively with the present results. In the gas-phase R2PI spectra of jet-cooled adenine there are two origins at 4.40 and 4.48 eV, where the low-energy one has been assigned to a $n \rightarrow \pi^*$ transition, and the higher energy one to a $\pi \rightarrow \pi^*$ transition.[24,25]

3.2.2. Hypoxanthine. If an oxygen atom replaces the amino group in adenine, the resulting molecule is hypoxanthine (6CO). 6CO is an intermediate of purine metabolism in living organisms.[26]

The ordering of the excited states calculated here for 6CO at the MRMP2 level is the same as that for P. All three A′ states showed in Table 3 have large oscillator strengths. Unlike 6A and P, the lowest A′ excited state is primarily an H → L excitation (L_a state) and it is the brightest state among the ones calculated. When an oxygen is present, the A″ states can originate from excitation from the lone pair of oxygen (n_O), so direct comparison with purine, which does not have this type of orbitals, becomes more difficult. To examine the contributions of the $n \rightarrow \pi^*$ excitations we calculated partial CHELPG atomic charges for the ground and excited states and examined in which atoms the electron distribution changes mostly. This procedure facilitates our assignments since the orbitals are often mixed and difficult to categorize. We found that the wave functions for the 1 ^{1}A″ have excitations from n_O whereas 2 ^{1}A″ involves mostly excitations from n_N. Shukla and Mishra[27] have studied the dipole moments and CHELPG charges for the ground and excited states of several bases including 6CO, and they have discussed the observed changes.

Previous calculations on 6CO have been done using time-dependent density functional theory (TDDFT)[28] and multiconfiguration perturbation theory method MCQDPT2.[29] TDDFT gave excitation energies of 4.75 (A′), 5.26 (A″), 5.43 (A′), and 6.22 (A′) eV whereas MCQDPT2 gave 4.63 (A′), 5.35 (A′), 5.48 (A′), 5.75 (A″), and 5.78 (A′) eV.[29] Our results agree well with these values for the A′ states but we predict the A″ states to be much lower. This is especially surprising for the previous MCQDPT2 case. We have used a larger active space which includes all three *n* orbitals, and this seems to have a big effect on the results. The basis set was also different since the previous work used the 6-31+G(d) basis set with diffuse functions.

Experimental absorption maxima for the $\pi \rightarrow \pi^*$ states in vapor phase are 4.41, 5.19, and 5.51 eV,[11] almost uniformly 0.2 eV lower than our calculated values of 4.61, 5.39, and 5.67 eV.[29] Especially the gap between the excited states is in great agreement between theory and experiment.

3.3. 2-Substituted Purine Bases. ***3.3.1. 2-Aminopurine.*** 2-Aminopurine (2A) is probably the most widely used fluorescent DNA base analog, being utilized as a probe for DNA conformational dynamics,[30,31] due to the environmental specificity of its quantum yield. The present MRMP2 results predict the first excited state to be a bright $\pi \rightarrow \pi^*$ state, which is red-shifted by 0.6−0.7 eV compared to that of purine and adenine. An $n \rightarrow \pi^*$ state is slightly higher in energy. The character of the 2 ^{1}A′ and 3 ^{1}A′ states is switched compared to that of adenine and purine with the L_a state being the first excited state. This state is mainly a H → L excitation, whereas 3 ^{1}A′ involves mixing of H − 1 → L and H → L + 1. The oscillator strengths for these two states are very similar, again deviating from the adenine behavior.

The excited states of 2A have been studied theoretically with a wide variety of methods, including MCSCF,[32] MCQDPT,[33] CASPT2,[34,35] DFT,[36] DFT/MRCI,[37] and MRCI.[38] These studies all point to the bright absorption of the first $\pi \rightarrow \pi^*$ state and its H → L character.

The experimental absorption maxima of 2A in PVA films are 4.05, 4.46, and 5.13 eV for $\pi \rightarrow \pi^*$, $n\pi^*$, and $\pi \rightarrow \pi^*$ states, respectively.[39] These values are in good agreement with the values calculated here, 4.18, 4.23, and 5.01 eV, and the same ordering of states is predicted. The excited-state electronic structure has been studied with double resonance spectroscopy by Kleinermanns and co-workers,[37] and also in the presence of electric fields using Stark spectroscopy by Stanley and co-workers.[38] Experimentally, the first absorption band is red-shifted compared to that of 9H-adenine, by about 0.46 eV.[25,40]

3.3.2. 2-Oxopurine. Introduction of a carbonyl group at C^2 gives 2-oxopurine (2CO). The calculations predict its first excited state to be even more red-shifted than 2A. The first A′ state is 1 eV lower than the corresponding state in P and 6A. The character of the excited-state wave functions is similar to that of 2A, with the first A′ state being mainly H → L (L_a) whereas the second one involves H − 1 → L. 2 ^{1}A′ is the brightest state.

Table 3 shows the energies of the first two bright states and the experimental values. The calculated energies agree very well with the experimental ones. Specifically, the L_a state is greatly red-shifted compared to that of P. This is actually the most red-shifted energy among the compounds studied here, as seen both experimentally and theoretically. As will be discussed in section 3.5, this is consistent with the idea that an electron-donating group at position C^2 of the ring lowers the energy of this state. The carbonyl group is a stronger electron-donating group compared to the amino group and its effect should be stronger, as is indeed observed here.

Since oxygen pairs from the carbonyl group are present in 2CO, the A″ states can be excitations from the oxygen or the nitrogen lone pairs. Examination of the orbitals and the CHELPG partial charges however shows that the A″ states are mainly n_N.

3.4. Doubly Substituted Purine Bases. ***3.4.1. 2,6-Diaminopurine.*** 2,6-Diaminopurine (2,6A) has two amino groups as substituents. Since it has the amino group in both C^2 and C^6 positions, it can be considered an intermediate structure between 6A and 2A. Examination of the excited states of this compound and of xanthine below may address questions about the additivity of substituent effects, and this is a main reason we have included them in this work. The ordering of states at the MRMP2 level is predicted to be $\pi \rightarrow \pi^*$, $\pi \rightarrow \pi^*$, $n \rightarrow \pi^*$, $n \rightarrow \pi^*$, $\pi \rightarrow \pi^*$, and $n \rightarrow \pi^*$. The A′ states are mixed. 2 ^{1}A′ includes three main configurations, H → L, H → L + 1, and H − 1 → L, (L_b), whereas 3 ^{1}A″ is primarily an H → L configuration (L_a). This is similar to what is seen in P and 6A. In terms of the character of the wave functions, 2,6A is much more similar to 6A than to 2A, indicating that position 6 dominates. Energetically, 2 ^{1}A′ is red-shifted compared to P, but only by 0.2 eV, whereas 2A is red-shifted by 0.6 eV and 6A is blue-shifted by 0.1 eV. So the energy of 2 ^{1}A′ in 2,6A seems to be an average of the other two molecules.

There are no high level ab initio calculations on the excited states of 2,6A, to the best of our knowledge, but there are some previous semiempirical calculations.[41,42] Experimental absorption maxima in aqueous solution are shown in Table 3.[11,43] They differ from the calculations by less than 0.2 eV, which could be because of the solvatochromic shift. 2,6A fluoresces but the quantum yield is less than that of 2A,[42,44] a behavior intermediate between 2A and 6A. It has also been studied with R2PI spectroscopy, for reasons similar to the ones here, namely comparison with 2A and 6A.[25]

3.4.2. Xanthine. Xanthine (2,6CO) serves an important role in purine metabolism, as an intermediate in nucleic acid degradation, produced from oxidative deamination of guanine.[45] 2,6CO has two carbonyl groups at positions C^2 and C^6 of the purine ring. These groups disturb the electron distribution of the ring more than the other substituents. The ordering of states is $n \rightarrow \pi^*$, $\pi \rightarrow \pi^*$, $\pi \rightarrow \pi^*$, $\pi \rightarrow \pi^*$, $n \rightarrow \pi^*$, and $n \rightarrow \pi^*$. 2 $^1A'$ is mostly H → L but it is not the brightest state. 3 ^{1}A′ is instead the brightest state with a main contribution from H →

L + 1. The character of these states is similar to the character of the corresponding states in 6CO and 2CO. Energetically, however, xanthine resembles 6CO more compared to 2CO. As we saw in 2,6A, the doubly susbtituted system resembles more the 6-substitiuted than the 2-substituted one. The A″ states here are excitations from the lone pairs on oxygens. Whereas the first A″ is the lowest excited state, the other two are much higher in energy, above 6 eV.

Semiempirical methods have been used for calculating the electronic absorption spectrum of 2,6CO[41,46,47] but there are no high level ab initio methods. The experimental absorption maximum of 2,6CO in aqueous solution is given in Table 3. This is about 0.5 eV lower than the value calculated here, the largest discrepancy between theory and experiment in the present series of molecules.[48] 2,6CO has also been studied with R2PI spectroscopy.[49]

The discrepancy between theoretical results and experimental values may be caused by the presence of carbonyl groups in this system. Previous studies on uracil[50,51] and guanine[20] have indicated that correlation is more important for these bases compared to the corresponding bases without a carbonyl group. For example, the first $\pi \rightarrow \pi^*$ excited state in uracil requires much more correlation to be accurately described compared to the corresponding state in cytosine.[50,51] Similarly, in guanine, correlation has been shown to be very important.[20] Here, xanthine has two carbonyl groups and it seems reasonable that the requirements for high-level correlated description of the excited states will be stronger than those of the other molecules studied in this work.

3.4.3. Guanine. Guanine (Gua) is a doubly substituted purine where both the amino and the carbonyl groups are present. The first two states are predicted to be $\pi \rightarrow \pi^*$ states at 4.60 and 5.37 eV with similar oscillator strengths. This differs from 6A where the brightest state is the second $\pi \rightarrow \pi^*$ state. The dominant configurations in these states differ from those in 6A as well, but they resemble many of the other substituted purines. In Gua the 2 ^{1}A′ state is mostly H → L excitation (L_a state) whereas 3 ^{1}A′ is mostly H → L + 1 (L_b state), so the ordering between L_a and L_b is reversed compared to that of 6A. The next A′ state is at 6.00 eV. The $n \rightarrow \pi^*$ states are well-separated from the $\pi \rightarrow \pi^*$ states starting at 5.47 eV. 1 ^{1}A″ involves excitation from the lone pair on oxygen, which does not exist for purine and amino-substituted purines. These results agree qualitatively with previous calculations where always the first excited states are A′ and the A″ are much higher in energy.[14,20,21,52−55]

Experimentally, Gua shows spectral features with similarities to those of other purines. There exist two peaks in aqueous solution at 4.51 and 4.95 eV with relatively low intensity and much stronger bands higher than 6 eV. The oscillator strengths for the first two peaks are similar, 0.14 and 0.21, respectively.[14,56] Gas-phase spectra are more difficult to assign experimentally because of the presence of many stable tautomers in the gas phase.[57−61]

3.4.4. Isoguanine. Isoguanine (iGua) is an isomer of Gua, having the same substituents but in switched positions on the ring. This causes changes in the energies of the excited states. The ordering remains the same, but all energies are red-shifted compared to those of Gua. The first $\pi \rightarrow \pi^*$ state is mainly H → L as in Gua and it has the largest oscillator strength. The second one involves H → L + 1 and H − 1 → L. The A″ states are mixed excitations from n_O and n_N orbitals. iGua can be considered as a combination of 6A and 2CO. The 2 ^{1}A′ state in 6A is blue-shifted compared to that in P whereas it is extremely red-shifted in 2CO. iGua seems to be a compromise between the two molecules in terms of the energy of this state. The character of the states however is closer to 2CO than to 6A.

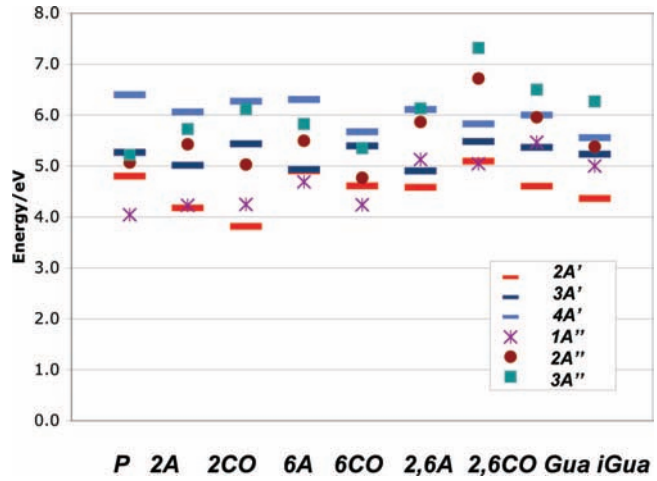

Figure 3. Vertical excitation energies of the excited states of purine and its derivatives discussed, obtained at the MRMP2 level.

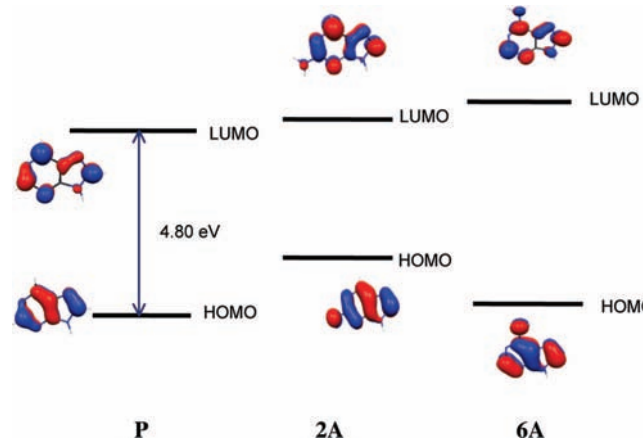

Figure 4. Schematic diagram of the energy levels of the HOMO and LUMO orbitals in purine, 2-aminopurine, and adenine.

Experimental absorption maxima of iGua in film are shown in Table 3.[62] They differ by less than 0.1 eV from our calculated vertical excitation energies for the bright states.

3.5. Trends. The main point of this work is to examine whether systematic trends exist on the effect of the substituents on the excitation energies. For a pictorial view of these effects the excited-state energy levels for all systems studied are shown in Figure 3.

Trends on excitation energies based on substituent effects were calculated previously in pyrimidine bases and explained using Frontier Molecular Orbitals (FMO) arguments. Here, we will look for any systematic trends in the excitation energies of the substituted purine bases. Both amino and carbonyl groups can be considered as electron-donating groups, where the carbonyl group has a much stronger effect compared to the amino group. According to FMO theory, electron-donating substituents destabilize both the HOMO (H) and LUMO (L) π-type orbitals. Figure 4 shows these orbitals for purine, a 2-substituted purine, and a 6-substituted purine. A node exists between the ring and the substituent in all cases, which will destabilize the energy of this orbital. The in-plane lone pairs on the other hand will not be affected substantially by these substituents. As a result, $n \rightarrow \pi^*$ transitions of substituted

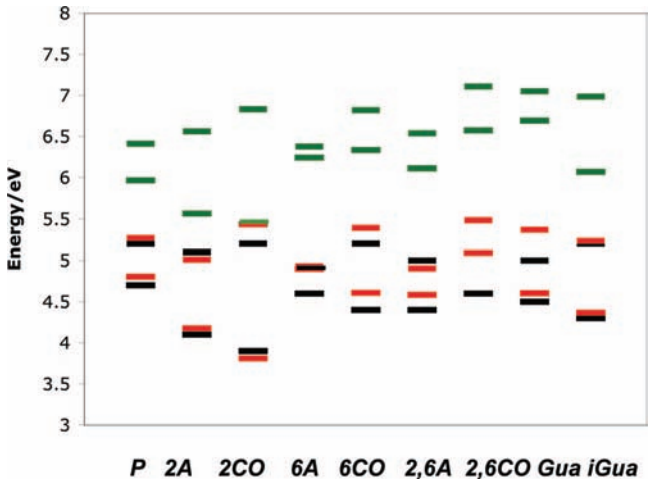

Figure 5. Vertical excitation energies of the 2 ^{1}A′ and 3 ^{1}A′ excited states of purine and its derivatives (i) obtained at the CIS level (green), (ii) obtained at the MRMP2 level (red), and (iii) obtained from experimental absorption maxima (black).

purines are expected to be blue-shifted compared to those of purine since the gap of the orbitals will increase. This increase of energy is observed in our results where the first A″ state for all molecules studied is higher than that of purine as can be seen in Figure 3. Furthermore, according to these energies, the effect is small for 2-substituted purines but much stronger for 6-substituted purines and even more for double-substituted ones. Of course, it should be kept in mind that for the carbonyl substituents there are additional lone pairs on the substituent, so the substituent does not merely perturb the existing states, but introduces additional orbitals and states. Only P, 6A, and 6CO have an A″ dark state below the A′ bright states. A dark state below the first absorbing state may have important implications in the subsequent photophysics of these molecules. Specifically, it may increase the possibility of fluorescence quenching since nonadiabatic transitions can lead population from the bright state to the dark state with small oscillator strengths for emission.

The effect on the $\pi \rightarrow \pi^*$ states is more complicated since all orbitals involved are destabilized by electron-donating groups, and the overall effect depends on the relative destabilization between H and L. Furthermore, the situation becomes even more complicated because there are two $\pi \rightarrow \pi^*$ states around 5 eV and each of these states has contributions from more than one configuration. It is instructive to observe the trends predicted by the CIS method first. These are shown in Figure 5 for the 2 ^{1}A′ and 3 ^{1}A′ states. CIS predicts 2 ^{1}A′ to be mainly an H $\rightarrow$ L configuration in all purine molecules. The lack of correlation in CIS should make the FMO trends prominent. Figure 5 shows that an electron-donating substituent at position 2 stabilizes the 2 ^{1}A′ state and destabilizes the 3 ^{1}A′ one. A substituent at position 6 has less dramatic effects. It destabilizes somewhat both 2 ^{1}A′ and 3 ^{1}A′ states. The carbonyl produces stronger substituent effects compared to the amino group, as was expected based on its greater electron-donating ability.

Figure 5 in addition to the CIS energies also includes the energies of states 2 ^{1}A′ and 3 ^{1}A′ at the MRMP2 level, as well as experimental absorption maxima. In the more sophisticated MRMP2 calculations the large stabilization of 2 ^{1}A′ states for 2-substituted purines is still present. The smaller effects in 6-substituted purines are more sensitive to the level of calculation. The energy of the 2 ^{1}A′ state is slightly higher than P for 6A and stays the same for 6CO. Double substitution does not produce an additive effect in general, but the effect is more similar to that on 6-substituted systems. Gua and iGua both have 2 ^{1}A′ red-shifted compared to P with the energy of 2 ^{1}A′ in iGua being lower. This indicates again the carbonyl effect is stronger than the effect of the amino group since isoguanine has the carbonyl group at position 2 and is responsible for the dominant shift.

Experimentally, all absorption maxima are either red-shifted or the same as in P. 6A and 6CO have about the same first absorption energy as P whereas all other molecules have 2 ^{1}A′ energies red-shifted compared to P. The largest red shift is seen in 2CO followed by 2A. These observations agree qualitatively with our results. The second excited state shows much smaller dependence on the substituents and is usually slightly red-shifted. The calculations also predict smaller shifts for that state. Consequently, the gap between 2 ^{1}A′ and 3 ^{1}A′ states is larger for the 2-substituted derivatives than the 6-substituted and doubly substituted ones.

Interestingly, similar attempts to categorize the trends and substituent effects on purines were made about 40 years ago by Kwiatkowski using the Pariser−Parr−Pople semiempirical method.[10,41,63] These calculations were able to predict some of the qualitative trends seen here with the more sophisticated calculations.

The origin of electronic transitions for several purines have been reported by de Vries and co-workers.[25,49,57−59] The trends of the origins do not always agree with the trends we calculated here for vertical absorptions. The origins for 2,6A, 2A, 6A, and 2,6CO increase in this order, whereas vertical excitations increase as 2A, 2,6A, 6A, and 2,6CO. So for this collection of molecules there is agreement except for the pair 2A and 2,6A. There is no rule that the energetic ordering of the origins has to agree with that of the vertical excitations. In the cases they do not agree this is an indication that the excited-state potential energy surfaces are complicated and the substituent shifts are not applied uniformly on the surfaces. The presence of many closely spaced states may cause such complications since it can create conical intersection seams and state switching which will complicate the surfaces substantially.

4. Conclusions

We have calculated vertical excitation energies for substituted purine bases and examined the effect of the amino and carbonyl substituents on the energies. Several trends have been observed: substitution at the C^2 position decreases the energy of the first $\pi \rightarrow \pi^*$ state considerably whereas substitution at the C^6 position has a much smaller effect; the carbonyl group has in general a stronger effect than the amino group; $n \rightarrow \pi^*$ states for all substituted purines are blue-shifted compared to purine. In general, simple FMO theory explains some qualitative effects of the shifts but detailed ab initio calculations are needed to calculate their magnitude accurately. Purine bases are much more complicated compared to pyrimidine bases because of the mixing of more than one configuration in the excited-state wave functions.

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