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Charge-Transfer $\pi\pi^*$ Excited State in the 7-Azaindole Dimer. A Hybrid Configuration Interactions Singles/Time-Dependent Density Functional Theory Description

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The hybrid configuration interaction singles/time dependent density functional theory approach of Dreuw and Head-Gordon [Dreuw, A.; Head-Gordon, M. *J. Am. Chem. Soc.* **2004**, *126*, 4007] has been applied to study the potential energy landscape and accessibility of the charge-transfer $\pi\pi^*$ excited state in the dimer of 7-azaindole, which has been traditionally considered a model for DNA base pairing. It is found that the charge-transfer $\pi\pi^*$ excited state preferentially stabilizes the product of a single proton transfer. In this situation, the crossing between this state and the photoactive electronic state of the dimer is accessible. It is found that the charge-transfer $\pi\pi^*$ excited state has a very steep potential energy profile with respect to any single proton-transfer coordinate and, in contrast, an extremely flat potential energy profile with respect to the stretch of the single proton-transfer complex. This is predicted to bring about a pair of rare fragments of the 7-azaindole dimer, physically separated and hence having very long lifetimes. This could have implications in the DNA base pairs of which the system is an analogue, in the form of replication errors.

1. Introduction

The molecular stability of the genetic code and the processes inducing mutagenesis are much researched topics. The genetic code is encoded in the sequence of adenine−thymine and cytosine−guanine base pairs of DNA, each pair being held together through a double (or triple) hydrogen bond. It was already suggested by Watson and Crick[1] and Löwdin[2] that the double proton-transfer (DPT) reaction along two parallel hydrogen bonds in any base pair could bring about rare tautomers, and if these alterations were to remain stable during the process of DNA unwinding and strand separation, this could be a possible cause for transcription errors (mutagenesis). The DPT reaction is unfavorable in the electronic ground state but turns out to be easier in the first excited singlet electronic state, which can be populated due to photoabsorption in the UV−vis region of the spectrum.[3] Recent theoretical work has revealed that internal conversion after DPT from the first singlet excited state to the ground state is feasible and can hence reduce the lifetime of this excited state, thus providing an elegant explanation for the photostability of the genetic code.[4]

Nevertheless, the reactivity in the photoactive state is the key to understanding possible photochemical processes that could occur and have mutagenic consequences. The photoactive singlet excited state in DNA base pairs is what can be described as a “valence-excited” electronic state: such states, in molecular orbital terminology, can be described by an excitation that is localized roughly on the same region of the supermolecule (base pair). Some time ago, theoretical work done at the configuration interaction singles (CIS) level of theory established the existence of a “charge-transfer” excited state that could greatly stabilize the intermediate of a hypothetical stepwise DPT reaction in the excited state, namely the product of just one proton transfer.[3] In general, a charge-transfer excited state can be described, in molecular orbital terminology, by an excitation between two geometrically distinct parts of the molecule, or in the case of DNA base pairs, between different moieties of it. Even though the optical transition from the ground state to this charge-transfer excited state might be allowed by symmetry, the corresponding transition dipole moment between both states will be vanishingly small and thus this charge-transfer excited state can only be accessed through conversion from the photoactive state, not by photon absorption. This “dark” charge-transfer excited state was predicted to have a deep minimum in the region describing the products of a single proton transfer.[3] Sobolewski and Domcke have also determined the existence of this dark state using complete active space self-consistent field (CASSCF) theory with second-order perturbation theory corrections (CASPT2) in the cytosine−guanine base pair.[4]

A homologous charge-transfer state has also been found in DNA base-pair analogue systems: the dimer of 7-azaindole ($7AI_2$, depicted in Figure 1) is a related, interesting system that has been long acknowledged as a useful model for the photophysics of DNA base pairs through double hydrogen bonds, being much more accessible to experimental measurements. Theoretical investigations at the CIS level of theory predicted the existence of this charge-transfer state for $7AI_2$, with a deep minimum corresponding to the product of the first proton transfer.[5] The nature, accessibility and especially the lifetime of this charge-transfer state are expected to be relevant in processes of mutagenesis.

It is difficult to overemphasize the importance and helpfulness of theoretical chemistry when discussing excited-state properties, reaction mechanisms and dynamics. Contrary to electronic ground state properties, computation of excited state properties is still a tricky issue in theoretical chemistry. CIS can only be considered as the most basic technique, and results at this level are to be considered with care. CASSCF, and especially CASPT2, are acknowledged as more precise techniques. They have been used to study the spectroscopy behavior of the dimer of 7-azaindole[6] and, more recently, the photophysics of the guanine−cytosine base pair.[7] However, their routine application to reactivity is not straightforward, as it is difficult to guarantee

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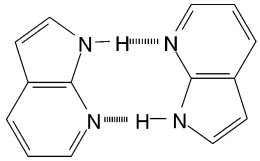

Figure 1. Dimer of 7-azaindole ($7AI_2$), where 7-azaindole is the common name for 1*H*-pyrrolo[2,3]pyridine.

that the active space chosen remains of equivalent quality along the whole reaction path. An interesting alternative is posed by time-dependent density functional theory (TDDFT) methods, which have much more modest computational requirements and are hence well suited to study large systems. Current TDDFT methods use standard ground-state exchange functionals. Despite this, TDDFT is known to provide an accurate description of valence-excited states (except for largely delocalized π systems).[8−10] However, Dreuw et al. have proved that TDDFT fails abismally to describe the proper asymptotic behavior in long-range charge-transfer states, providing far too small excitation energies.[11,12] Although there is no “rigorous” workaround to the failure of TDDFT to describe long-range charge-transfer states, Dreuw et al. have proposed a hybrid approach that combines the proper asymptotical behavior of CIS with DFT and that has been applied to describe charge-transfer states in the dimer of zeaxanthin−chlorophyll,[13] the quenching of chlorophyll fluorescence by xanthophylls,[14] and the complexes of zincbacteriochlorin−bacteriochlorin and bacteriochlorophyll−spheroidene.[12] In the last work referenced, this hybrid approach had accuracies around 0.1−0.2 eV for the lowest lying charge-transfer states. To our knowledge, this is the best fix that exists at present for charge-transfer states in TDDFT.

In this paper we report the first application of this correction to describe the $\pi\pi^*$ charge-transfer excited singlet state energetics by applying the TDDFT methodology to the dimer of 7-azaindole and discuss the implications that this dark state might have in mutagenic processes.

2. Computational Details

To make use of the hybrid CIS/TDDFT approach proposed by Dreuw et al.,[11,12] it is necessary to determine CIS excitation energies and the charge-transfer state DFT energies for a given set of structures. All quantum chemistry calculations have been done with the GAUSSIAN 03 package.[15] The basis set chosen has been 6-31G(d,p)[16−18] for all atoms except nitrogen, for which 6-31+G(d,p) has been chosen instead.[19] All electronic structure calculations have been done while enforcing C_s global symmetry. CIS calculations in this work are in all ways standard. For DFT and TDDFT calculations, the hybrid B3LYP functional has been selected.

In a intermolecular charge-transfer state, in general, one electron in the *a*th molecular orbital in molecule A is transferred to the *b*th orbital in molecule B (for the current study, A and B are the two moieties comprising the dimer). To determine a TDDFT estimate of the charge-transfer state, the hybrid formula due to Drew et al. has been used:[12]

$$\omega_{\mathrm{CT}}^{\mathrm{TDDFT}}(R) \sim \omega_{\mathrm{CT}}^{\mathrm{CIS}}(R) + [\Delta\mathrm{DFT}(R_0) - \omega_{\mathrm{CT}}^{\mathrm{CIS}}(R_0)] \quad (1)$$

In this formula, R is a geometrical parameter that might induce the stability of the charge-transfer state: in our case, it corresponds to the distance between the centers-of-mass of the two monomers in the dimer (transferrable protons excluded). $\omega_{\mathrm{CT}}^{\mathrm{m}}$ indicates the excitation energy for the charge-transfer state using methodology m (m = CIS, TDDFT). ΔDFT is the energy difference between the DFT ground state and the DFT charge-transfer state:

$$\Delta\mathrm{DFT}(R_0) = U_{\mathrm{CT}}^{u\mathrm{DFT}}(R_0) - U_{\mathrm{GS}}^{\mathrm{DFT}}(R_0) \quad (2)$$

where $U_{\mathrm{GS}}^{\mathrm{DFT}}$ is the (closed-shell) potential energy of the ground state, and $U_{\mathrm{CT}}^{u\mathrm{DFT}}$ is the (open-shell) potential energy of the charge-transfer state, determined by exchanging orbitals *a* (in moiety A) and *b* (in moiety B) in the β-spin part of the electronic wave function. This calculation is done within the unrestricted UHF formalism. To converge this open-shell DFT calculation, a quadratic convergence algorithm has been used.[15] Finally, R_0 is the shortest value of R for which this calculation actually converges to the charge-transfer state. This approach is the known ΔDFT method.[20] The actual value for the absolute energy of the charge-transfer state potential energy, $U_{\mathrm{CT}}^{\mathrm{TDDFT}}$ is given then by

$$U_{\mathrm{CT}}^{\mathrm{TDDFT}}(R) \sim U_{\mathrm{S}_0}^{\mathrm{DFT}}(R) + \omega_{\mathrm{CT}}^{\mathrm{TDDFT}}(R) \quad (3)$$

where $U_{\mathrm{S}_0}^{\mathrm{DFT}}(R)$ corresponds to the ground-state potential energy obtained through a closed-shell DFT calculation, and $\omega_{\mathrm{CT}}^{\mathrm{TDDFT}}(R)$ is the corrected excitation energy, obtained through eq 1.

3. Results and Discussion

The double proton-transfer process in the excited state of $7AI_2$ has been the object of heated debate in recent years concerning the mechanism that operates within: stepwise[3,5,21−24] or concerted.[25−30] Though this work does not concern this discussion, it is important to highlight that the relevance of the $\pi\pi^*$ charge-transfer state is connected to the stepwise mechanism. The hypothetical intermediate of the stepwise mechanism of the DPT in the electronic excited state would correspond to a structure in which one moiety has transferred a proton to the other. Although it is known that the most stable minimum in the electronic ground state of $7AI_2$ belongs to symmetry point group C_{2h}, our study on the $\pi\pi^*$ charge-transfer state will consider structures in the less restrictive C_s symmetry point group.

The $\pi\pi^*$ photoactive electronic excited state in $7AI_2$ is what is known as a valence-excited electronic state: in the molecular orbital description, the excitation involves only orbitals mainly localized on the same moiety of the dimer. If only a proton has been transferred, the $\pi\pi^*$ valence excited state is destabilized at large separation between the resulting fragments, because it implies the separation of two net charges of opposing sign in the gas phase. Especially at large separation between these fragments the possibility of a combined proton *and* electron transfer (i.e., H-atom transfer) is preferred: as such, no net charge separation exists and the state is more stable than its valence-excited counterpart. Again, in the molecular orbital picture, the excited electronic state that corresponds to this situation is described by an excitation implying molecular orbitals located in different moieties of the dimer. Schematically this is represented in Figure 2 for the product of the single-proton-transfer complex (SPT-complex). Because this charge-transfer state will imply excitation between molecular orbitals sitting in different moieties of the dimer, usually it has a vanishingly small transition dipole and is thus an inactive optical transition. Hence, the $\pi\pi^*$ charge-transfer state can properly be called a dark state.

From the previous discussion, it is clear that the sole geometrical parameter that can cause the $\pi\pi^*$ charge-transfer state to be preferentially stabilized with respect to the $\pi\pi^*$

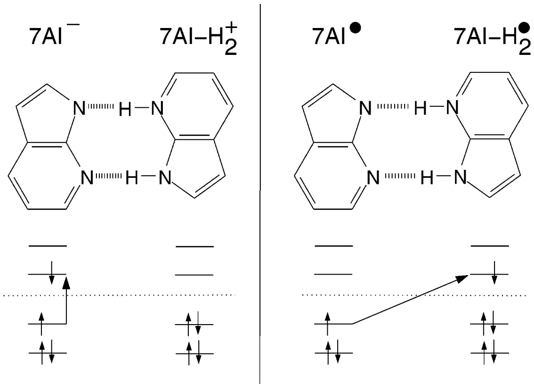

Figure 2. Schematic representation of the excitations involved in the valence excited state (left) and charge-transfer state (right) in the single proton-transfer complex (SPT-complex).

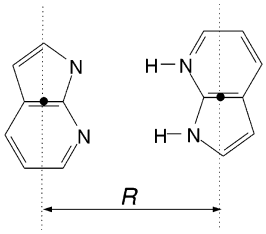

Figure 3. Schematic representation of the hypothetical intermediate in the double-proton-transfer reaction in $7AI_2$. The solid dots denote the centers-of-mass of each monomer (excluding the transferable protons), and *R* is the distance between both centers-of-mass.

valence excited state in the SPT-complex is the distance between the two fragments. Because in this work we are interested in studying the preferential stabilization of the charge-transfer state, one needs to determine the energy of both excited states for different values of this distance. In Figure 3 a scheme of the system under study is presented, and the geometrical parameter that has been explored throughout the paper is *R*, defined as the distance between the centers-of-mass of both monomers, excluding the transferrable hydrogen atoms.

The procedure followed has been as follows: first, the most-stable ground-state minimum potential energy structure within C_{2h} symmetry point group has been located using DFT. This structure has both protons bound to the pyrrolic nitrogens of each moiety. In this structure, the distance between the pyrrolic nitrogen atoms and the bound proton is of 1.031 Å, whereas the distance between the pyridino-N atoms and the proton is of 1.944 Å. The value of *R* for this structure is 5.576 Å. Next, while the internal structure of each monomer is kept intact, the first proton transfer has been forced by placing one proton 0.990 Å from the pyridino-N atom of the accepting monomer (0.990 Å is the pyridino-N−H distance in the $\pi\pi^*$ charge-transfer state in the SPT complex, as reported in ref 5). By doing this, one prepares a structure resembling the product of the first step of a hypothetical stepwise mechanism, which we have called up to now the single proton-transfer complex (SPT-complex). Finally, a set of structures were prepared by varying the value of *R* on this intermediate, spanning values between 4.5 and 8.5 Å. For each of the structures in this series (which in essence describes the stretching motion between both fragments) a CIS and a TDDFT point calculation have been carried out. The corresponding adiabatic electronic states have been scrutinized to identify the first $\pi\pi^*$ valence excited state and the first $\pi\pi^*$ charge-transfer excited state (henceforth VL-$\pi\pi^*$ and CT-$\pi\pi^*$, respectively), besides the electronic ground state. The results obtained in this way are presented in Figure 4.

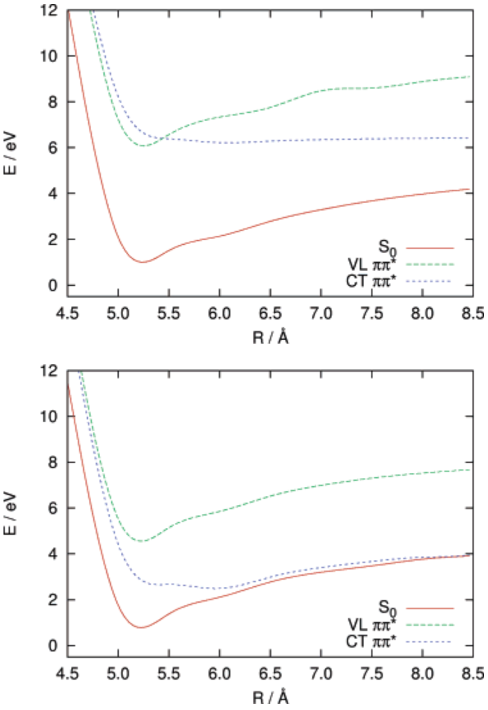

Figure 4. Potential energy profiles at levels CIS (top) and TDDFT (bottom) corresponding to the SPT-complex stretch when the structure of the molecular fragments is that of the DFT S_0 minimum.

It can be noticed that the minimum in S_0, even with DFT, is substantially displaced toward shorter *R* values from that of the absolute minimum in S_0 ($R = 5.576$ Å). One needs to remember though that the system for which the profile has been built has been forced to undergo a single proton transfer. In these circumstances, the ground state corresponds to the product of a single proton transfer between the monomers, creating two singly charged species, which is stabilized by reducing the distance between.

The overestimation of excitation energies in CIS is a well-known problem, and consequently both the actual VL-$\pi\pi^*$ and CT-$\pi\pi^*$ states are expected to lie substantially below the CIS predicted values in Figure 4. Nevertheless, it is suggestive that at the CIS level the VL-$\pi\pi^*$ and CT-$\pi\pi^*$ states are predicted to cross at values $R \sim 5.5$ Å. The VL-$\pi\pi^*$ state presents a pronounced minimum roughly on top of that in S_0. Beyond $R \sim 5.5$ Å the CT-$\pi\pi^*$ state becomes more stable. However, the asymptotic behavior of both states is substantially different: whereas the VL-$\pi\pi^*$ state presents a continuous rise in energy, being almost parallel to S_0, the CT-$\pi\pi^*$ state is almost flat for large *R*.

TDDFT is considered to provide a much better description of valence excited states. However, as Figure 4 tells eloquently, TDDFT fails abismally to correctly describe the energetics of the CT-$\pi\pi^*$ state, for almost any value of *R*: for $R \gtrsim 6.0$ Å TDDFT predicts the CT- state to lie barely 0.08 eV above S_0! To understand the reason for such failure, Figure 5 shows the orbitals involved in the excitations describing both states. The CT-$\pi\pi^*$ state involves an excitation departing from the monomer that has transferred the proton and arriving in the monomer that has received the proton, thus describing a combined proton + electron, i.e., hydrogen atom, transfer. The fact that the molecular orbitals involved in the excitation are located in different parts of the system (i.e., nonoverlapping) is the cause behind the breakdown of TDDFT in describing this state.

To obtain a reasonable description of the CT-$\pi\pi^*$ state, the CIS/TDDFT hybrid approach of Dreuw et al. has been used.[12]

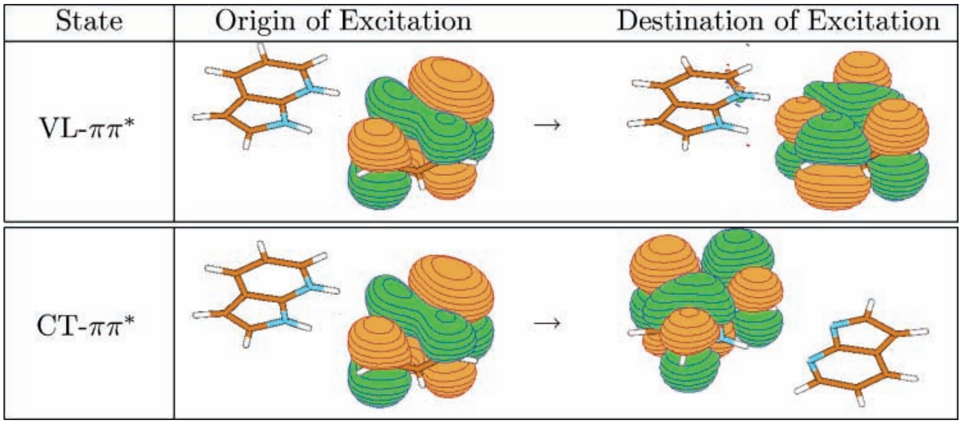

Figure 5. Isodensity surfaces corresponding to the molecular orbitals involved in the excitations describing the VL-$\pi\pi^*$ (top) and CT-$\pi\pi^*$ (bottom) states. Orbitals on the left represent those from which the electron departs and those on the right those receiving the electron.

TABLE 1: Determination of the Optimal Energy Shift for the Charge-Transfer State for the Potential Energy Profile Corresponding to the Stretch of the SPT-Complex, Where the Structure of the Monomers Is Kept as in the DFT Minimum in S_0

R_0, Å	ω_{CT}^{CIS}, eV	ΔDFT, eV	ΔDFT − ω_{CT}^{CIS}, eV
6.0	4.08	0.00	
6.5	3.50	1.54	−1.96
7.0	3.05	1.19	−1.86
7.5	2.71	0.95	−1.76
8.0	2.43	0.78	−1.65
8.5	2.21	0.65	−1.56

To apply eq 1, it is necessary to determine the energy of the DFT charge-transfer state. The straightforward DFT calculation of the ground state for this system converges to the proton-transfer (as opposed to hydrogen atom transfer) wave function (i.e., $7AI^{-}\cdots 7AI{-}H_2^{+}$). To determine the DFT charge-transfer state, the *a* and *b* molecular orbitals localized in each monomer, as defined in section 2, are swapped in the β-spin part of the wave function. In this way, it is possible to converge to a different solution in which a hydrogen atom has been transferred (i.e., $7AI^{\bullet}\cdots 7AI{-}H_2^{\bullet}$) for distances $R \geq 6.5$ Å. At shorter distances this calculation also yields the product of proton transfer. The difference between the DFT charge-transfer state and the ground-state is what is defined as ΔDFT. The set of results from this calculations are presented in Table 1. Equation 1 estimates the TDDFT excitation energy as the CIS excitation energy plus a correction term which is that depicted in the fourth column of Table 1. The actual value to be used in the determination of the corrected potential energy profile for the CT-$\pi\pi^*$ state is that of the shortest value of R for which it is possible to converge the ΔDFT calculation: in this case −1.96 eV. Application of eq 1 is then straightforward and the resulting, corrected potential energy profile of the CT-$\pi\pi^*$ state is represented in Figure 6. Comparing to Figure 4, the Dreuw correction formula has shifted the CT-$\pi\pi^*$ state up in energy, and it can be seen that its shape is now very similar to that of the corresponding CIS state, but with substantially lower energies. Also it is remarkable that at large R the correction formula brings the assymptotic value of the CIS/TDDFT CT-$\pi\pi^*$ state close to the ground state, which is the correct behavior.

The corrected potential energy profile for the CT-$\pi\pi^*$ state predicts that, now at the TDDFT level too, there is a crossing between this state and the VL-$\pi\pi^*$ excited state. This crossing is predicted to occur around $R \sim 5.2$ Å, which is somewhat shorter than the value of R for the absolute DFT minimum in S_0. According to these results, it seems that the crossing between the photoactive excited VL-$\pi\pi^*$ and the dark CT-$\pi\pi^*$ states is easily accessible *if* the reaction should occur sequentially, at least for part of the systems.

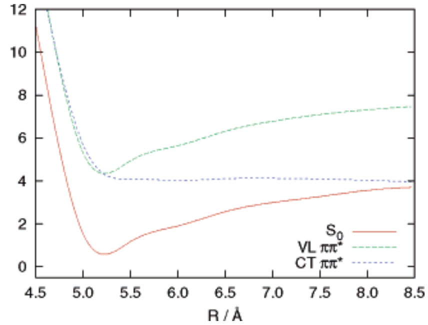

Figure 6. Potential energy profile for the SPT-complex stretch in $7AI_2$, where the structure of the molecular fragments is kept at the geometry of the DFT minimum in S_0. The energies for the CT-$\pi\pi^*$ state (only) have been corrected through use of eq 1. The VL-$\pi\pi^*$ excited-state energies are computed at the TDDFT level of theory.

To discuss to what extent it is possible that the 7-azaindole dimer, optically promoted to the VL-$\pi\pi^*$ excited state, transfers to the CT-$\pi\pi^*$ state, one has to note that the previous results refer to the specific situation in which the geometry of the monomers has stayed as it was in the minimum in S_0, which is just one limiting case: that of a very fast process compared to intramolecular relaxation. Another limiting case is that in which the system (i.e., the structure of the monomers) adopts a structure that minimizes energy in the CT-$\pi\pi^*$ state. This would imply, if one wanted to mimick the procedure so far followed, minimization of energy in the CT-$\pi\pi^*$ state at TDDFT level and then scanning the coordinate corresponding to the SPT-complex stretch. However, this optimitzation is at present unfeasible (any TDDFT-capable code which also allows minimization would incorrectly describe the charge-transfer state). As a compromise, we have opted for locating the C_s minimum energy structure in the CT-$\pi\pi^*$ state corresponding to the SPT product at the CIS level of theory and use that structure to compute the potential energy profiles as described previously. The resulting potential energy profiles are depicted in Figure 7. The ΔDFT calculation data are collected in Table 2, and the corrected TDDFT potential energy profile for the CT-$\pi\pi^*$ state is shown in Figure 8.

In this new conformation of the fragments of $7AI_2$, the value of R_0 is 1 Å shorter than in the previous case. It is remarkable that when the monomers in $7AI_2$ adopt the conformation of minimum energy in the C_s CIS CT-$\pi\pi^*$ state, there is a short interval ($R < 5.0$ Å) where both states are almost degenerate at the CIS level of theory, and afterward the CT-$\pi\pi^*$ state is the

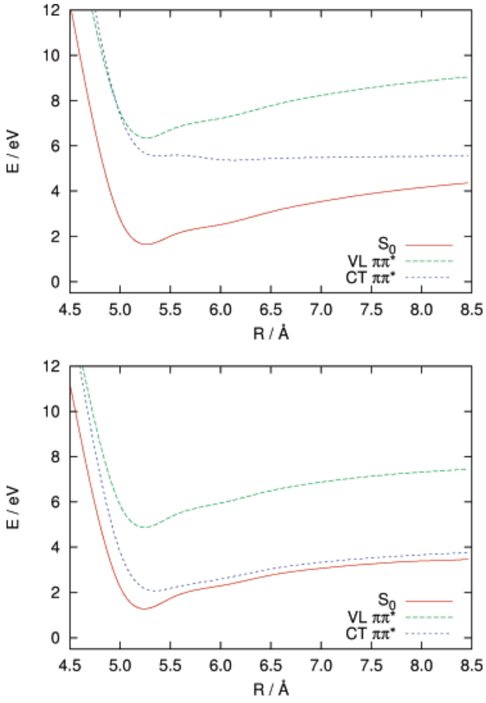

Figure 7. Potential energy profiles at levels CIS (top) and TDDFT (bottom) corresponding to the stretch of the SPT-complex when the structure of the molecular fragments is that of the C_s CIS CT-$\pi\pi^*$ minimum.

TABLE 2: Determination of the Optimal Energy Shift for the Charge-Transfer State for the Potential Energy Profile Corresponding to the Stretch of the SPT-Complex Where the Structure of the Monomers Is Kept as in the C_s CIS CT-$\pi\pi^*$ Minimum

R_0, Å	$\omega_{\mathrm{CT}}^{\mathrm{CIS}}$, eV	ΔDFT, eV	ΔDFT − $\omega_{\mathrm{CT}}^{\mathrm{CIS}}$, eV
5.0	4.61	0.00	
5.5	3.57	1.92	−1.65
6.0	2.87	1.33	−1.54
6.5	2.35	0.94	−1.41
7.0	1.95	0.68	−1.27
7.5	1.63	0.50	−1.13
8.0	1.38	0.37	−1.01
8.5	1.17	0.27	−0.90

most stable and continues to have a negligible assymptotic behavior at large R. In the same way as before, the pure TDDFT potential energy profile for the CT-$\pi\pi^*$ state is severely underestimated in energy. The Dreuw formula corrects this result, bringing the TDDFT CT-$\pi\pi^*$ state higher in energy, also with a short interval where it is almost degenerate with the VL-$\pi\pi^*$ excited state, and describing also a flat assymptote at large values of R, which yields roughly the same energy as the ground state in that limit. In essence, the corrected CIS/TDDFT result seems to be qualitatively correct.

As a whole, results obtained at the CIS and corrected-TDDFT levels of theory indicate that crossing between the excited VL-$\pi\pi^*$ and CT-$\pi\pi^*$ states is feasible. In the actual photoinduced process, $7AI_2$ is prepared in the VL-$\pi\pi^*$ excited state. If one assumes that some systems might experience stepwise proton transfer, then those systems are in a situation that resembles the first of the two extreme cases considered (Figures 4 and 6). The dynamics of $7AI_2$ in the excited state, as far as the proton-transfer reaction is concerned, have been described as ultrafast, which would mean that it is likely that little relaxation for the internal structure of the monomers has occurred. In this state of affairs, crossing over to the CT-$\pi\pi^*$ state may occur.

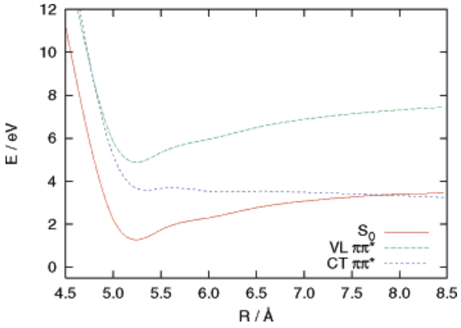

Figure 8. Potential energy profile for the stretch of the SPT-complex in $7AI_2$, where the structure of the fragment is kept at the geometry of the C_s CIS CT-$\pi\pi^*$ minimum. The energies for the CT-$\pi\pi^*$ state (only) have been corrected through use of eq 1. The VL-$\pi\pi^*$ excited-state energies are computed at the TDDFT level of theory.

The question remains as to what is to happen once the system transfers to the CT-$\pi\pi^*$ state. Moreno et al.[5] found that the point of minimum energy in this excited state (at CIS level of theory) was very deep, and that if at least some dimers of 7-azaindole would transfer to this state, then they would probably vibrationally relax to the bottom of this minimum. Because this minimum is in a region of configurational space without a corresponding minimum in S_0, relaxation to the electronic ground state would be slow. The consequences of this, in the DNA base pair system (of which $7AI_2$ is an analog) are clear: this would be one of the so-called “rare tautomers”, with an extended lifetime and a candidate for transcription errors if it all were to happen during a DNA unwinding and strand separation process. However, the potential energy profiles for this CT-$\pi\pi^*$ state that have been determined in this work (both CIS and corrected-TDDFT) show a rather flat energy landscape with respect to the stretch of the SPT-complex, which seems to clash with the previous statement of Moreno et al. of its being a deep minimum.[5]

To further clarify this point, a normal-mode analysis on the C_s CIS stationary point on the CT-$\pi\pi^*$ state has been performed. This normal-mode analysis has revealed that the stationary point located is not a true minimum but rather a second-order stationary point. However, the two imaginary frequencies are very small (10i and 34i cm^{-1}), and both of them belong to the A″ representation. This means that the true minimum in the CT-$\pi\pi^*$ state has C_1 symmetry, even though it is likely that its energy is similar to that of the C_s structure. In any case, examining the normal modes one finds that the mode corresponding to the SPT-complex stretch has a very low frequency of 61 cm^{-1}, which is in agreement with the potential energy profiles in this work for CT-$\pi\pi^*$. Also, one finds that there is a very high-frequency mode (3970 cm^{-1}) that corresponds to basically the stretching of the pyridino-N−H bond (that is, the proton that has been transferred). This high frequency indicates that *in the direction of the single, stepwise proton transfer that has just been completed* the potential energy profile is actually very steep, which agrees with the observations of Moreno et al.[5] Besides, another high-frequency mode (3920 cm^{-1}) describes the stretching of the pyrrolo-N−H bond, which is in effect the yet-to-be-transferred proton.

Summarizing, the stretch of the SPT-complex and any single proton transfer are orthogonal directions. Along the first of them the potential energy profile is almost completely flat, whereas along the second it is very steep. As such, if the system should cross over the CT-$\pi\pi^*$ state, it would be difficult to revert the single proton-transfer reaction or to complete the double proton-transfer process. Figure 9 qualitatively describes this situation.

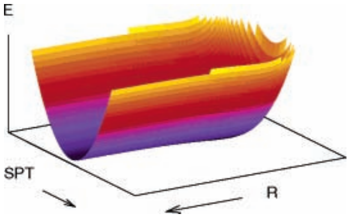

Figure 9. Pictorial representation of the potential energy surface expanded in the stretching of the SPT-complex (R) and any of the single-proton-transfer (SPT) modes. The arrows indicate the direction along which the coordinate increases value.

If the system were to enter the CT-$\pi\pi^*$ state, it could just evolve along the stretching coordinate of the SPT-complex, because it has almost no dependence on R except at small values of it. In that case, the likely evolution of the system would be dissociation of the SPT-complex in two unlike, doublet (radical) fragments: 7AI$^\bullet$ and 7AI$-$H$_2^\bullet$, because no noticeable potential energy minimum exists in CT-$\pi\pi^*$ *along the R coordinate*, which might have kept both moieties together. Moreover, any SPT-complex entering into the CT-$\pi\pi^*$ state would be vibrationally hot and, upon relaxing to the botton of this state, this excess vibrational energy would likely turn into relative translational energy of both fragments with respect to each other. Moreover, radiative transition to S$_0$ is likely to be very slow owing to the inexistence of a potential energy minimum in the ground state in this region of configurational space. The overall effect of crossing over to the CT-$\pi\pi^*$ state would be the creation of two fragments, both different from the 7-azaindole molecule, with a very long lifetime because recombination would be unlikely. In DNA base pairs, the model of which 7AI$_2$ is, this would mean that the base pair would dissociate in an equivalent way. It seems likely that this situation would leave both bases separated for a time long enough to allow transcription errors, if it should happen, again, during DNA transcription.

Needless to say, the extent to which this is to be a significant mechanism in the overall processes started upon photoabsorption by 7AI$_2$ depends greatly on (1) the effective number of systems that would show single (or stepwise double) proton transfer after photoabsorption and (2) how accessible the charge-transfer $\pi\pi^*$ state is. To answer this question, sophisticated dynamical simulations are indispensable. This is currently work in progress in our laboratory.

4. Conclusions

In this work the first application of the hybrid CIS/TDDFT formula due to Dreuw et al.[11,12] to describe, within the TDDFT theory, the $\pi\pi^*$ charge-transfer state in the dimer of 7-azaindole, a generally acknowledged model for DNA base pairing, is reported. This charge-transfer state was described some time ago at the CIS level of theory,[5] being related to the first step of the stepwise excited state proton-transfer process in the dimer of 7-azaindole, namely the transfer of a single proton. The photoactive $\pi\pi^*$ excited state is what is described as a valence excited state, in which only a proton transfer has occurred, whereas the $\pi\pi^*$ charge-transfer state represents the situation in which also an electron has been transferred alongside and consequently is preferentially stabilized with respect to the photoactive $\pi\pi^*$ excited state when the distance between the two fragments increases.

Potential energy profiles have been computed at the CIS and TDDFT levels of theory for the nuclear coordinate describing the stretch of the SPT-complex. It is found that at the CIS level of theory, depending on the internal geometrical configuration of the monomers of 7AI$_2$, either the $\pi\pi^*$ charge-transfer state is more stable than the photoactive $\pi\pi^*$ excited state or both states cross at a configuration energetically and geometrically close to that of the minimum in the photoactive $\pi\pi^*$ excited state. Even though CIS is known to poorly describe the energetics of excited states, the qualitative conclusions of this part of the work are reasonable and expected to be correct.

TDDFT describes satisfactorily the valence $\pi\pi^*$ excited state but fails completely to describe the potential energy profile for the charge-transfer state. Application of the hybrid formula of Drew et al.[12] corrects the TDDFT profile for the $\pi\pi^*$ charge-transfer state, which turns out to be almost lacking in any dependence on the stretch coordinate of the SPT-complex at large values of it. In agreement with the CIS description of both states, the corrected TDDFT approach also predicts that a crossing between the excited $\pi\pi^*$ valence and $\pi\pi^*$ charge-transfer states is possible. It is concluded that the $\pi\pi^*$ charge-transfer state is accessible to those systems that undergo a stepwise double proton-transfer process in the 7-azaindole dimer.

The almost flat potential energy profile for the SPT-complex stretch apparently clashes with previous descriptions of the minimum in the $\pi\pi^*$ charge-transfer state for this system being very deep. A normal-mode analysis at the planar CIS stationary point in this state reveals that indeed the frequency associated with the stretch of the SPT-complex is very small, whereas the frequencies associated with the single proton stretches (which are modes that could induce single proton transfers) are among the highest for this structure.

The steep potential energy profile along the single-proton-transfer coordinates and the flat potential energy profile along the stretch of the SPT-complex in the $\pi\pi^*$ charge-transfer state will likely imply that those systems that have undergone single proton transfer after photoexcitation, likely cross to the $\pi\pi^*$ charge-transfer state because it is more stable and the crossing seems energetically and geometrically accessible. Once in the $\pi\pi^*$ charge-transfer state, the steep energy profile to either revert the proton transfer that had just occurred or carry out the second proton transfer, makes the product of the single proton (in this case hydrogen atom) transfer unusually stable. Moreover, the flat potential energy profile at this point along the SPT-complex stretch coordinate makes it likely that those systems arriving in the $\pi\pi^*$ charge-transfer state dissociate. This behavior would largely increase the lifetime of the single-proton-transfer product in the excited state. In the analogue system of the DNA base pairs, this would greatly extend the lifetime of the strange tautomers believed to induce replication errors in DNA transcription.

Finally, from the methodological point of view, the results presented here confirm that using the hybrid configuration interaction singles/time dependent density functional theory approach of Dreuw and Head-Gordon[12] for the charge-transfer state yields a qualitative good picture of the potential energy curves along an intermolecular separation coordinate.

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