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Ultrafast Decay of Electronically Excited Singlet Cytosine via a π,π^* to n_O,π^* State Switch

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Recently, one of us determined the singlet fluorescence lifetimes of adenosine, cytidine, guanosine, and thymidine by femtosecond pump−probe spectroscopy.[1] The excited states produced by 263 nm light in these nucleosides decay in the subpicosecond range (290−720 fs). Ultrafast radiationless decay to the ground state greatly reduces the probability of photochemical damage, and has motivated the present theoretical study of isolated cytosine, the chromophore of cytidine. The experimental lifetime of 720 fs indicates that there must be an ultrafast decay channel for this species. Here we present an overview of the possible decay channels and approximate energetics, using a valence-bond derived analysis to rationalize the structural details of the paths. The mechanism favored by our calculations and new experimental data[1c] involves (1) a *two-mode decay coordinate* composed of initial bond length inversion followed by internal vibrational energy redistribution (IVR) to populate a carbon pyramidalization mode (see the two-mode model previously proposed for double bond photoreactivity[2]), (2) a *state switch* between the π,π^* and n_O,π^* excited states, and (3) *decay to the ground state* through a conical intersection.

The excited states for cytosine (Scheme 1) are π,π^*, n_O,π^* and n_N,π^* (excitation from the π system and the oxygen and nitrogen lone pairs, respectively; n and π orbitals are labeled in Scheme 1 for clarity, and the 2s lone pair of oxygen has been left out). CASSCF and time-dependent density-functional (TD-B3LYP) calculations of the excited states confirm this approach (see Table 1 and Supporting Information for computational details). Both methods reveal two close-lying lowest excited states, π,π^* and n_O,π^*, whereas the n_N,π^* state is higher. The n_O,π^* state has not been unambiguously identified by spectroscopists because of its proximity to the π,π^* state and its low oscillator strength.[3] The TD-B3LYP[4] results agree very well with the experimental excitation energies. The CASSCF energies are 0.6−0.8 eV (14−18 kcal mol^{-1}) greater than experiment because dynamic correlation energy is not included, but the energetic ordering is reproduced.

For our calculations we have used the CASSCF/6-31G* level of theory with the Gaussian program.[5] The full active space is 14 electrons in 10 orbitals (8 π orbitals and two lone pairs). For optimizations, orbitals with occupations close to 2.00 were eliminated from the active space. The reaction paths were calculated with intrinsic reaction coordinate calculations, and the energetics recomputed with single-point calculations for a balanced treatment of the three excited states (see Supporting Information). Gas-phase calculations on cytosine are a good model for the experimental study of the ribonucleoside in water because the excited states are covalent (small solvent effect expected) and the nitrogen where the sugar moiety is attached does not participate in the excitations. We studied the amino-keto tautomer, the one almost exclusively present in water.[6]

Scheme 1

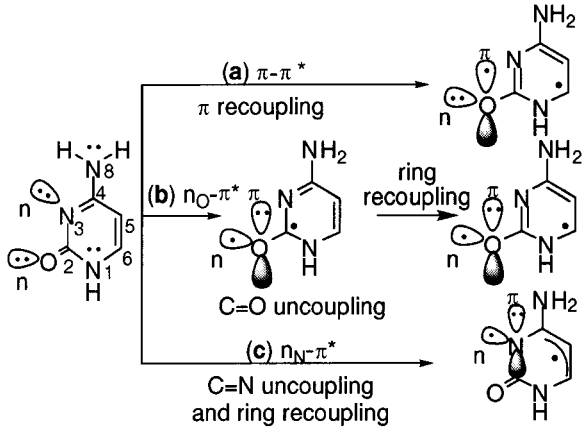

Table 1. Calculated Vertical Excitation Energies (oscillator strengths in parentheses)

state	TD-B3LYP	CASSCF(14,10)	experiment[3]
$S_1(\pi,\pi^*)$	4.71 (0.036)	5.21	4.6 (0.14)
$S_2(n_O,\pi^*)$	4.76 (0.002)	5.24	
$S_3(n_N, \pi^*)$	5.15 (0.001)	6.00	5.2 (0.03)

A valence-bond analysis (Scheme 1 and Supporting Information) shows that the ground state of cytosine has three localized double bonds. The π,π^* excitation (Scheme 1a) *reverses the coupling* between single and double bonds (N_1 and N_8 lone pairs are unaffected). On the other hand, the n,π^* excitations (Scheme 1b,c) promote a lone pair electron into a π bond, *uncoupling a* π *bond* (C═O and C═N bonds). This leaves two electrons in the π orbital of the heteroatom and one in the π orbital of the neighboring carbon. In the n_O,π^* case, the unpaired electron in the ring recouples with the π system, resulting in a ring bond pattern *equivalent to the* π,π^* *one*. Thus, the π,π^* and n_O,π^* states will have similar behavior.

Several radiationless decay paths are possible. Paths from the n,π^* states must go via a state switch from the spectroscopic π,π^* state through an avoided crossing or a conical intersection. The nuclear coordinate that leads to a decrease in energy (and ultimately to intersection with the ground state) for the π,π^* and n_O,π^* states must involve changes in the bond lengths of the π system following

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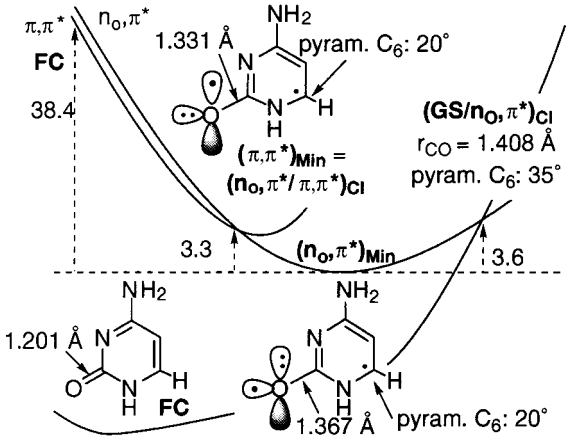

Figure 1. Proposed decay path for the lowest energy singlet π,π^* state of cytosine via a state switch to the n_O,π^* state (energies in kcal mol^{-1}).

the recoupling. The n_N,π^* route will effect the 4-electron-2-center group formed by N_3 (3 electrons) and C_4 (one unpaired electron after recoupling of the C_5, C_6 electrons). Exploratory calculations showed that possible tautomerization paths have high barriers, and are therefore not considered here.

The proposed mechanism for decay of the π,π^* state (see Figure 1) involves decay along a coordinate composed of bond inversion (see for example the stretching of the carbonyl bond) and pyramidalization of C_6 (i.e. out-of-plane bending of hydrogen substituent, see Supporting Information). Along the relaxation path, the π,π^* and the n_O,π^* states remain close in energy, and the coordinate leads to $\mathbf{(\pi,\pi^*)_{Min}}$. This minimum is essentially coincident with the conical intersection $\mathbf{(n_O,\pi^*/\pi,\pi^*)_{CI}}$, the minimum for an S_1/S_2 crossing associated to the π,π^* to n_O,π^* state switch. The efficiency of the state switch depends on the nature of the surface crossing, i.e. the extent to which it is avoided (see for example calculations on the photochemical ring opening of cyclohexadiene[7]). Our results suggest that the S_1/S_2 crossing at $\mathbf{(n_O,\pi^*/\pi,\pi^*)_{CI}}$ is only weakly avoided (small value of the interstate coupling vector, see Supporting Information), and nonadiabaticity may slow the decay. Further along the coordinate, we have optimized $\mathbf{(n_O,\pi^*)_{Min}}$, a minimum on the S_1 surface, and $\mathbf{(GS/n_O,\pi^*)_{CI}}$, the minimum for the S_0/S_1 crossing responsible for the radiationless decay. The initial part of the decay (see Supporting Information) preserves the ring planarity and involves purely bond inversion. It leads to a flat region (plateau) with respect to pyramidalization of C_6, which has radical character (i.e. no charge transfer, see Supporting Information). Apart from further bond stretching, decay to $\mathbf{(\pi,\pi^*)_{Min}}$ and $\mathbf{(n_O,\pi^*/\pi,\pi^*)_{CI}}$ needs pyramidalization of C_6 to 20°, and further to 35° at $\mathbf{(GS/n_O,\pi^*)_{CI}}$. The molecule should accumulate enough vibrational energy during the decay to surmount the small barrier of 3.6 kcal mol^{-1} to the sloped intersection $\mathbf{(GS/n_O,\pi^*)_{CI}}$, but IVR to the pyramidalization mode is required and will occur in the plateau. Dynamics calculations are needed to further clarify how the limiting factors, state switch and IVR give rise to the experimental lifetime of 720 fs.

An alternative decay mechanism involves a switch from the quasidegenerate π,π^* and n_O,π^* states to the n_N,π^* state, followed by decay to the ground state through a peaked conical intersection (Figure 2). The state switch takes place via a transition structure (i.e. fully avoided crossing), and the nuclear coordinate is an out-of-plane bending of the amino group and a distortion of the ring.

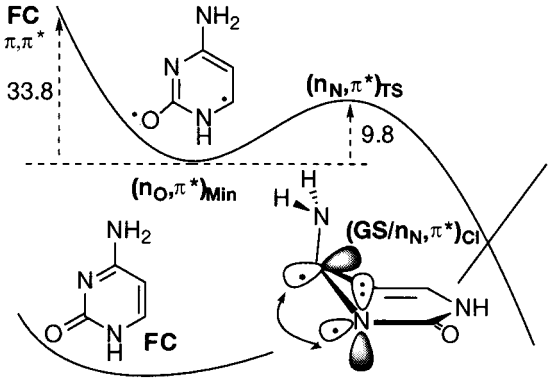

Figure 2. Alternative state switch to the n_N,π^* state (energies in kcal mol^{-1}).

This minimizes repulsion between the π orbital of N_3, which is doubly occupied in the excited state, and the π orbital of C_4. The calculated barrier for the state switch (9.8 kcal mol^{-1}) is significantly higher than the barrier along the n_O,π^* path. Although these values do not include dynamic correlation, the prediction of decay via the n_O,π^* state is corroborated by experimental evidence. Subpicosecond relaxation is still observed on protonated cytidine at low pH despite the loss of the n_N,π^* state by protonation at N_3.[1c] The importance of the n_N,π^* state for the ultrafast decay of purine base nucleosides, which lack the carbonyl group, has been proposed on the basis of theoretical and experimental results.[8] Depending on the barrier height, our calculated n_N,π^* route could be involved in the ultrafast decay observed there,

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Supporting Information Available: Computational details, IRC calculations, and Cartesian coordinates of the structures (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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