Quantum Chemical Study of the π-Electronic States of the DNA Base Pairs

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The results of calculations of the lowest π-electronic states of the DNA base pairs with the SCF MO LCAO method both without taking into account configuration interaction and taking into account all the singly excited configurations are presented. The first excited singlet state and the first triplet state of both pairs in a one-configurational approximation are shown to be the states where the excitation is localized on one of the bases. The calculations in a multi-configurational interaction give qualitatively the same result. The possibility of the UV irradiation-induced mutations, the mechanism of which is caused by the proton tunneling on the hydrogen bonds in DNA, is discussed. The results of calculations are compared with the proton transfer constants in the base pairs.

Die Ergebnisse von Elektronen-Rechnungen für DNA-Basenpaare (ohne CI für den Grund-zustand) werden mitgeteilt. Der erste Singulett- und Triplettzustand sind jeweils Zustände mit lokali-sierter Anregung. Auch die Wechselwirkung mit mehrfach angeregten Konfigurationen ändert daran nichts. Ferner wird die Möglichkeit von UV-induzierten Mutationen diskutiert und die Resultate der Rechnungen mit Protonentransfer-Konstanten der Basenpaare verglichen.

Calculs des plus bas états électroniques π des paires de base du DNA avec la méthode SCF MO LCAO sans et avec interaction de configurations avec tous les monoexcités. On montre que le premier état excité singulet et le premier état excité triplet des deux paires dans l'approximation à une configuration sont les états où l'excitation est localisée sur l'une des deux bases. Dans le cas multiconfigurationnel on obtient qualitativement le même résultat. Discussion de la possibilité de mutations induites par irradiation UV, provoquées par transfert tunnel du proton dans les liaisons hydrogène. Les résultats du calcul sont comparés avec les constantes de transfert du proton dans les paires de bases.

For the study of the DNA base pairs the zero-differential overlap approximation of the SCF MO LCAO method has been used, both without and with taking into account a limited number of singly excited configurations [1–7]. The analysis of these results [8] leads to a conclusion about the necessity of enlarging the initial configuration set.

In the present paper, the most interesting results of calculations of singlet and triplet π-electronic states of the DNA base pairs by the SCF MO LCAO method in the one-configurational approximation and taking into account all the singly excited configurations (77 for the $A - T$ pair and 84 for the $G - C$ pair) are given.

A description for the method of approximation of the necessary integrals is given elsewhere [9, 10].

Each of the obtained in the one-configurational approximation self-consistent pair orbitals originates mostly from only one base orbital; in connection with this fact, one may give an approximate classification of the singly excited

configurations. Depending upon the fact whether the i and k pair orbitals originate from the orbitals of one base or of different bases we shall refer to corresponding configurations as non-charge-transfer configurations (the excitation is localized on one of the bases) or charge-transfer ones (the excitation is delocalized onto two bases).

In Table 1 the energies (ΔE) of the four first transitions to singlet (S_α, where α is the number of the state) and triplet (T_α) excited states of pairs are listed; the number of the MO's between which an electron transition leads to a corresponding one-configurational state are also given. The oscillator strengths (f) of the singlet-singlet transitions are also listed in Table 1. The types of considered states (configurations) and the numbers of electronic transitions in bases (see [10]) are given in brackets.

From these data one may see that the first (by energy) S_1 and T_1 states are non-charge-transfer ones.

One may note that the singlet excited charge transfer state $n \to n + 1$ which is formed as a result of an electron transfer from the highest filled (φ_n) to the lowest vacant (φ_{n+1}) MO[1] is, according to its energy the third one in the $A - T$ pair and the second one – in the $G - C$ pair. The $n \to n + 1$ triplet pair state lies higher than the T_4 state as it follows from Table 1.

On the fact that the $n \to n + 1$ state is the charge-transfer one, some authors [1, 2, 11, 12] have based the interpretation of the UV light mutagenic effect the mechanism of which is caused by the H-bond proton tunneling. However, in these papers transition energies have not been calculated; therefore, it has not been known to which transition (according to its energy) the excited singlet $n \to n + 1$ state corresponds. We have repeated the calculations made in [1, 2, 12]; the transition energies have been calculated additionally. The singlet state has been shown to be the second one by energy in the $G - C$ pair and the third one in the $A - T$ pair; as far as the S_1 state of both pairs is concerned, it represents a state with an excitation localized on one of bases.

Although in the pair calculations with the Mataga-Nishimoto approximation of $\gamma_{\mu\nu}$ the $n \to n + 1$ state is not the first one, according to its energy, it contributes (as was shown earlier [10]) to the first absorption band which is usually applied for the induction of mutations. Therefore, the contribution of the $n \to n + 1$ state into the UV mutagenesis is to be accounted. However, the identification of the equilibrium constant between rare and usual tautomeric pair forms in the $n \to n + 1$ state with the mutation frequency [11, 12] is valid only in the case when the mutagenic effect of the UV light occurs only in states which exceed the S_1 state by energy. This means the hindrance of non-radiative pair transitions from the excited charge transfer states. No data about this phenomenon which occurs in molecules extremely rarely are available for DNA. Therefore, the UV light will naturally effect DNA also in the S_1 state. The contribution of the S_1 state to the frequency of the experimentally observed mutations (assuming the equal effectivity in the induction of mutations by the S_1 and S_2 or S_3 state) exceeds that of the $n \to n + 1$ state on 4–5 orders because the excitation intensities (cf. the oscillator strengths values in Table 1) and the lifetimes of the latter are extensively lower.

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[1] For the $A - T$ pair $n = 11$, for the $G - C$ pair $n = 12$.

Table 1. *Characteristics of the four first transitions to singlet and triplet excited states of the DNA base pairs calculated in a one-configurational approximation*

Base pair	$A-T$				$G-C$			
Transition	1	2	3	4	1	2	3	4
ΔE^S	5.439	5.513	5.668	5.842	4.493	4.675	4.678	5.293
$i \to k$	$10 \to 12(1T)$	$11 \to 13(1A)$	$11 \to 12(A-T)$	$11 \to 15(2A)$	$12 \to 14(1G)$	$12 \to 13(G-C)$	$11 \to 13(1C)$	$12 \to 15(2G)$
f	0.724	0.760	0.025	0.495	0.639	0.003	0.276	0.623
ΔE^T	2.573	3.637	4.469	5.256	2.731	2.842	3.844	4.620
$i \to k$	$10 \to 12(1T)$	$11 \to 13(1A)$	$11 \to 15(2A)$	$11 \to 16(3A)$	$12 \to 14(1G)$	$11 \to 13(1C)$	$12 \to 15(2G)$	$12 \to 17(3G)$

Table 2. *Characteristics of the first singlet and triplet excited states of the DNA base pairs calculated in a multi-configurational approximation*

States	$A-T$			$G-C$		
	ΔE	$X_{i \to k}$	f	ΔE	$X_{i \to k}$	f
Singlet	5.139	0.875 $(10 \to 12)$ −0.244 $(11 \to 13)$ −0.235 $(11 \to 12)$	0.530	4.352	0.913 $(12 \to 14)$ 0.267 $(11 \to 13)$ 0.237 $(12 \to 13)$	0.439
	5.320	0.605 $(11 \to 15)$ 0.509 $(11 \to 13)$ 0.352 $(9 \to 13)$ 0.320 $(10 \to 12)$ 0.234 $(11 \to 12)$	0.183	4.572	−0.871 $(11 \to 13)$ 0.423 $(12 \to 13)$	0.243
	5.394	−0.771 $(11 \to 13)$ 0.551 $(11 \to 15)$ 0.215 $(9 \to 13)$	0.341	4.654	0.854 $(12 \to 13)$ 0.368 $(11 \to 13)$ −0.338 $(12 \to 14)$	0.059
	5.635	0.912 $(11 \to 12)$	0.007	5.105	0.943 $(12 \to 15)$	0.389
	5.894	0.970 $(10 \to 14)$	0.143	5.789	0.617 $(9 \to 13)$ 0.609 $(10 \to 13)$ 0.427 $(11 \to 16)$	0.148
Triplet	1.779	0.908 $(10 \to 12)$ −0.265 $(10 \to 17)$		2.086	0.877 $(11 \to 13)$	
	2.771	0.851 $(11 \to 13)$ −0.208 $(8 \to 13)$		2.204	0.931 $(12 \to 14)$	

This fact authomatically decreases the frequency of the mutations induced by the $n \to n+1$ state by 4–5 orders; in [11, 12] this frequency has been identified with the calculated equilibrium constant value ($\sim 10^{-5}$). Now the induced mutation frequency estimated theoretically becomes equal to $10^{-10} - 10^{-11}$ which is comparable with the theoretical value of the spontaneous mutation frequency calculated from the equilibrium constant for the S_0 of base pairs [13].

Hence, the excited charge transfer states calculated in the one-configurational approximation practically do not contribute to the UV mutagenesis.

The results of calculations obtained in a multi-configurational approximation are given (for the five first singlet excited states and the two first triplet states of the $A - T$ and $G - C$ pairs) in Table 2. It contains the transition energies ΔE, the oscillator strengths f of singlet transitions and the expansion coefficients $X_{i \to k}$ of the wave function state on the singly excited configurations, which are equal or exceed 0.2.

When considering the structure of the S_1 or T_1 state for both pairs (Table 2), one should pay attention to the fact that the non-charge-transfer configuration possesses the maximal weight in it. The contribution of the charge-transfer configuration $(X_{n \to n+1}^2)$ is very small. This result is not an unexpected one: we have shown (see above) that in a one-configurational approximation the lowest state (by energy) is not a charge-transfer one, but a state with the excitation localized on one of the bases.

This consideration allows to judge about the character of the excitation distribution in pairs. One may see that in the T_1 state an excitation is mainly localized on a pyrimidine base, whereas in the S_1 state an excitation is mainly localized on the pyrimidine base in the $A - T$ pair and on the purine base in the $G - C$ pair.

As at the transition of each pair into the S_1 state the excitation is localized mainly on one of the bases, one may expect that the change in the form of H-bond potential curves will be small. In connection with the equilibrium between the rare and usual tautomeric pair forms, this will lead to a small change of the equilibrium constant. However, this problem requires a special investigation which is now in progress in our laboratory.

The results of the calculations may be compared with the proton transfer constants through the H-bond between bases in the S_1 and T_1 states of pairs.

Table 3. *Constants of the proton transfer on the hydrogen bond in the ground, first singlet excited (S*) and first triplet (T*) states of the DNA base pairs*[a]

$A - T$	$5.0 \cdot 10^{-7}$	$A - U$	$2.0 \cdot 10^{-6}$ $(1.1 \cdot 10^{-6})$
$A - T_{S*}$	$1.5 \cdot 10^{-7}$	$A - U_{S*}$	$1.5 \cdot 10^{-6}$ $(5.5 \cdot 10^{-7})$
$A_{S*} - T$	$2.7 \cdot 10^{-6}$	$A_{S*} - U$	$1.1 \cdot 10^{-6}$ $(1.2 \cdot 10^{-7})$
$A_{S*} - T_{S*}$	$8.1 \cdot 10^{-7}$	$A_{S*} - U_{S*}$	$7.9 \cdot 10^{-6}$ $(6.2 \cdot 10^{-8})$
$A - T_{T*}$	$1.7 \cdot 10^{-8}$	$G - C$	$7.9 \cdot 10^{-6}$ $(9.5 \cdot 10^{-6})$
$A_{T*} - T$	$2.3 \cdot 10^{-8}$	$G - C_{S*}$	$2.6 \cdot 10^{-5}$ $(4.2 \cdot 10^{-3})$
$A_{T*} - T_{T*}$	$7.2 \cdot 10^{-10}$	$G_{S*} - C$	$2.2 \cdot 10^{-6}$ $(2.8 \cdot 10^{-4})$
—	—	$G_{S*} - C_{S*}$	$7.4 \cdot 10^{-6}$ $(1.2 \cdot 10^{-1})$

[a] Data [26] are given in brackets.

The values of these constants which can be determined from the enthalpy of the room-temperature proton transfer [14, 15] are given in Table 3^2.

An information about the distribution of an electronic excitation in the pairs is necessary for the calculation of the constants. In [14], the excitation of both bases within the transition to the S_1 state has been assumed. This assumption does not agree with the results of our calculations. Therefore in Table 3 the proton transfer constants in the $A - U$ and $G - C$ pairs calculated from the data [14] for the cases of the localization of an excitation on one of the bases, are also given. Besides that to give a thorough picture, we have presented there the constants for the case of excitation of both bases in the $A - T$, $A - U$ and $G - C$ pairs; their values can be easily obtained from the data [15].

One can see from the Table 3 that the proton transfer is hindered both in the S_1 and in the T_1 state for the cases of the localization of an excitation in the $A - T$ $(A - U)$ pair which follows from the results of our calculations. In the $G - C$ pair the proton transfer constant does not change, accordingly to [15], but increases more than on an order as compared with the S_0 state accordingly to [14]. However, even in the latter case a predominant part of the $G - C$ pairs is presented by the Watson-Crick configuration.

The situation is entirely different in the S_4 state of the $A - T$ pair and the S_3 state of the $G - C$ pair which also belong to the first absorption band. These states are almost completely built of the $n \to n+1$ charge transfer configuration; this fact leads to a substantial charge transfer from adenine to thymine (~ 0.83) and from guanine to cytosine (~ 0.73). In this connection, the H-bond potential functions will drastically bitterly change in the above mentioned states as compared with the S_0 state, whereas the equilibrium constant values will considerably increase. However, the participation of these states in the induction of mutations meets in principle the same objections as in the case of a one-configurational approximation.

Thus, both theoretical and experimental data seem to show that the contribution of a tunneling mutation mechanism into the UV mutagenesis is small. A detailed discussion of this problem is given by one of us in the monography [8].

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^{2} The values of pK for nucleotides in the S_0 state necessary for the calculation of constants from the data in [15] are taken from [16].

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