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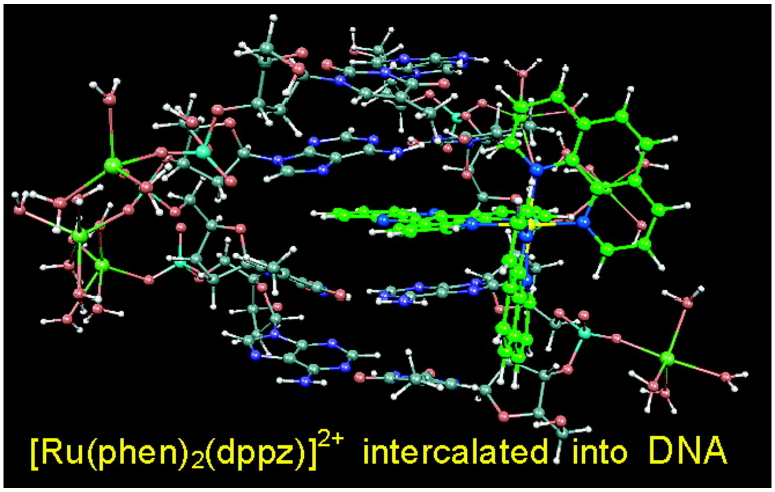

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Photophysical Properties of $[Ru(phen)_2(dppz)]^{2+}$ Intercalated into DNA: An Integrated Car−Parrinello and TDDFT Study

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The unique photophysical properties of the DNA-intercalating $[Ru(phen)_2dppz]^{2+}$ complex, **1**, have attracted considerable interest over the last 15 years, due to the so-called "light-switch" effect.[1−3] This complex does not luminesce in water, but the emission is switched on by interaction with DNA.[1−3] Moreover, the absorption spectrum of the free complex in solution shows well characterized metal-to-ligand charge transfer (MLCT) bands, which are perturbed upon binding to DNA.[3] Therefore, complex **1** represents a sensitive spectroscopic probe for DNA.

Despite the large number of experimental studies performed on **1** and on related systems, only a few theoretical studies have been performed to date,[4] and a detailed understanding of the electronic structure of Ru light-switch complexes intercalated into DNA is still missing. Pourtois et al. have investigated the absorption and emission properties of **1** by means of semiempirical and time-dependent density functional theory (TDDFT) calculations in vacuo,[4a] finding two separate emitting states of $\pi-\pi^*$ and MLCT character, which are computed by Batista et al. to be nearly degenerate in the related $[Ru(bpy)_2dppz]^{2+}$ complex in solution.[4c] We reported TDDFT calculations on **1** in different solvents,[4b] demonstrating the crucial role of solvation in describing its electronic structure and providing a detailed assignment of its absorption spectrum.

In this communication, we present a full quantum mechanical study of the geometry and electronic structure of **1** intercalated into an adenine−thymine tetramer, $d(ATAT)_2$, to provide a detailed description of the low-lying excited states involved in the absorption and emission processes for this prototype system. We first optimized the geometry of **1** (Δ enantiomer), isolated and intercalated, **1**@$d(ATAT)_2$, including 8 Na^+ counterions solvated by 32 water molecules for a total of 409 atoms (see Figure 1) by means of the Car−Parrinello (CP) method.[5] CP optimizations were performed on both the singlet ground state (S) and lowest triplet state (T) of **1**@$d(ATAT)_2$, using the PBE functional,[6] a plane-wave basis set, and ultra-soft pseudopotentials.[7] From the S and T geometries, we extracted the systems composed by **1** and the two closest AT base pairs, **1**@$(AT)_2$ (Supporting Information), saturating the N−C bonds connecting the bases to the DNA backbone by H atoms. S and T **1**@$(AT)_2$ models were used for TDDFT calculations of the low-lying singlet and triplet excitations, which are related, respectively, to the absorption and emission processes. In this stage, we used the Gaussian03 (G03) code,[8] with the B3LYP functional[9] and a standard 3-21G* basis set. Even though failures of TDDFT in describing excited states of small molecules[10a] and CT excitations in extended systems[10b] have been reported, the absorption spectra of Ru(II) complexes are generally accurately reproduced by TDDFT, provided solvation effects are taken into account.[11] The 3-21G* basis provides a similar orbital pattern and lowest excitation energies for **1**@$(AT)_2$ compared to larger basis sets (Supporting Information), allowing us to simulate a large portion of the absorption spectrum at a reasonable computational cost. G03 calculations were performed in water solution, by means of the non-equilibrium C-PCM implementation.[12] Calculations were also performed on **1** and on $(AT)_2$ at the **1**@$(AT)_2$ geometries.

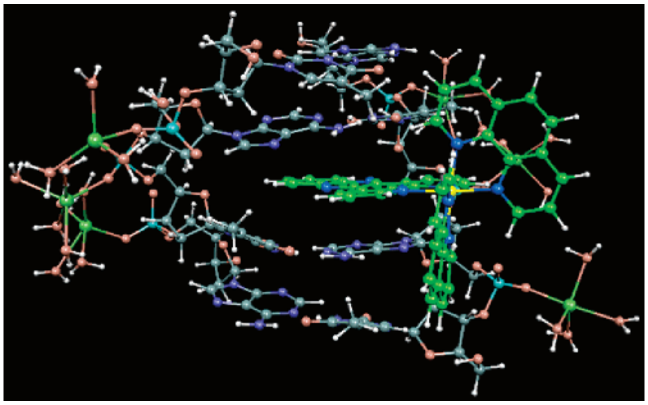

Figure 1. Optimized geometrical structure of **1**@$d(ATAT)_2$. Gray = C, white = H, pink = O, blue = N, pale green = Na, turquoise = P, yellow = Ru atoms. C and N atoms of **1** are green and light blue, respectively.

The CP-optimized geometry of **1** in its singlet ground state is in good agreement with available experimental data[13] and with our previous theoretical calculations using the B3LYP functional (Supporting Information).[4b] The optimized geometry of **1**@$d(ATAT)_2$ shows the dppz moiety intercalated with an orientation similar to that suggested experimentally;[3b] the geometry of **1** is only marginally affected by intercalation (Supporting Information).

A molecular oribital diagram for **1**@$(AT)_2$ at the S geometry is reported in Figure 2. The four highest occupied molecular orbitals (HOMOs), lying within 0.23 eV, have A and T character, while the HOMO-4/HOMO-6, lying 0.09 eV below the HOMO-3, are essentially t_{2g}(Ru) orbitals. The HOMO-7, lying 0.62 eV below HOMO-3, is of π(dppz) character (not shown). The lowest unoccupied molecular orbitals (LUMOs) of **1**@$(AT)_2$ are similar to those of complex **1**. The LUMO and LUMO+5, of π^*(dppz) character, are the unoccupied orbitals which are mostly destabilized with respect to **1** (Supporting Information), while the LUMO+1/LUMO+4, mainly localized on the phen ligands, are marginally affected by intercalation. A−T unoccupied orbitals lie at higher energies (Supporting Information). This electronic structure picture is not qualitatively altered by embedding **1**@$(AT)_2$ in solvents of different polarity, while in vacuo, the LUMO/LUMO+3 are of π^*(phen) character (Supporting Information).

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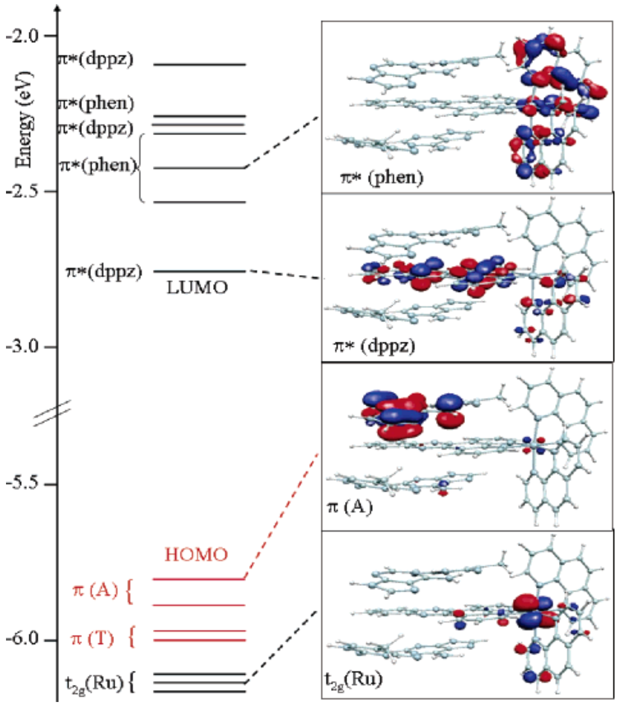

Figure 2. Energy levels (eV) of **1**@(AT)$_2$ at the S geometry. Isodensity plots of relevant molecular orbitals are also shown. Red (black) lines refer to states which are maximally localized on the AT bases (complex **1**).

Table 1. Wavelength (nm) and Character of the Lowest Triplet and Singlet Excited States of **1**@(AT)$_2$ at the S and T Geometries[a]

	S		T	
	character	λ (nm)	character	λ (nm)
T1	40% (Ru→L) 58% (A→L)	608	40% (Ru→L) 60% (A→L)	628
T2	5% (Ru→L′) 84% (T→L′)	531	7% (Ru→L) 80% (T→L′)	532
T3	6% (Ru→L′) 77% (T→L/L′)	523	15% (Ru→L/L′) 54% (A/T→L/L′)	528
S1	94% (A→L)	510(0.03)	95% (A→L)	528(0.02)
S2	6% (Ru→L′) 80% (T→L/L′)	482(0.01)	6% (A→L) 76% (T→L/L′)	486(0.02)
S3	91%(A→L)	479(0.06)	87%(A→L)	485(0.05)

[a] L and L′ denote the dppz and phen ligands, respectively. For singlet excited states, oscillator strengths are reported in parentheses. For triplet excited states, calculated oscillator strengths are zero, due to the neglect of spin−orbit coupling.

The three lowest singlet and triplet excited states of **1**@(AT)$_2$ calculated at the S and T geometries are reported in Table 1. A detailed list of excitation energies is reported as Supporting Information. The first singlet excited state (S1), characterized by an oscillator strength f of 0.03, is originated by a single excitation from the π(A) HOMO to the π*(dppz) LUMO. Similarly, the more intense excitation ($f = 0.06$) giving rise to S3, is assigned to as a π(A) HOMO-1 → LUMO transition. S2 is mainly originated by a weaker π(T) HOMO-2 → LUMO excitation. Therefore, S1−S3 give rise to quite intense absorptions involving charge redistribution from the AT bases to the dppz moiety, with little participation of metal orbitals. These states are responsible of the modifications observed in the low-energy region of the absorption spectrum of **1** intercalated into DNA,[3b] which shows, with respect to the isolated molecule spectrum, the appearance of a shoulder of the 440 nm MLCT band, at ca. 500 nm.[3b] Most notably, the position of the MLCT band is also well reproduced by our calculations (433 nm); see Supporting Information for a comparison of calculated and experimental spectra. For both the S and T geometries, the lowest excited state is of triplet character (T1), being composed by a combination of Ru(t$_{2g}$) (ca. 40%) and A(π) (ca. 60%) orbital excitations, both having the π*(dppz) LUMO as arriving state. T1 is calculated at the T geometry to lie 628 nm above the ground state, in excellent agreement with the experimentally characterized emission maximum of **1** intercalated into DNA (618 nm)[2a] and poly[d(AT)] (621 nm).[2b] At shorter wavelengths (ca. 530 nm), two almost degenerate triplet states mainly localized on the phen ligands are found. The presence of metal character in T1 is consistent with the bright luminescence observed for **1** intercalated into DNA since the transition probability for decay from T1 to the singlet ground state is governed by spin−orbit coupling, which is a property related to the metal center. The calculated A contribution to T1 is, on the other hand, consistent with the reported sensitivity of the emission properties of **1** upon intercalation into different base pairs,[2b] showing a shift of the emission maximum from 620−621 to 606−607 nm upon binding of **1** to AT or GC oligomers, respectively.[2b] Moreover, the mixed Ru/A → dppz character of T1 is consistent with the observation of DNA-mediated resonance energy transfer to **1**,[14] which appears as a base-specific increase in the emission intensity of **1** upon intercalation into AT with respect to GC oligomers.[14b]

In conclusion, we have provided a detailed characterization of the excited states involved in the absorption and emission processes of **1**@d(ATAT)$_2$ and shown the remarkable influence of the AT base pairs on the electronic structure of this prototype system. These observations might help in the comprehension of the action mechanism and design of DNA-targeting agents.

Supporting Information Available: Computational details, optimized structures, excitation energies, and absorption spectra. This material is available free of charge via the Internet at http://pubs.acs.org.

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