An INDO/S (Intermediate Neglect of Differential Overlap/Spectrum) Study of Photochemical Reactivity of 2,4,6,8(1*H*,3*H*,7*H*,9*H*)-Pyrimido[5,4-*g*]pteridinetetrone 5-Oxide

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The specific photochemical reactivity of 2,4,6,8(1*H*,3*H*,7*H*,9*H*)-pyrimido[5,4-*g*]pteridinetetrone 5-oxide (1), an effective photochemical oxygen-atom transfer agent, was discussed based on the results of molecular orbital (INDO/S-CI (intermediate neglect of differential overlap/spectrum-configuration interaction)) calculations of the excited states, in comparison with several simple aromatic *N*-oxides, pyridine 1-oxide (2), pyrazine 1-oxide (3), acridine 10-oxide (4), and phenazine 5-oxide (5). The lowest $\pi-\pi^*$ excited singlet ($S_1^{\pi-\pi^*}$) state of 1 was most characterized by the high proportion of the $\psi_{a_2} \rightarrow \psi_{b_2}^*$ transition for the CI (configuration interaction) state and by the marked decrease of the N-O bond order, distinct from those of 2–5. The low reactivity in photorearrangement of 1 was interpreted to result from the decrease of the N-O bond order in the $S_1^{\pi-\pi^*}$ state. Also, the high photochemical oxygen-atom transfer reactivity of 1 was well correlated to the special features of the lowest unoccupied molecular orbital in the ground state.

Keywords 2,4,6,8(1*H*,3*H*,7*H*,9*H*)-pyrimido[5,4-*g*]pteridinetetrone 5-oxide; aromatic *N*-oxide; molecular orbital; INDO/S-CI; photo-oxidation; photorearrangement

In the photochemistry of *N*-oxides the photorearrangement and photodeoxygenation have been extensively studied experimentally and theoretically.¹⁾ It has been well established that the photorearrangements of aromatic *N*-oxides are responsible for the lowest $\pi-\pi^*$ excited singlet ($S_1^{\pi-\pi^*}$) states and that the photochemical intermediates are oxaziridines.²⁾ The formation of oxaziridines in the excited state and the regioselectivity have also been well explained based on the molecular orbital consideration by HMO and PPP-CI methods.³⁾ Much experimental data, on the other hand, has suggested that the triplet state is responsible for the photodeoxygenation of aromatic *N*-oxides.⁴⁾ The efficiencies in photodeoxygenation for most *N*-oxides were generally low because of the occurrence of photorearrangement as the side reaction. Maki and his colleagues recently reported, however, that 2,4,6,8(1*H*,3*H*,7*H*,9*H*)-pyrimido[5,4-*g*]pteridinetetrone 5-oxide (1), unlike most *N*-oxide derivatives, acts as an efficient oxygen-atom transfer agent to various substrates without any appreciable side reaction.⁵⁾

The photoreaction of 1 is quite different from those of most *N*-oxides in the nature of the excited state responsible for the photodeoxygenation and in the reactivity for the photorearrangement. It has been clarified that the photodeoxygenations of 1 proceed through a single electron transfer (SET) in the $S_1^{\pi-\pi^*}$ state or in the $S_1^{\pi-\pi^*}$ state of

the charge transfer (CT) complex with a substrate.⁵⁾ It has also been shown that the photoreactions of 1 gave no product other than those by oxygen-atom transfer to substrates and that 1 is quite stable on the ultraviolet (UV) irradiation in the absence of substrates.⁵⁾

Thus, with a view to gaining insight into the nature of the electronic structure of 1 in the excited state, we have carried out molecular orbital calculations of the excited states for 1 and several structurally related aromatic *N*-oxides, such as pyridine 1-oxide (2), pyrazine 1-oxide (3), acridine 10-oxide (4), and phenazine 5-oxide (5), using the INDO/S-CI (intermediate neglect of differential overlap/spectrum-configuration interaction) method.

Calculations

The geometries of the *N*-oxides (1–5) were estimated by the full geometry optimization in the MNDO method.⁶⁾ Standard bond lengths and bond angles⁷⁾ were used as the starting geometric parameters for the calculations. The equilibrium structures thus calculated for all the *N*-oxides (1–5) were of nearly planar C_{2v} symmetry and were employed for the calculations of the excited states.

The CNDO/S-CI method with standard parametrization⁸⁾ and use of the Mataga–Nishimoto formula⁹⁾ for two-center two-electron repulsion integrals did not reproduce the observed UV spectrum of 1⁵⁾; the INDO/S-CI method was therefore applied for calculations of the excited state. The INDO/S-CI calculations were performed by the method and parameters given by Ridley and Zerner.¹⁰⁾ In the CI procedure, the number of configurations to be included was the 60 lowest singly excited states. The calculated transition energies reproduced acceptably the UV spectra of 1–5.^{5,11)}

Calculations were carried out on a FACOM M-780/20 computer at the Computation Center of Nagoya University and on a HITAC M680-H computer at the Computer Center of the Institute of Molecular Science.

Results and Discussion

It is plausible that the difference in the photochemical

1

2

3

4

5

Chart 1

behavior of **1** from most *N*-oxides is due to the geometrical distortion of the *N*-oxide moiety from the planar structure which results from the steric hindrance by the carbonyl oxygen atoms at both the *peri*-positions. However, the structures optimized by the MNDO method were nearly planar for all the *N*-oxides examined and no anomalous feature in the geometry was shown for **1**.

The calculated singlet-singlet transition energies by the INDO/S-CI method are shown in Table I, together with the observed data.^{5,11)}

For all the *N*-oxides examined, the calculated lowest excited singlet states were the $n\text{-}\pi^*$ states, and the $S_1^{\pi\text{-}\pi^*}$ states associated with the photoreactions of *N*-oxides were the second lowest.

The configuration mixings in the $S_1^{\pi\text{-}\pi^*}$ states of **1**—**5** are shown in Fig. 1 together with the coefficient distributions and nodal properties of the relevant molecular orbitals. The $S_1^{\pi\text{-}\pi^*}$ states of **1**—**5** were mainly constructed (over 95%) from the transitions between two higher occupied (ψ_{a_2} and ψ_{b_2}) and two lower unoccupied π -molecular orbitals ($\psi_{a_2}^*$ and $\psi_{b_2}^*$) in the ground state. The ψ_{b_2} 's and $\psi_{b_2}^*$'s have large orbital polarization on the *N*-oxide moiety, and the ψ_{a_2} 's and $\psi_{a_2}^*$'s on carbon atoms of a ring involving the *N*-oxide moiety. The ψ_{b_2} 's and $\psi_{b_2}^*$'s for **2**—**5** are the highest occupied molecular orbitals (HOMO's) and the lowest unoccupied molecular orbitals (LUMO's), respectively, in the ground state. The ψ_{b_2} orbital of **1**, however, is the next highest occupied molecular orbital (NHOMO) in the ground state.

TABLE I. Calculated Transition Energies (ΔE in eV) and Oscillator Strengths (f)

1			2			3			4			5		
Sym.	Calc. ΔE	Obs. ^{a)} ΔE	Sym.	Calc. ΔE	Obs. ^{b)} ΔE	Sym.	Calc. ΔE	Obs. ^{b)} ΔE	Sym.	Calc. ΔE	Obs. ^{b)} ΔE	Sym.	Calc. ΔE	Obs. ^{b)} ΔE
	f			f			f			f			f	
A_2	2.47		A_2	3.07		A_2	2.94		A_2	2.82		A_2	2.73	
B_1	3.43	0.098	B_1	3.81	0.016	B_1	3.99	0.004	A_1	3.18	0.392	A_1	3.25	0.351
B_2	3.84		A_1	4.20	0.449	B_2	4.25		B_1	3.20	0.034	B_1	3.30	0.021
A_1	4.06	0.040	B_2	5.14		A_1	4.36	0.471	B_1	4.27	0.043	B_2	3.89	
A_2	4.21		B_2	5.26		B_1	5.37	0.416	A_1	4.40	0.000	B_1	4.26	0.117
B_1	4.46	0.772	B_1	5.47	0.373	A_2	5.38		B_1	4.53	1.026	A_1	4.42	0.063
A_1	4.72	0.583	A_2	6.00		B_2	5.52		A_1	4.63	0.017	B_1	4.57	1.839

a) Ref. 5. b) Ref. 11.

Fig. 1. Configuration Mixing in the $S_1^{\pi\text{-}\pi^*}$ States and the Relevant Molecular Orbitals

The proportion (%) of each configuration to the total is shown above the arrow indicating the transition.

The photoreactions in the *N*-oxide moiety are apparently associated with ψ_{b_2} and $\psi_{b_2}^*$; and the nodal properties of those orbitals on the hypothetical C...O bond between the oxygen and the *ortho*-carbon atoms and on the C-N bond showed that both the electronic transitions from ψ_{b_2} and those to $\psi_{b_2}^*$ are favorable for the formation of oxaziridine. Examination of Fig. 1 reveals that the configuration mixings in the $S_1^{\pi-\pi^*}$ state vary greatly with the compounds. The $S_0-S_1^{\pi-\pi^*}$ transitions in 1, 2, and 3 were of B_1 character and it was shown that the proportions of the $\psi_{a_2} \rightarrow \psi_{b_2}^*$ transition for the CI state of the $S_1^{\pi-\pi^*}$ state increase in the order of $2 < 3 < 1$. The high proportion of the $\psi_{a_2} \rightarrow \psi_{b_2}^*$ transition for 1 is due to the small energy separation between ψ_{a_2} and $\psi_{b_2}^*$ and the large energy separation between ψ_{b_2} and $\psi_{a_2}^*$. These features in the energy separation of the orbitals for 1 result from the lowering in energy of the b_2 orbitals due to the electroinductive uracil rings. On the other hand, the $S_0-S_1^{\pi-\pi^*}$ transitions for 4 and 5 are of A_1 character and are mainly due to the $\psi_{b_2} \rightarrow \psi_{b_2}^*$ transition. This is thought to be due to the small energy separations between ψ_{b_2} and $\psi_{b_2}^*$ caused by the electronic conjugation with fused benzene rings.

A quantum chemical study of the reactivity in photorearrangement of *N*-oxides has been reported by Koyano *et al.*, who showed that for a series of nitrones an increase in the quantum yield is correlated to an increase in the C...O bond order and a decrease in the C-N bond order associated with the excitation.¹²⁾ The changes (ΔP) of the C...O, C-N and N-O bond orders associated with the excitation to the $S_1^{\pi-\pi^*}$ state were thus calculated for the *N*-oxides (1–5) based on the configuration mixings and the orbital coefficients. The results are shown in Fig. 2.

The ΔP_{CO} and ΔP_{CN} values for 1 were not much different from those for 2–5. However, the ΔP_{NO} value for 1 was obviously different from those for 2–5 and was largely negative. This marked decrease in the N-O bond order of 1 is considered to be due to the high proportion of the $\psi_{a_2} \rightarrow \psi_{b_2}^*$ transition for the configuration and the property of the $\psi_{b_2}^*$ orbital which has large orbital coefficients and a node on the N-O bond. Taking into account that the changes of the N-O bond order on the excitation are small for the *N*-oxides (2–5) as well as for a series of nitrones

Fig. 2. Changes (ΔP) in the Bond Order Associated with the Excitation to the $S_1^{\pi-\pi^*}$ State

ΔP values were calculated as $\Delta P_{rs} = \sum d_{k(i-j)}^2 (C_i^j C_r^i - C_i^i C_r^j)$, in which $d_{k(i-j)}$ is the coefficient of k -th configuration and C_i^j is the coefficient on r -th atom of j -th molecular orbital.

investigated by Koyano *et al.*,¹²⁾ the marked decrease for 1 is noteworthy and may be related to the distinct difference in the photoreactivity of 1 from other *N*-oxides.¹³⁾

The decrease in the N-O bond order will lead to an increase of the N-O bond length, and this might lower the formation of oxaziridine owing to the change of the electronic structure induced by the geometric change. Thus, we have examined the change in N-O bond length associated with the excitation to the $S_1^{\pi-\pi^*}$ state and the effects of this length change on the N-O, C...O and C-N bond orders in the $S_1^{\pi-\pi^*}$ state for 1. The examinations were also performed for 2, which showed an increase of the N-O bond order on the excitation to the $S_1^{\pi-\pi^*}$ state.

The change in N-O bond length on excitation to the $S_1^{\pi-\pi^*}$ state was examined on the basis of variations in the energy of the ground (S_0) state and in the $S_0-S_1^{\pi-\pi^*}$ transition energy which were accompanied by an increase of the N-O bond length. As shown in Fig. 3, the potential curve of the $S_1^{\pi-\pi^*}$ state for 1 had a minimum at an N-O

Fig. 3. Potential Curves in the Change of N-O Bond Length

Δr_{NO} represents the change of N-O bond length from its equilibrium bond length in the ground state. Energies in the ground state were calculated by the MNDO method. Dashed lines represent the changes in $S_0-S_1^{\pi-\pi^*}$ transition energy.

TABLE II. Effects of an Increase in N-O Bond Length on the Bond Orders

Compound	Bond	$\Delta P_0^a)$	$\Delta P_{0.1}^b)$	$\Delta \Delta P^c)$	$\Delta P_G^d)$
1	N-O	-0.181	-0.177	+0.004	-0.064
	C...O	+0.144	+0.140	-0.004	-0.004
	C-N	-0.122	-0.141	-0.019	+0.039
2	N-O	+0.093	+0.098	+0.005	-0.086
	C...O	+0.208	+0.191	-0.017	+0.027
	C-N	-0.116	-0.111	+0.005	+0.029

a) Change of the bond order associated with the excitation in ground state equilibrium geometry. b) Change of the bond order associated with the excitation in the geometry with N-O bond length stretched by 0.1 Å from its equilibrium length in the ground state. c) $\Delta \Delta P = \Delta P_{0.1} - \Delta P_0$. d) Change of the bond order in the ground state accompanied by an increase of N-O bond length by 0.1 Å. Values were calculated by the MNDO method.

distance longer than that of the ground state. This is due to a decrease in $S_0-S_1^{\pi-\pi^*}$ transition energy with an increase in N–O distance. Thus, it was confirmed that the N–O bond length in **1** increases upon excitation to the $S_1^{\pi-\pi^*}$ state. On the other hand, the potential curve of the $S_1^{\pi-\pi^*}$ state for **2** had a minimum at a shorter N–O distance than that of the ground state, due to an increase in $S_0-S_1^{\pi-\pi^*}$ transition energy with an increase in N–O distance.

The effects of increased N–O bond length on the formation of oxaziridine were investigated on the basis of the effects of that length on the bond orders in the $S_1^{\pi-\pi^*}$ state. That is, changes of the N–O, C...O and C–N bond orders in the $S_1^{\pi-\pi^*}$ state with an increase in N–O bond length by 0.1 Å were evaluated by both changes (ΔP) of the ΔP values and changes (ΔP_G) of the bond orders in the ground state. The results are shown in Table II. We note that the positive changes for the N–O and C...O bond orders in Table II do not necessarily correspond to an increase in strength of the bond, since a comparison in strength between bonds of different lengths cannot directly be made on the bond orders (P values). However, a decrease of bond order accompanied by an increase of bond length may be correlated to the weakening of the bond. Since both the ΔP and the ΔP_G values for the C...O bond of **1** are negative, it is certain that at least in **1** the increase of N–O bond length in the $S_1^{\pi-\pi^*}$ state leads to the weakening of the C...O bond, *i.e.* reduction in the formation of oxaziridine.

From the results described above, it may be concluded that the marked decrease of the N–O bond order on the excitation for **1** is responsible for the noticeable stability of **1** towards the UV light, although other factors such as lifetime of the excited state are also important for photochemical reactions.

We next discuss the reactivity of the SET which is the initial step in the photochemical oxygen-atom transfer reaction of **1**. According to the Rehm–Weller treatment¹⁴⁾ for the free energy change of the SET process in the excited state, the feasibility of the SET from a substrate to the *N*-oxides in the excited state is evaluated by the excitation energy (ΔE_{ex}), the reduction potential (ΔE_{red}) in the ground state for the *N*-oxides and the oxidation potential (ΔE_{ox}) for a substrate. Thus, the greater the sum of the ΔE_{ex} and ΔE_{red} values for the *N*-oxides is, the more feasible the SET is. The ΔE_{ex} value for the $S_1^{\pi-\pi^*}$ state of **1** is smaller than those of **2** and **3** by *ca.* 0.6 eV and greater than those of **4** and **5** by *ca.* 0.2 eV, as shown in Table I. However, the ΔE_{red} value of **1**⁵⁾ is greatest among the examined *N*-oxides¹⁵⁾ and the differences from **2**, **3**, **4** and **5** are 1.33, 0.84, 0.33, and 0.002 V, respectively. These differences in ΔE_{ex} and ΔE_{red} values among **1**–**5** indicate that **1** is the

most feasible for the SET in the $S_1^{\pi-\pi^*}$ state, and this is attributed to the high ΔE_{red} value of **1**. The correlation of the ΔE_{red} value with the LUMO energy is well known; in fact, the ΔE_{red} values of **1**–**5** were well correlated to the LUMO ($\psi_{b_2}^*$) energies. Also, since the orbital polarization and the nodal property in the LUMO's ($\psi_{b_2}^*$) of *N*-oxides are dissociative for the N–O bond, the introduction of an electron to the LUMO by the SET is considered favorable for the subsequent deoxygenation. The orbital polarization on the N–O bond in the LUMO for **1** is greatest among those for **1**–**5**. Thus, the high photochemical oxygen transfer reactivity of **1** is well correlated to the features of the LUMO in the ground state.

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