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Studies on the Tautomers of Purines and Pyrimidines. I. All-Valence-Electronic Properties of Purine Tautomers

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The Bene-Jaffe MCNDO method, combined with extensive CI treatment, has been applied to the calculation of the valence-shell-electronic structures of the purine tautomers. Consequently, promising results have been obtained for the electronic transitions as well as the ground-state properties.

So far as the π-electrons are concerned, the electronic properties of purine tautomers, which are of interest in view of the tautomerism of biological purines, have undergone fruitful studies by means of the Pariser-Parr-Pople theory.[2-4)] Very recently, the all-valence-electrons SCF-MO method with complete neglect of differential overlaps (CNDO) has begun to be extended to large conjugated N-heterocycles such as the purine tautomers,[5,6)] All of these calculations, however, have ended in failure regarding the prediction of the transition energies. This shortcoming inherent in the original CNDO method will certainly be removed by semi-empirical reselection of the two-center repulsion integrals which were nonempirically calculated in order to preserve rotational invariance and by extensive inclusion of configuration interactions. Among several different modifications along this scheme, the one used by Bene and Jaffe[7)] may be most applicable to the purine tautomers because the parametrizations were made sufficient to reproduce the experimental spectral data of a series of azabenzenes.

The aim of the present work is to explore the availability of the modified CNDO method to the prediction of the transition energies as well as of the ground-state properties.

Calculation Method

An outline of the calculation method is given for convenience of later discussions. The secular matrix elements for the CNDO-SCF iteration process are represented as

$$F_{\mu\mu} = -\frac{1}{2}(I_\mu + A_\mu) + \left[(P_{AA} - Z_A) - \frac{1}{2}(P_{\mu\mu} - 1)\right]\gamma_{AA} + \sum_{B \neq A}(P_{BB} - Z_B)\gamma_{AB},$$

$$F_{\mu\nu} = \frac{1}{2}\kappa(\beta_A^0 + \beta_B^0)S_{\mu\nu} - \frac{1}{2}P_{\mu\nu}\gamma_{AB},$$

where $-1/2(I\mu + A\mu)$ is the core integral, P_{AA} and $P_{\mu\mu}$ the atomic and orbital charge densities, respectively, $P_{\mu\nu}$ the orbital bond-order, Z_A the core-charge on the atom A, γ_{AB} the Coulomb-repulsion integral, β_A^0 the empirically determined resonance integral term characteristic of the atom A, $S_{\mu\nu}$ the overlap integral, and κ the new empirical parameter to differentiate resonance integrals between π-orbitals from those between σ-orbitals.

1) Location: *Oshika, Shizuoka-shi.*

2) P.-S. Song, *Int. J. Quant. Chem.*, **2**, 281 (1968).
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4) I. Fischer-Hjalmers and J. Nag-Chaundhuri, *Acta Chem. Scand.*, **23**, 2963 (1969).
5) B. Pullman and H. Berthod, *Tetrahedron*, **26**, 1483 (1970).
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7) J.D. Bene and H.H. Jaffe, *J. Chem. Phys.*, **48**, 1807 (1968).

TABLE I. The Parameters used in the Calculation

Atom	$1/2(I_S+A_S)$	$1/2(I_P+A_P)$	γ_{AA}	β_A^0	All in eV unit
H	7.176	—	12.845	−12	
C	14.051	5.572	11.089	−17	
N	19.316	7.275	12.016	−26	

The parameter κ was taken as 0.585, the value adopted by Bene and Jaffe.

TABLE II. Observed and Calculated Data of the Electronic Transitions

	Obsd.	Calcd.		
	ΔE ($\varepsilon_{max}\times10^{-3}$), [$f$]	ΔE[a)]	f[a)]	ϕ(°)
1H-Purine		$\sigma\rightarrow\pi^*$ 3.18	0.00	
		$\sigma\rightarrow\pi^*$ 3.40	0.00	
		$\pi\rightarrow\pi^*$ 3.57	0.04	−169
		$\sigma\rightarrow\pi^*$ 3.78	0.00	
		$\pi\rightarrow\pi^*$ 3.89	0.03	18
		$\sigma\rightarrow\pi^*$ 4.73	0.00	
	4.6 (6.0)[b)]	$\pi\rightarrow\pi^*$ 5.15	0.30	128
		$\sigma\rightarrow\pi^*$ 5.57	0.00	
3H-Purine		$\pi\rightarrow\pi^*$ 3.50	0.04	−129
		$\sigma\rightarrow\pi^*$ 3.54	0.00	
		$\sigma\rightarrow\pi^*$ 3.65	0.00	
		$\pi\rightarrow\pi^*$ 3.89	0.14	86
		$\sigma\rightarrow\pi^*$ 4.19	0.00	
		$\sigma\rightarrow\pi^*$ 4.67	0.00	
	4.5 (7.0)[c)]	$\pi\rightarrow\pi^*$ 5.04	0.28	134
		$\sigma\rightarrow\pi^*$ 5.05	0.00	
7H-Purine		$\sigma\rightarrow\pi^*$ 3.12	0.00	
		$\sigma\rightarrow\pi^*$ 3.89	0.00	
	4.22[0.0036][d)]	$\sigma\rightarrow\pi^*$ 4.20	0.00	
	4.72[0.093]	$\pi\rightarrow\pi^*$ 4.22	0.13	70
	4.96[0.0078]	$\sigma\rightarrow\pi^*$ 4.73	0.00	
	5.39[0.00015]	$\pi\rightarrow\pi^*$ 5.64	0.05	−167
		$\sigma\rightarrow\pi^*$ 5.72	0.00	
	6.20[0.35]	$\pi\rightarrow\pi^*$ 5.85	0.45	−69
		$\pi\rightarrow\pi^*$ 6.33	0.40	160
	6.53[0.192]	$\pi\rightarrow\pi^*$ 6.56	0.78	70
9H-Purine		$\sigma\rightarrow\pi^*$ 3.01	0.00	
		$\sigma\rightarrow\pi^*$ 3.74	0.00	
	4.28(0.6)[e)]	$\sigma\rightarrow\pi^*$ 4.11	0.00	
	4.68(6.9)	$\pi\rightarrow\pi^*$ 4.20	0.15	−119
		$\sigma\rightarrow\pi^*$ 4.66	0.00	
	5.17(3.0)	$\pi\rightarrow\pi^*$ 5.57	0.13	−94
		$\sigma\rightarrow\pi^*$ 5.61	0.00	
	6.20(18.1)	$\pi\rightarrow\pi^*$ 6.15	0.44	152
		$\pi\rightarrow\pi^*$ 6.27	0.37	−76
	6.59(21.1)	$\pi\rightarrow\pi^*$ 6.56	0.71	69

a) ΔE is singlet-singlet transition energy in eV, and f is oscillator strength.
b) L.B. Townsend and R.K. Robbins, *J. Heterocycl. Chem.*, **3**, 241 (1966).
c) L.B. Townsend and R.K. Robbins, *J. Org. Chem.*, **27**, 990 (1962).
d) H.Ho Chen and L.B. Clark, *J. Chem. Phys.*, **51**, 1862 (1969).
e) L.B. Clark and I. Tinoco, Jr., *J. Am. Chem. Soc.*, **87**, 11 (1965).
f) ϕ is the angle of the transition moment with the y-axis (counted counterclockwise).

The semiempirical evaluation of the one-center Coulomb integrals is made as the difference between the ionization potential and the electron affinity of 1S orbital for hydrogen and of 2P orbitals for carbon and nitrogen. The two-center Coulomb integral is given by the extrapolation approximation of Ohno:[8]

$$\gamma_{AB} = 14.399 \Big/ \left(R_{AB}^2 + \left(\frac{7.1995}{\gamma_{AA}} + \frac{7.1995}{\gamma_{BB}}\right)^2\right)^{1/2}$$

where R_{AB} is the distance in Å between the atoms A and B.

The transition energies are calculated with the virtual orbital approximation:

$$\Delta E_{i\to j} = \varepsilon_j - \varepsilon_i - J_{ij} + 2K_{ij}$$

where ε_i and ε_j are the i th and j th orbital energies, and J_{ij} and K_{ij} are the molecular Coulomb and exchange integrals. The transition moments are calculated with the ZDO approximation:

$$\boldsymbol{M}_{i\to j} = \sqrt{2}\sum_{A}\sum_{\mu}^{A} C_i^{\mu} C_j^{\mu} (\mu|\boldsymbol{r}_A|\mu),$$

where we note that the transition moments of σ—π^* transition are reduced to be identically zero because the product $C_i^{\mu}\, C_j^{\mu}$ vanishes for each basis number μ.

The total energies were calculated with the following equation:

$$E = \sum_{A}\sum_{\mu}^{A} P_{\mu\mu} U_{\mu\mu} + \frac{1}{2}\sum_{A}\sum_{\mu}^{A}\sum_{\nu}^{A}\left(P_{\mu\mu}P_{\nu\nu} - \frac{1}{2}P_{\mu\nu}^2\right)\gamma_{AA} + \sum_{A<B}\sum_{\mu}^{A}\sum_{\nu}^{B}\left(2P_{\mu\nu}\beta_{\mu\nu} - \frac{1}{2}P_{\mu\nu}^2\gamma_{AB}\right)$$
$$+ \sum_{A<B}(Z_A Z_B/R_{AB} - P_{AA}V_{AB} - P_{BB}V_{BA} + P_{AA}P_{BB}\gamma_{AB})$$

, and the total dipole moments were calculated with the following equation:

$$\boldsymbol{D} = e\sum_{A}(Z_A - P_{AA})\boldsymbol{R}_A - 2e\sum_{A}\sum_{\mu<\nu}^{A} P_{\mu\nu}(\mu|\boldsymbol{r}_A|\nu)$$

where nonvanishing integrals $(\chi_{2s}|x|\chi_{2px})$, $(\chi_{2s}|y|\chi_{2py})$, and $(\chi_{2s}|z|\chi_{2pz})$ are obtained as $5\times 0.5292/(\sqrt{3}z^*)$Å ($z^*$ = effective nuclear charge)

The CI calculations for electronic transitions are performed including the total 64 singly excited configurations which correspond to all one-electron excitations between the highest eight occupied orbitals and the lowest eight vacant orbitals.

The geometries of the heterocyclic rings were assumed to be regular hexagone and pentagone, both with the ring-distance of 1.39 Å. The lengths of >C-H, >C-NH_2 and >N-H bonds were assumed to be 1.08, 1.34 and 1.03 Å, respectively.

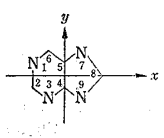
Table III. Calculated Data of the Total Energies

1H-Purine	−954.480 eV
3H-Purine	−953.306
7H-Purine	−954.874
9H-Purine	−955.039

Table IV. Observed and Calculated Data of the Total Dipole Moments

	Obsd.	Calcd.	ϕ[c]
1H-Purine	6.52—6.94 D[a]	9.21 D	63
3H-Purine	4.40—4.91[a]	5.58	138
7H-Purine	5.61[a]	7.21	−31
9H-Purine	4.3[b]	4.84	−134

a) The dipole moments of the corresponding N-substituted derivatives; B. Pullman, *et al.*, *Tetrahedron*, **26**, 1483 (1970)
b) H. De Voe and I. Tinoco, Jr., *J. Mol. Biol.*, **4**, 500 (1962).
c) ϕ is the angle of the dipole moment with the y-axis (counted counterclockwise).



8) K. Ohno, *Theoret. Chim. Acta*, **2**, 219 (1964).

Result and Discussion

Electronic Spectra

The calculated data of the 9H-tautomer were compared with the solution spectrum of purine because this tautomer is considered to be most stable at free-molecule state. The x_1- and x_2- bands at 4.68 and 5.17 eV appear to have their counterparts in the theoretical $\pi \rightarrow \pi^*$ transitions. Thus, a theoretical support can not be added here to the suggestion of Drobnik and Augenstein that the x_2-band is likely to be a $n \rightarrow \pi^*$ transition in view of observations for solvent shifts.[9] The calculated data of the 7H-tautomer were compared with its crystal spectrum measured by Ho Chen and Clark. The assignments by them are as follows; the first absorption band at 4.22 eV is a out-of-plane $n \rightarrow \pi^*$ transition, the next band at 4.72 eV a in-plane $\pi \rightarrow \pi^*$ transition polarized at 48° from the y-axis toward the C (6), the weak band at 4.96 eV another $n \rightarrow \pi^*$ transition, the very weak band at 5.39 eV a long-axis $\pi \rightarrow \pi^*$ transition, the band at 6.20 eV $\pi \rightarrow \pi^*$ transition polarized at 51° from the y-axis, and the band at 6.53 eV the third $n \rightarrow \pi^*$ transition. The calculated data serve to confirm the above-mentioned classifications of the bands but for the one at 6.53 eV, though good predictions have not been obtained for the polarization directions. The calculated data of the 1H- and 3H-tautomers were compared with the spectra of the corresponding N-methyl derivatives. The calculated data indicate that a remarkable bathochromic shift occurs at the $\pi \rightarrow \pi^*$ transitions.

Ground-State Properties

The total energies of the purine tautomers were calculated with a view of examining whether or not the relative stability of the tautomers is correctly reproduced by this calculation. The results given here show that the sequence of the energy values is 9H<7H<1H<3H. This is in accord with the experimental data that the 9H-tautomer is most stable in solution and the 7H-tautomer is also found in crystal phase.

The total dipole moments calculated here are by 1—2 Debye larger than those obtained with the original CNDO method.[5] However, the predicted direction of the moment of 9H-purine is fairly close to the observed angle of −128° with the y-axis.[5]

On the whole, the modified CNDO method is found to preserve the applicability to the calculation of ground-state properties.

The calculations have been performed with a HITAC 5020-E computer at the Computation Center of the University of Tokyo and with a NEAC 2200—400 computer at the Computation Center of Shizuoka Prefecture.

9) J. Drobnik and L. Augenstein, *Photochem. Photobiol.*, **5**, 13 (1966).