

HYDROGEN BONDS AND PROTON TRANSFER IN IMIDAZOLE OLIGOMERS AND (IMIDAZOLE)₂H⁽⁺⁾ SYSTEM: QUANTUM-CHEMICAL CALCULATIONS

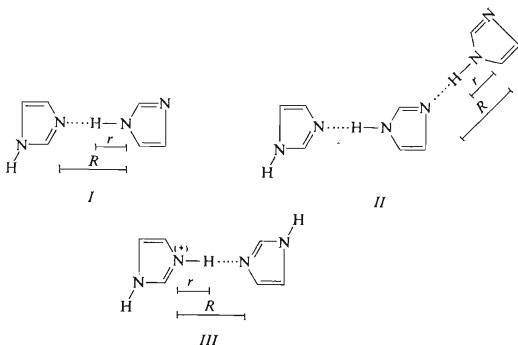
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The semi-empirical PCILO method has been applied to study of hydrogen bonds and proton transfer in linear n -mers of imidazole ($n = 3$). The calculated hydrogen bond energy in the dimer is 30.64 kJ mol⁻¹. In imidazole trimer interaction energy of the "second" hydrogen bond increased to 32.02 kJ mol⁻¹. One-minimum functions only have been found by calculations of the proton potential functions in imidazole dimer and trimer for the equilibrium distances $R_{N\dots N}$. For somewhat longer distances $R_{N\dots N} = 0.30$ nm a second minimum was observed as shoulder. On the contrary, for the (imidazole)₂H⁺ system the proton potential curve has two minima for the equilibrium distance $R_{N\dots N} = 0.252$ nm, the second minimum is more stable by 3.97 kJ mol⁻¹.

Imidazole belongs among the compounds which can form hydrogen bonds both as proton-donors and as proton-acceptors. Occurring in side chain of histidine, imidazole represents an important part of many proteins. The hydrogen-bond properties of imidazole were studied experimentally^{1,2}. These studies have shown that imidazole



forms linear oligomers in non-polar solvents. The ¹H-NMR study³ of imidazole self-association showed that the compound exists predominantly as a trimer in chloroform solutions. Protonation of imidazole was studied by Zundel and Muehlinghaus⁴. Addition of the proton enables formation of N—H⁽⁺⁾⋯N bonds and, hence, the Grotthus proton conductivity through imidazole chains⁵.

This paper deals with hydrogen bond and proton transfer in the imidazole dimer *I* and trimer *II* and in (imidazole)₂H⁺ system *III* with the use of the quantum-chemical PCILO method¹³. Recently this method was successfully applied to study of intermolecular interactions⁶⁻⁹, proton affinities¹⁰ and proton potential functions^{11,12}.

CALCULATIONS

The calculations of equilibrium geometry, hydrogen bond energy, and the proton potential functions were carried out by the original PCILO method¹³ using experimental geometry of imidazole¹⁴. Geometry of the studied complexes was optimized with respect to $r_{\text{N-H}}$ and $R_{\text{N...N}}$ distances (Fig. 1), the N—H⋯N bonds being considered linear in the calculations.

The hydrogen bond energy E_{HB} was defined as the difference between total energy of the hydrogen-bonded complexes ($E(\text{MIN})$) and total energy of the isolated molecules (E_{∞}).

$$E_{\text{HB}} = E(\text{MIN}) - E_{\infty} . \quad (1)$$

The calculations were carried out on a Siemens 4004/150 computer in Computer Centre of the Comenius University, using the program QCPE No. 220.

RESULTS AND DISCUSSION

Energy of Hydrogen Bond

Table I gives the equilibrium geometry, interaction energy, and dipole moments of the studied hydrogen-bonded systems. The hydrogen bond N—H⋯N in imidazole dimer has medium strength, with energy of 30.64 kJ mol⁻¹. Interaction energy of the "second" hydrogen bond in imidazole trimer increased to the value of 32.02 kJ mol⁻¹. Hence, positive cooperation effect is observed in the trimer. Similar increase in the hydrogen bond energy was also observed by theoretical studies of formation of linear water polymers^{7,15}, linear polymers of formic acid⁹, formamide¹⁶, and methanol¹⁷.

Wang and coworkers³ used ¹H-NMR spectroscopy for determination of hydrogen bond enthalpy in imidazole presuming the equilibrium monomer-dimer-trimer. The hydrogen bond energy values 16.74 and 12.97 kJ mol⁻¹ for the dimer and trimer, respectively, are considerably lower than those calculated by the PCILO method, however, the authors³ did not involve the imidazole-solvent (CHCl₃) interactions in the calculations of enthalpy of formation of the imidazole dimers and trimers. Chloroform can use its C—H bond for hydrogen bond formation¹⁸ and thus participate in a competitive equilibrium giving imidazole-chloroform complex.

The calculated N...N distance of the second hydrogen bond in imidazole trimer was somewhat longer than that in the dimer. But compared with the experimental distance found in imidazole crystal¹⁴ (0.286 nm), the both calculated distances are shorter.

(+)
Energy of N—H...N hydrogen bond in (imidazole)₂H⁺ system is markedly higher than that in the imidazole dimer.

The Proton Transfer

The results of the proton potential functions calculation for the proton transfer (+) in the N—H...N and N—H...N bonds are represented in Figs 1–3. The potential functions were calculated for the proton transfer between the proton donor and the proton acceptor using fixed geometries and intermolecular distances. In the cases of imidazole dimer and trimer using $R_{N...N}$ equilibrium distance (Figs 1, 2, curves a) the calculated potential functions only have one minimum corresponding thus to a "simple" hydrogen-bonded complex. The proton transfer was not observed. Calculation of the proton potential function in imidazole dimer at longer distance

TABLE I
PCILO Calculated Equilibrium Geometry, Interaction Energy, and Dipole Moments of the Systems Studied

System	$R_{N...N}$, nm	r_{N-H} , nm	E_{HB} , kJ mol ⁻¹	$\mu \cdot 10^{29}$, Cm
(Imidazole) ₂	0.270	0.107	30.64	2.36
(Imidazole) ₃	0.275	0.109	32.02	4.30
(Imidazole) ₂ H ⁺	0.252	0.118	194.31	4.72

TABLE II
Charge Shift (CS) and Charge Transfer (CT) Calculated by PCILO Method for the Systems Studied

System	CS _N	CS _H	CS _{N-H}	CT
(Imidazole) ₂	-0.002 ^a	0.063	-0.080 ^a	0.033
(Imidazole) ₂ H ⁺	0.155	0.045	-0.276 ^a	0.260

^a Negative CS values mean increasing electron density as compared with the monomers.

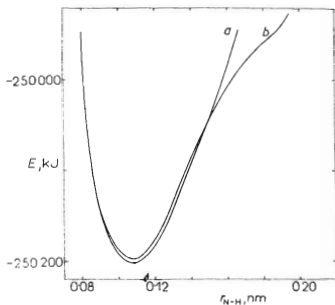


FIG. 1

Proton Potential Functions for Proton Transfer in Imidazole Dimer

$a R_{N\dots N} = 0.270$ nm, $b R_{N\dots N} = 0.30$ nm.

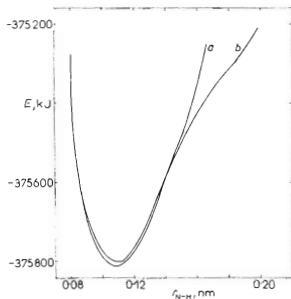


FIG. 2

Proton Potential Functions for Proton Transfer in Imidazole Trimer

$a R_{N\dots N} = 0.270$ nm, $b R_{N\dots N} = 0.30$ nm.

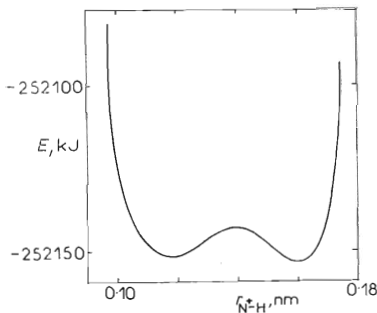


FIG. 3

Proton Potential Function for Proton Transfer in (Imidazole)₂H⁽⁺⁾ System ($R_{N\dots N} = 0.252$ nm)

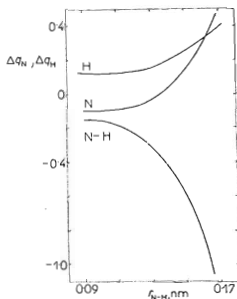


FIG. 4

Dependence of Net Charge Densities of Hydrogen-Bonded N—H...N Atoms on N—H Distance in Hydrogen Bond of Imidazole Dimer ($R_{N\dots N} = 0.270$ nm)

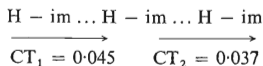
$R_{N...N} = 0.30$ nm (Fig. 1, curve *b*) indicate a second minimum as a shoulder. This shoulder increases with addition of the third imidazole molecule (acting as proton donor) in the imidazole trimer (Fig. 2, curve *b*). Chojnacki¹⁹ studied recently the proton transfer in imidazole dimer by CNDO/2 method. His CNDO/2 calculations at the experimental distance $R_{N...N} = 0.286$ nm showed existence of an asymmetrical minimum, the proton transfer was also accompanied by electronic charge transport.

The PCILO calculation of the proton potential function in the N—H⁽⁺⁾...N bond of (imidazole)₂H⁺ system at the equilibrium distance $R_{N...N} = 0.252$ nm indicates a curve with two minima at 0.118 and 0.160 nm. The second minimum was found more stable by 3.97 kJ mol⁻¹. The energy barrier between the both minima represents the value of 22.35 kJ mol⁻¹.

Zundel⁵ studied hydrogen bonds and the proton transfer in imidazole and found that when no excess proton is present, the potential wells in the N—H...N bonds between the imidazole molecules are asymmetrical with one minimum. In the presence of excess protons the bonds N—H⁽⁺⁾...N are formed, the proton potential functions have two minima, and if weak electric field is present, the proton is conducted by the chain of imidazole molecules. Our PCILO calculations agree with these experimental data. Whereas in imidazole dimer the calculated proton potential function only has one asymmetrical minimum, in the case of (imidazole)₂H⁺ system the PCILO calculation presents potential curve with two minima, the proton transfer being an exothermic process. However it must not be forgotten that semi-empirical methods reproduce the potential functions of the proton transfer at most semi-quantitatively²⁰. Calculation of realistic proton potential function necessitates *ab initio* calculations with extended bases, and also it is necessary to consider a part of correlation energy in some way^{20,21}.

Charge Shifts and Charge Transfer

Table II gives charge shifts and charge transfer in hydrogen-bonded atoms of imidazole dimer and in (imidazole)₂H⁺ system. In the both cases the proton-donor nitrogen atom in imidazole acquires electron density. Electron density of the proton-acceptor nitrogen atom in imidazole dimer increases but little. On the contrary, in (imidazole)₂H⁺ system this nitrogen considerably loses electron density with hydrogen bond formation. Charge transfer from the electron donor is much more marked in (imidazole)₂H⁺ system (Table II). In imidazole trimer the following charge transfer takes place (im means imidazole nucleus):



That means that the charge transfer decreases with increasing number of molecules in imidazole chain.

Dependence of net charge of N—H...N atoms in imidazole dimer (for the equilibrium distance $R_{N...N} = 0.270$ nm) on the length r_{N-H} is given in Fig. 4. The net positive charge at the proton-acceptor nitrogen atom increases with increasing r_{N-H} , and, simultaneously, the net negative charge at the proton-donor nitrogen atom increased, too. Similarly, the net positive charge increases at the hydrogen atom of H-bond. The same charge changes take place also in the proton transfer within imidazole trimer. On the contrary, in (imidazole)₂H⁺ system the net negative charge increases at the hydrogen atom of H-bond.

REFERENCES

1. Pimentel G. C., McClellan A. L.: *The Hydrogen Bond*. Freeman, San Francisco 1960.
2. Joesten M. D., Schaad L. J.: *Hydrogen Bonding*. M. Dekker, New York 1974.
3. Wang S. M., Lee L. Y., Chen J. T.: *Spectrochim. Acta* 35A, 765 (1979).
4. Zundel G., Muehlinghaus J.: *Z. Naturforsch.* 26b, 546 (1971).
5. Zundel G. in the book: *The Hydrogen Bond, Recent Developments in Theory and Experiments* (P. Schuster, G. Zundel, C. Sandorfy, Eds). North-Holland, Amsterdam 1976.
6. Hobza P., Zahradník R.: *Weak Intermolecular Interactions in Chemistry and Biology*. Academia & Elsevier, Prague 1980.
7. Singh R. D.: *Advan. Mol. Relax. Interact. Processes* 11, 87 (1977).
8. Remko M.: *Advan. Mol. Relax. Interact. Processes* 14, 37 (1979).
9. Remko M.: *Advan. Mol. Relax. Interact. Processes* 15, 193 (1979).
10. Tollehaere J. P., Moereels H.: *Tetrahedron Lett.* 1978, 1347.
11. Remko M.: *Advan. Mol. Relax. Interact. Processes* 16, 155 (1980).
12. Remko M., Krasnec L.: *Advan. Mol. Relax. Interact. Processes* 18, 1 (1980).
13. Diner S., Malrieu J. P., Jordan F., Gilbert M.: *Theor. Chim. Acta* 15, 100 (1969).
14. Martinez-Carrera S.: *Acta Crystallogr.* 20, 783 (1966).
15. Del Bene J. E., Pople J. A.: *J. Chem. Phys.* 52, 4858 (1970).
16. Sheridan R. P., Lee R. H., Peters N., Allen L. C.: *Biopolymers* 18, 2451 (1979).
17. Remko M.: *Advan. Mol. Relax. Interact. Processes* 17, 135 (1980).
18. Remko M., Polčín J.: *Z. Phys. Chem., (Wiesbaden)* 102, 161 (1976).
19. Chojnacki H.: *Int. J. Quantum Chem.* 16, 299 (1979).
20. Schuster P., Jakubetz W., Beier G., Meyer W., Rode B. M. in the book: *Chemical and Biochemical Reactivity* (E. D. Bergman, B. Pullman, Eds). Academic Press, Jerusalem 1974.
21. Schuster P. in the book: *Intermolecular Interactions from Diatomics to Biopolymers* (B. Pullman, Ed.). Wiley-Interscience, New York 1978.

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