ELECTRONIC STRUCTURE OF CHLORO-SUBSTITUTED PYRIMIDINES

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The electron-density distribution in the molecules of six chloro-substituted pyrimidines was calculated by the MO LCAO method within the Hoffmann and Pariser–Parr–Pople approximations. The reactivities and transmission of the effect of substituents in these compounds are discussed. The π charges and orders of the π bonds in the excited states of the chloropyrimidines were calculated with allowance for the interaction of the configurations. An interpretation of their electronic spectra is given.

Owing to the lability of the chlorine atoms in the 2, 4, and 6 positions, chloro-substituted pyrimidines are the usual intermediates in the synthesis of pyrimidine itself and its derivatives [1]. However, certain problems in the reactivities of these compounds have not up to now been worked out. For example, the problem of the relative ease of nucleophilic substitution of the chlorine atoms in the 2 and 4 positions is not completely clear. As a rule, the experimental data indicate preferred substitution of the chlorine atom attached to C_4 (for example, see [2]); however, according to [3, 4], the chlorine atom attached to C_2 is more labile (Mamaev and co-workers [4] explain the contradictory results by means of the effect of the medium in which the reaction occurs). It has been proposed [5] that an electron-acceptor substituent (Cl, Br) is capable, all by itself, of activating the chlorine atom in the 4 position. Calculation of unsubstituted pyrimidine [1] shows that the C_2 atom has a greater deficit of π electrons than C_4; however, the opposite conclusion was drawn on the basis of Hückel calculations [6].

We have performed a quantum-chemical calculation of 4-chloro- (I), 2-chloro- (II), 4,6-dichloro- (III), 2,4-dichloro- (IV), 2,4,6-trichloro- (V), and 2,4,5,6-tetrachloropyrimidines (VI) with allowance for all of the valence electrons by means of the Hoffmann method [7] and within the π-electron approximation by the Pariser–Parr–Pople (PPP) method. The following interatomic distances were used in the calculation: $r_{C-C} = 1.37$ Å, $r_{N-C_4} = 1.345$ Å, $r_{N-C_2} = 1.33$ Å, and $r_{C-Cl} = 1.718$ Å. The calculation by the Hoffmann method was performed with the program in [8] with an M-220 computer with parameters taken in accordance with [9]. The calculation by the PPP method was performed with a BÉSM-6 computer (the program was provided by V. I. Danilov); the one-center coulombic integrals were calculated from the data in [10], while the two-center integrals were calculated with the Mataga–Nishimoto formula [11].

Electron Distribution

The charges on the atoms in molecules of I-VI are presented in Table 1. Calculation of the hybridization of the atoms from the diagonal elements of the partial population matrix shows that deviation from sp^2 type with an increase in s character is observed for all of the carbon atoms, particularly those bonded to the chlorine atom; for example, in VI, the hybridizations of C_2, C_4, and C_5 are, respectively, $s^{1.01}p^{1.24}$, $s^{1.07}p^{1.40}$, and $s^{1.11}p^{1.62}$. The hybridization of the nitrogen atoms in all of the molecules is the same – $s^{1.48}p^{2.98}$ – i.e., the ratio between the s and p components of the σ population corresponds precisely to the sp^2 type. It is known [1, 12] that the unshared electron pairs of the nitrogen atoms in pyrimidine molecules are partially delocalized, while the properties of the C_5 atom recall those of the carbon atom of the benzene ring. The discrepancy between our results and these circumstances is probably associated with the overstatement of the absolute values of the charges on the atoms that is typical for the Hoffmann method. In

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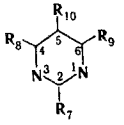
TABLE 1. Changes (Δq) on the Atoms of I-VI*



Compound	Parameter	N_1	C_2	N_3	C_4	C_5	C_6	R_7	R_8	R_9	R_{10}
I	Δq	−0,888	0,693	−0,893	0,831	−0,209	0,378	0,084	−0,210	0,097	0,117
$E=-651{,}991$ eV	Δq_σ	−0,467	0,374	−0,464	0,531	−0,143	0,153	0,084	−0,292	0,097	0,117
	Δq_π	−0,421	0,319	−0,429	0,300	−0,076	0,225	—	0,082	—	—
II	Δq	−0,899	1,092	−0,899	0,406	−0,189	0,406	−0,223	0,097	0,097	0,112
$E=-652{,}205$ eV	Δq_σ	−0,462	0,743	−0,462	0,153	−0,127	0,153	−0,304	0,097	0,097	0,112
	Δq_π	−0,437	0,349	−0,437	0,253	−0,062	0,253	0,081	—	—	—
		(−0,249)	(0,183)	(−0,249)	(0,137)	(−0,043)	(0,137)	(0,084)	—	—	—
III	Δq	−0,916	0,700	−0,916	0,812	−0,271	0,812	0,084	−0,214	−0,214	0,122
$E=-760{,}108$ eV	Δq_σ	−0,464	0,478	−0,464	0,534	−0,140	0,534	0,084	−0,292	−0,292	0,122
	Δq_π	−0,452	0,222	−0,452	0,278	−0,131	0,278	—	0,079	0,079	—
		(−0,270)	(0,182)	(−0,270)	(0,144)	(−0,096)	(0,144)	—	(0,084)	(0,084)	—
IV	Δq	−0,929	1,097	−0,933	0,836	−0,237	0,384	−0,222	−0,210	0,097	0,117
$E=-760{,}349$ eV	Δq_σ	−0,463	0,746	−0,459	0,534	−0,133	0,156	−0,303	−0,292	0,097	0,117
	Δq_π	−0,466	0,351	−0,474	0,302	−0,104	0,228	0,081	0,082	—	—
		(−0,270)	(0,185)	(−0,286)	(0,148)	(−0,078)	(0,134)	(0,082)	(0,085)	—	—
V	Δq	−0,956	1,102	−0,956	0,817	−0,298	0,817	−0,222	−0,213	−0,213	0,122
$E=-868{,}467$ eV	Δq_σ	−0,459	0,749	−0,459	0,537	−0,140	0,537	−0,303	−0,292	−0,292	0,122
	Δq_π	−0,497	0,353	−0,497	0,280	−0,158	0,280	0,081	0,079	0,079	—
		(−0,304)	(0,186)	(−0,304)	(0,145)	(−0,115)	(0,145)	(0,081)	(0,082)	(0,082)	—
VI	Δq	−0,952	1,080	−0,952	0,766	0,186	0,766	−0,225	−0,213	−0,213	−0,242
$E=-975{,}984$ eV	Δq_σ	−0,457	0,740	−0,457	0,532	0,268	0,532	−0,304	−0,289	−0,289	−0,284
	Δq_π	−0,495	0,340	−0,495	0,234	−0,082	0,234	0,079	0,076	0,076	0,042
		(−0,300)	(0,171)	(−0,300)	(0,114)	(−0,086)	(0,114)	(0,078)	(0,078)	(0,078)	(0,052)

* The charges calculated by the PPP method are indicated in parentheses.

TABLE 2. Electron Transitions in Molecules of III-VI

Molecule	State	Electron transition parameters (ΔE is the energy in eV, f is the oscillator strength, and ε is the extinction)		
		calculated		Exptl.,* ΔE (ε)
		configurat.	ΔE (f)	
III	S_1	5→6	5,563 (0,047)	4,887 (4600)[14]
	S_2	4→6	6,545 (0,042)	
	S_3	4→7	7,042 (0,059)	
	S_4	5→7	7,209 (0,372)	
	T_1	5→6	3,638	
IV	S_1	5→6	5,436 (0,082)	4,811 (5400)[14]
	S_2	5→7	6,632 (0,063)	
	S_3	4→6	7,127 (0,530)	
	S_4	4→7	7,587 (0,328)	
	T_1	5→6	3,643	
V	S_1	6→7	5,412 (0,074)	4,720 (4900)[13]
	S_2	5→7	6,561 (0,003)	
	S_3	6→8	7,019 (0,572)	
	S_4	5→8	7,136 (0,551)	
	T_1	6→7	3,676	
VI	S_1	7→8	5,061 (0,115)	4,465 (5200)[13]
	S_2	7→9	6,181 (0,076)	5,350 (8200)[13]
	S_3	6→8	6,919 (0,545)	
	S_4	6→9	7,122 (0,413)	
	T_1	7→8	3,541	

*In aqueous solutions; the maxima of the UV spectra of IV-VI in the vapor state are shifted hypsochromically by about 0.1 eV [13].

fact, the experimental values of the σ and π charges on the nitrogen atoms determined for II and III by the nuclear quadrupole resonance (NQR) method [12] are somewhat lower than the values calculated by the Hoffmann method; at the same time, the magnitudes of the π charges are in good agreement with the values calculated by the PPP method.

The populations of the individual bond in I-VI change little from molecule to molecule. The C_5-C_6 bond is characterized by the maximum population (1.10-1.11), while the C−Cl bond is characterized by the minimum population (0.72-0.73); the populations of the N_1-C_2 and N_1-C_6 bonds are, respectively, 0.98 and 0.91.

Reactivities

As seen from Table 1, in all cases in which the chlorine atoms are situated in the 2 position and in the 4 position, there is a larger deficit of electrons on C_2 than on C_4. Despite the assumption in [5], a chlorine atom attached to C_5 not only does not change this relationship but even reinforces it. Thus nucleophilic substitution of the chlorine atoms in polychloropyrimidines should proceed preferably at C_2 if the solvent does not have a specific effect on the reaction. However, one cannot exclude the possibility that an electron-acceptor substituent in the 5 position of greater strength than the chlorine atom is capable of disrupting this regularity due to creation on C_4 of a high positive charge.

The introduction of a chlorine atom into the 4 position appreciably changes the magnitude of the chargeon C_6 due to the π components, while the charge on C_2 remains practically unchanged in this case (II-V), as does the charge on C_4 (I, III-V), when the substituent attached to C_2 is changed. Consequently, the transmission of the effect of a substituent from C_4 to C_6 in pyrimidine molecules is more effective than between C_2 and C_4. Both of these conclusions are in complete accord with the results of kinetic measurements [4]. Calculations by the Hoffmann method do not make it possible to distinguish the degree of transmission of the substituent effect from C_2 to C_4 and from C_4 to C_2. As one should have expected, the magnitudes of the charges on the carbon atoms of V and VI depend markedly on the nature of the substituent attached to C_5. Except for the VI molecule, the π charges on the nitrogen atoms increase as the number of chlorine atoms increase; the charges on the chlorine atoms are constant. The results of calculation by the PPP method confirm the above-indicated tendencies of the effect of substituents on the distribution of π-electron charges.

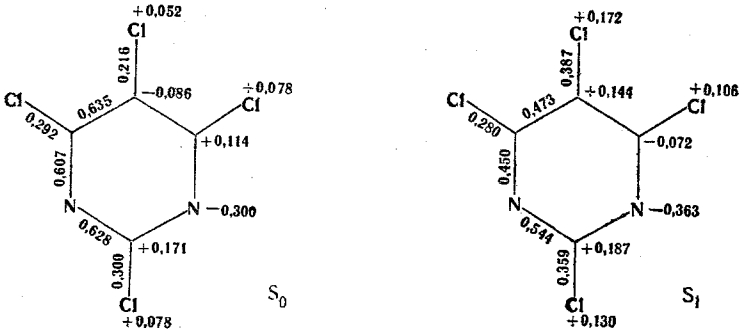
Electronic Spectra

Calculation by the Hoffmann method shows that the first vacant molecular orbital of I-VI is a delocalized π* orbital. The closest filled orbitals from which electronic transitions to it are allowed, also

have π character. Consequently, the long-wave absorption band in the UV spectra of I-VI should be due to a $\pi \rightarrow \pi^*$ transition.

The effect of several chlorine atoms on the electron transitions in the molecules of heterocycles has received little theoretical study. We therefore calculated the UV spectra of III-VI within the π approximation with inclusion of all of the singly excited configurations.

The results of the calculation are presented and compared with the experimental data [13, 14] in Table 2. It is seen that the calculated characteristics of the first singlet $\pi \rightarrow \pi^*$ transition convey the regularity of the changes observed experimentally when the number of chlorine atoms increases – the bathochromic shift of the absorption band and the increase in its intensity. All four of the singlet-singlet transitions correspond with respect to symmetry type to those observed in unsubstituted pyrimidine; only a smaller energy difference of the third and fourth transitions can be noted. It follows from a comparison of the molecular diagrams of VI (the diagrams of the other molecules are qualitatively similar) for the ground and first excited singlet states that the long-wave $\pi \rightarrow \pi^*$ transition is associated with transfer of electron density from C_2 and C_5 to the adjacent atoms of the pyrimidine ring, during which the orders of the ring π bonds upon the whole, decrease. This circumstance additionally confirms the monotypic character of the first singlet-singlet transitions in benzene, pyrimidine, and III-VI molecules. The charges of the Cl_8 and Cl_9 atoms in the excited state increase somewhat, but the corresponding orders of the C–Cl bonds remain almost constant at a quite low value; the more appreciable increase in the charges on Cl_7 and Cl_{10} corresponds to an increase in the orders of the C–Cl bonds. Thus these atoms in the excited state are the most capable of direct conjugation with the pyrimidine ring; this is understandable if one takes into account the appearance of a deficit of π electrons on the C_2 and C_5 atoms. A comparison of the calculated and experimental ΔE values provides a basis for assuming that conjugation of the chlorine atoms with the pyrimidine ring is stronger than that, which follows from the calculation. However, within the framework of the PPP method, a further increase in conjugation would lead to too high orders of the C–Cl π bond, values that are not in agreement with the experimental bond lengths [15].



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