SPECTROSCOPIC STUDY OF THE ELECTRON-DONOR PROPERTIES OF 1-VINYL- AND 1-ETHYLAZOLES

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The thermodynamic parameters of the reaction of 1-vinyl- and 1-ethylazoles with phenol (K_{as}, $-\Delta H$, and $-\Delta S$) were calculated for 1:1 complexes with the aid of IR spectroscopy. The investigated compounds are arranged in the following order with respect to their basicities on the basis of their K_{as} and pK_a values: 1-ethylimidazole, 2-methyl-1-vinylimidazole, 1-ethylbenzimidazole, 1-vinylimidazole, 1-vinylbenzimidazole, 1-ethylpyrazole, 1-ethyl-1,2,4-triazole 3,5-methyl-1-vinylpyrazole, 1-vinyl-1,2,4-triazole, 1-ethylbenzotriazole, 1-vinylbenzotriazole, and 1-vinylpyrazole. The hypsochromic shifts of the bands and the change in the extinction coefficient in the electronic absorption spectra of imidazoles and benzimidazoles in HCl solution as compared with ethanol solutions are determined by the increase in the conjugation system of the azoles rather than by their basicities.

The biological activity of nitrogen-containing heterocyclic compounds is determined to a large extent by their acid–base properties. We have obtained the association constants, enthalpies, and entropies of the reaction of 1-ethyl- and 1-vinyl-substituted imidazoles, benzimidazole, pyrazoles, triazole, and benzotriazole with phenol in order to study the influence of the inductive and mesomeric effects on the electron-donor capacity of azoles during the formation of hydrogen bonds by them.

The thermodynamic parameters of the reaction of azoles (B) with phenol in CCl_4 solution were calculated on the basis of IR spectroscopic data. For this, we determined the spectral shifts ($\Delta\nu$), which are the differences between the frequencies of the stretching vibrations of the monomeric and associated OH groups of phenol and may be a measure of the energies of the hydrogen bonds.

Because of superimposition of a number of bands with maxima at 2600-3100 cm^{-1}, the absorption band of the stretching vibrations of the associated OH groups has a complex structure (Fig. 1). Their origin is explained by the considerable polarizability of the hydrogen bonds [1]. The presence in the spectra of one isopiestic point as the 1-vinylazole concentration is varied and the absence of any deviations in the K_{as} values make it possible to assume that only one type of 1:1 complex is present in solution [2].

The $-\Delta H$ and $-\Delta S$ values were obtained from the van't Hoff equation

$$\ln K = -\frac{\Delta H}{RT} + \frac{\Delta S}{R}.$$

The parameters of the linear equations that relate lnK to 1/T were determined by the method of least squares. The regression equation for 1-vinylimidazole has the form $\ln K = 2553\frac{1}{T} - 3.68$. The accuracy in the determination of $-\Delta H$ was ~10%.

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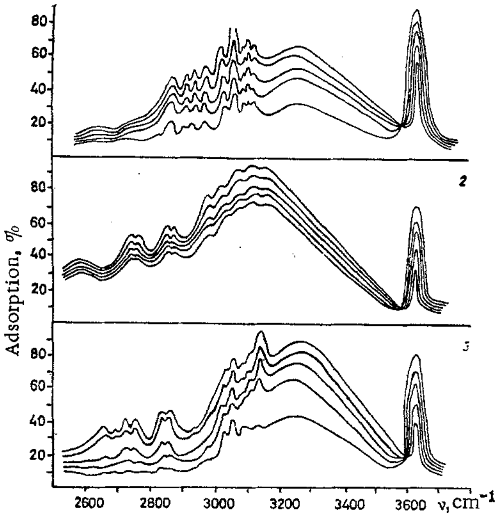

Fig. 1

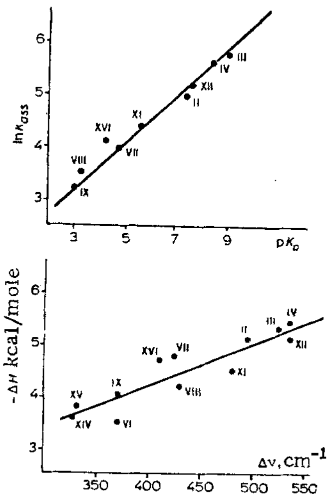

Fig. 2

Fig. 1. IR spectra of associates of phenol ($c_P^0 = 0.014$ mole/liter) with 1-vinylazoles in CCl_4 (with an LiF prism and an absorbing-layer thickness of 4.2 mm): 1) 1-vinylpyrazole (c = 0.013-0.110 mole/liter); 2) 1-vinylimidazole (c = 0.019-0.045 mole/liter); 3) 1-vinyl-1,2,4-triazole (c = 0.013-0.120 mole/liter).

Fig. 2. Relationship (a) between the ln K_{ass} and pK_a values of azoles and relationship (b) between the $-\Delta H$ and $\Delta\nu$ values during the formation of hydrogen bonds between 1-vinyl- and 1-ethylazole and phenol.

TABLE 1. pK_a, K_{ass}, $-\Delta H$, $-\Delta S$, and $\Delta\nu$ Values for 1-Vinyl- and 1-Ethylazoles and Their Complexes with Phenol

Compound*	pK_a†	K_{ass}, mole/liter at 20°C	$-\Delta H$, kcal/mole	$-\Delta S_{eu}$	$\Delta\nu$‡, cm^{-1}
III	8,87	310	5,3	6,79	525
IV	8,35	280	5,4	7,32	535
XII	7,49	183	5,1	7,60	535
II	7,32	150	5,1	6.79	495
XI	5,64	75	4,5	6,79	480
VII	4,67	56	4.8	7,30	425
XVI	4,22	65	4,7	7,64	410
VIII	3,22	30	4,2	7,25	430
IX	2,97	34	4.0	7.14	370
XV	—	32	3,8	6,17	330
XIV	—	15	3,6	6.76	325
VI	—	13	3,5	6,80	370

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*See Table 3 for the names of the compounds.

†Compounds and pK_a values: imidazole 9.09, benzimidazole 7.32, pyrazole 3.63, and triazole 4.83.

‡Obtained from $\Delta\nu = 3610 - \nu_{ass}$.

TABLE 2. Association Constants as Functions of the Temperature for Complexes of Azoles (B) with Phenol (in moles per liter)

t, °C	III	IV	XII	II	XI	VII	XVI	VIII	IX	XV	XIV	VI
15	360	330	214	180	83	64	73	38	28	47	17	15
20	310	280	183	150	75	56	65	34	25	32	15	13
25	260	240	157	127	68	49	57	30	23	29	14	12
30	220	210	135	112	58	45	51	27	20	26	13	11
35	190	170	117	93	50	40	45	23	18	23	11	10
40	160	151	102	82	46	34	39	21	17	21	10	9
45	140	132	89	72	42	28	35	19	15	19	10	8

TABLE 3. Quantitative Characteristics of the Electronic Spectra of Azoles (B)

No.	Compound	λ(ε), nm		
		dioxane	alcohol	0.1*N* HCl
I	Imidazole	—	210 (5000)	207 (5550)
II	1-Vinylimidazole	—	202 (7890)	—
		234 (12390)	230 (10770)	218 (8820)
III	1-Ethylimidazole	—	202 (5170)	—
		—	217 (5160)	211 (5110)
IV	2-Methyl-1-vinylimidazole	237 (11700)	233 (10950)	222 (9620)
V	Pyrazole	—	210 (3730)	214 (5420)
VI	1-Vinylpyrazole	—	212 (3730)	209 (5250)
		250 (12740)	250 (11550)	248 (9380)
VII	1-Ethylpyrazole	221 (4350)	221 (4610)	226 (6230)
VIII	3,5-Methyl-1-vinylpyrazole	—	227 (7060)	219 (7360)
		256 (15640)	255 (15070)	252 (9500)
IX	1-Vinyl-1,3,4-triazole	231 (14260)	228 (13730)	225 (10030)
X	Benzimidazole	—	201 (46660)	209 (11000)
		246 (7800)	245 (5500)	233 (3600)
		251 (7530)	250 (5660)	241 (3830)
		260 (4200)	259 (3300)	247 (3660)
		269 (4730)	267 (4110)	253 (3660)
		275 (6690)	273 (6090)	262 (4700)
		282 (7610)	280 (7080)	267 (7030)
				274 (7290)
XI	1-Vinylbenzimidazole	—	202 (31130)	—
		232 (16820)	227 (16730)	210 (18130)
		237 (19000)	233 (17100)	—
		252 (13960)	253 (11040)	—
		262 (9250)	260 (9360)	264 (8780)
		283 (5550)	281 (5130)	269 (9170)
		292 (5040)	290 (4360)	
				275 (7780)
XII	1-Ethylbenzimidazole	—	204 (46810)	—
		252 (5980)	249 (6040)	250 (3890)
		256 (6260)	254 (6220)	256 (4490)
		269 (4060)	267 (4180)	262 (5420)
		278 (4450)	275 (4840)	269 (7530)
		285 (4770)	282 (5190)	
				276 (7240)
XIII	Benzotriazole	—	199 (30740)	198 (22000)
		252 (6190)	254 (7480)	258 (5600)
		258 (5820)	260 (7400)	262 (5930)
		277 (4860)	276 (5990)	273 (5680)
		281 (4940)	—	
				279 (5460)
XIV	1-Vinylbenzotriazole	—	199 (25070)	198 (24950)
		—	215 (16780)	215 ((18920)
		220 (15390)	219 (17460)	218 (19250)
		233 (15980)	228 (14530)	227 (13720)
		262 (7050)	263 (7400)	265 (7430)
		270 (6610)	271 (6990)	273 (7340)
		299 (6800)	298 (6820)	297 (6250)
XV	1-Ethylbenzotriazole	—	202 (30070)	199 (25530)
		257 (6290)	258 (6600)	260 (6540)
		263 (6520)	263 (6900)	—
		273 (5210)	273 (5960)	273 (7380)
		279 (5790)	279 (6050)	279 (5790)
		284 (5690)	284 (5700)	284 (6260)

The $K_{a\,s}$, $-\Delta H$, and pK_a values determined by potentiometric titration in acetone solution quantitatively characterized the electron-donor capacity of the investigated compounds (Tables 1 and 2). A correlation is observed between the pK_a and ln K_{ass} values at the constant temperature of 20° (Fig. 2a); $r = 0.983$, and ln $K_{a\,s} = 1.78 + 0.471\ pK_a$.

Upon the whole, the energy of interaction of azoles with phenol ($-\Delta H$) changes in the same direction while the entropies ($-\Delta S$) remain almost constant. There is no strictly linear relationship between the $\Delta\nu$ and $-\Delta H$ values ($r = 0.91$), but there is only a general tendency for an increase in $-\Delta H$ as $\Delta\nu$ increases (Fig. 2b). This may be due to restriction of free orientation of the centers that participate in the hydrogen bond and the different electronic structures of the investigated azoles. In the case of the isostructural azoles the $\Delta\nu$ values for the 1-ethyl-substituted compounds are always higher than the values for 1-vinyl-substituted compounds.

Thus the set of pK_a, $K_{a\,ss}$, $-\Delta H$, and $\Delta\nu$ values makes it possible to compare the electron-donor capacities of the investigated compounds. The imidazoles have the highest basicities. The basicities of the triazoles and pyrazoles are reduced due to the mutual inductive effect of the nitrogen heteroatoms. The presence of methyl and ethyl groups in the heterorings of the corresponding azoles raises the electron density of the "pyridine" nitrogen atom. The $K_{a\,ss}$, $-\Delta H$, and $\Delta\nu$ values of 1-ethylazoles III, IV, VII, XII, XIII, and XVI are higher than the $K_{a\,ss}$ values of the corresponding 1-vinyl derivatives (II, VI, IX, XI, and XIV); this is in conformity with the electronic effects of the ethyl and vinyl groups.

1-Vinylpyrazole (VI) has the highest basicity of the investigated compounds. One's attention is directed to the change in the $K_{a\,ss}$ and $-\Delta H$ values on passing to 1-ethylpyrazole (VII). This is possibly due to the high sensitivity of the coordination center of the pyrazoles (the N_2 atom) to the inductive effect of the $CH_2=CH-$ and C_2H_5 groups and also to the superimposition of the effect of conjugation with the $CH_2=CH-$group.

The UV absorption spectra of solutions of the compounds in dioxane, alcohol, and aqueous alcoholic HCl (Table 3) were obtained to investigate the manifestation of acid–base interactions in the electronic absorption spectra of azoles. The universal intermolecular interactions in dioxane or alcohol media give rise to hypsochromic shifts of no more than 4 mm and a slight decrease in the absorption coefficient in the electronic absorption spectra of five-membered heterocycles (I-IX). Protonation of these compounds with 0.1 N HCl leads to a hypsochromic shift of the short-wave band to the region below 200 nm. The long-wave band is also shifted hypsochromically in the case of imidazoles I-IV and 1-vinyltriazole IX, and a greater shift is characteristic for 1-vinyl derivatives of imidazole (II, IV). The reverse effect is observed on protonation of the pyrazoles. The long-wave band has a red shift for pyrazole V and 1-ethylpyrazole VII and a blue shift for 1-vinyl derivatives VI and VIII. The absorption coefficient in the spectra of the protonated imidazoles, as a rule, remains almost unchanged or is only slightly reduced. The ε value increases when pyrazole V and 1-ethylpyrazole VII are protonated. In the case of 1-vinylpyrazoles VI and VIII the ε value increases for the short-wave band and decreases for the long-wave band. Thus both the magnitude of the shift of the bands and its direction are related to the electronic structure of the heterocycle, which determines the type of electron transitions and their energies. The 1-vinyl derivatives (II, IV, VI, and VIII), for which the shift in λ_{max} reaches 12 nm, are particularly sensitive to protonation.

Depending on the nature of the solvent (dioxane or alcohol), very slight changes are observed in the spectra of benzimidazoles and benzotriazoles X-XV. A hypsochromic shift of the bands of benzimidazole X and 1-ethyl- and 1-vinylbenzimidazoles XI and XII, which is greater in magnitude than the shift observed for I-X, occurs in the spectrum of a solution in HCl (this effect is maximal in the spectrum of vinyl derivative XI). Moreover, the vibrational structure of the bands becomes less distinct. The spectra of protonated benzotriazole and its substituted derivatives remain practically unchanged as compared with the spectra of their alcohol solutions.

Thus in the electronic absorption spectra of compounds with higher basicities (imidazoles and benzimidazoles) the magnitude of the hypsochromic shift of the band and the change in the extinction coefficient evidently are determined primarily by an increase in the conjugation system rather than by a change in the basicities. A large shift is observed for vinyl derivatives and benzazoles.

EXPERIMENTAL

The synthesis of the investigated compounds and their characteristics were described in [3].

The electronic absorption spectra of solutions of the azoles and their substituted derivatives in dioxane, alcohol, and 0.1 N HCl were obtained with a Pye Unicam Sp-8000 spectrophotometer.

The dissociation constants in acetone were determined by potentiometric titration with an LPM-60-M apparatus with glass and silver chloride electrodes. The apparatus was filled with a saturated acetone solution of lithium chloride and silver nitrate. The titrant was a solution of perchloric acid in acetone, the concentration of which exceeded the concentration of the titrated base by one order of magnitude. Measurements at two concentrations (0.01 and 0.005 M) gave the same dissociation constants. The dissociation constants of the cationic acids (the conjugate acids of the investigated bases) were calculated from the formula in [4]. Codeine (pK_a 9.62) [5] was used as the standard base.

The IR spectra of the 1-vinyl- and 1-ethylazoles and the $B-C_6H_5OH-CCl_4$ systems were obtained with a UR-20 spectrometer at 2500-3700 cm^{-1}. The measurements of the thermodynamic parameters were made at 15-40° at azole concentrations of $c^o_B=0.35-0.140$ mole/liter and phenol concentrations of $c^o_P=0.009-0.014$ mole/liter.

The K_{as} values were calculated from the formula

$$K_{as}=\frac{(c^{\circ}_{P}-c_{P})}{c_{P}(c^{\circ}_{B}-c^{\circ}_{P}-c_{P})}, \tag{1}$$

where c^{o}_{P} and c^{o}_{B} are the initial concentrations of phenol and the electron-donor compound (B), respectively, and c_P is the equilibrium phenol concentration determined from the change in the peak intensity of the band of the stretching vibrations of the monomeric OH groups of phenol at 3610 cm^{-1} [6,7]:

$$c_{P}=\frac{D}{\varepsilon d}, \quad D=\ln\frac{I_0}{I}; \quad I=I_0e^{-\varepsilon nd}, \tag{2}$$

where n is the true concentration of the free hydroxyl groups.

The degree of dissociation of the phenol molecules tied up in hydrogen bonds is $\alpha = n/c$, where c is the total phenol concentration. The following equation is obtained when the latter is substituted in Eq. (2):

$$D=\ln\frac{I_0}{I}=\varepsilon\alpha cd. \tag{3}$$

The dependence $\varepsilon\alpha = f(c)$ is linear for low concentrations of the CCl_4 solution of phenol from 0.1 to 0.01 mole/liter. When $c \rightarrow 0$, $\alpha \rightarrow 1$, and the segment cut out along the axis of ordinates gives the molar absorption coefficient of the free OH groups of phenol ($\varepsilon = 201$), which was used for the determination of c_P.

LITERATURE CITED

1. D. L. Powell and R. West, Spectr. Acta, 20, 983 (1964).
2. N. N. Chipanina, Yu. L. Frolov, N. A. Kazakova, E. S. Domnina, G. G. Skvortsova, and M. G. Voronkov, Dokl. Akad. Nauk SSSR, 216, 371 (1974).
3. M. F. Shostakovskii, G. G. Skvortsova, N. P. Glaskova, and E. S. Domnina, Khim. Geterotsikl. Soedin., No. 8, 1070 (1969).
4. A. M. Shkodin and L. M. Sadovnichaya, Izv. Vyssh. Uchebn. Zaved., Khim. Khim. Tekhnol., Ivanova, No. 7, 4 (1964).
5. N. A. Izmailov and T. V. Mozharova, Zh. Fiz. Khim., 34, 1543 (1969).
6. R. Lindemann and G. Zundel, J. Chem. Soc., Faraday Trans., 68, 979 (1972).
7. R. Mecke, Disc. Faraday Soc., 161 (1950).