in 4.6 M aqueous KCl and in 8.6 M KI (a precipitate formed immediately which slowly dissolved) and was soluble in 6 M HCl, but not in 6 M H_2SO_4, at room temperature. $(CF_3CFCF_3)HgCl$ had a characteristic but not unpleasant odor.

No reaction occurred when $(CF_3CFCF_3)HgCl$ was heated with an excess of $CF_3CF{=}CF_2$ either at 138 ± 2° for 24 hours in the absence of a solvent or in HF at 142 ± 2°. In the latter case very little, if any, reaction took place with the HF. After heating a mixture of 1.0 g. of $(CF_3CFCF_3)HgCl$, 12 g. of HF and 5 g. of $CF_3CF{=}CF_2$, 0.8 g. of $(CF_3CFCF_3)HgCl$, m.p. 77–78°, was recovered by sublimation.

Heptafluoroisopropylmercuric Hydroxide.—A glass ampule was charged under nitrogen with a slurry of 5.0 g. (0.012 mole) of $(CF_3CFCF_3)HgCl$ and 4.6 g. (0.020 mole) of Ag_2O in 30 ml. of a 1:1 mixture by volume of ethanol and deaerated water. After shaking for 5 hours at room temperature the ampule contents were filtered with a sintered glass filter and the residue washed four times with 20-ml. portions of 1:1 ethanol–water solution. Distillation of the filtrate under reduced pressure yielded 5.0 g. of gray solid residue. After treatment with 2 g. of activated charcoal in ether solution, 2.7 g. (0.007 mole 58%) of $(CF_3CFCF_3)HgOH$ was recovered which contained 52.5% Hg: calculated for C_3F_7HgOH, Hg 51.9%. This material formed a basic solution in water. It did not melt sharply. Noticeable decomposition began at about 254° with the formation of a pale yellow sublimate; at 265° almost complete melting had occurred.

An aqueous solution of 2.6 g. (0.0067 mole) of (CF_3CFCF_3)-HgOH was neutralized to litmus paper with 12 M HCl and 10 drops of excess acid added. Considerable heat was evolved. Extraction with CH_2Cl_2 gave a white crystalline solid which was sublimed to yield 2.4 g. (0.0059 mole) of $(CF_3CFCF_3)HgCl$, m.p. 77–78°, an 88% yield.

Efforts to prepare $(CF_3CFCF_3)HgF$ from $(CF_3CFCF_3)HgOH$ by treatment with 48% aqueous or anhydrous HF yielded a black tarry product from which no pure material could be isolated.

2-Iodoheptafluoropropane.—Reaction of both $(CF_3CFCF_3)_2Hg$ and $(CF_3)_2CFHgCl$ with iodine yielded CF_3CFICF_3. Its formation confirmed the structure of these compounds.

From 97.0 g. (0.18 mole) of $(CF_3CFCF_3)_2Hg$ and 124.5 g. (0.49 mole) of iodine heated in a glass ampule in a rocker shaker at 127 ± 2° for 24 hours was recovered by distillation 92.2 g. of crude product. Redistillation of this material after treatment with mercury to remove free iodine yielded 84.2 g. (0.284 mole, 79%) of CF_3CFICF_3, b.p. 40.2–40.8° (738 mm.).

Similarly, from 8.9 g. (0.022 mole) of $(CF_3CFCF_3)HgCl$ and 8.7 g. (0.034 mole) of iodine heated in a glass ampule for 10 hours at 132 ± 2° and 12 hours at 144 ± 2° was recovered 2.3 g. of easily volatile product. After washing with 5% aqueous sodium thiosulfate, water and drying over $MgSO_4$, 1.9 g. (0.0064 mole) of CF_3CFICF_3, b.p. 40.0–40.5° (743 mm.), was recovered by distillation.

The freshly distilled samples of CF_3CFICF_3, obtained as described above, were pink colored due to the presence of traces of free iodine. Treatment with mercury removed this color, but during distillation and on standing in diffuse light more iodine was formed. An almost completely colorless sample was obtained by treatment with mercury followed by careful redistillation in a dark room in the presence of a low intensity amber light. It had the properties: b.p. 40.6° (740 mm.), f.p. −60.5 to −61.1°, d^{20}_4 2.0990, n^{20}D 1.3283 (mol. wt. calcd. 296, found 302; I calcd. 42.9, found 43.3). Strong infrared absorption bands were observed at 7.81, 8.03, 8.46, 8.91, 10.45, 11.10, 13.31, 14.02 (and 14.10) μ. Since this work was carried out, the properties of CF_3CFICF_3 have been reported as b.p. 38°,[36] b.p. 40°,[37] n^{20}D 1.327[37] with infrared spectra consistent with the above-cited absorption bands.[36,37]

The infrared spectra, freezing points and densities clearly differentiate CF_3CFICF_3 from $CF_3CF_2CF_2I$; f.p. −95.3; d^{20}_4 2.0566,[38] 2.0626.[39]

(36) R. D. Chambers, W. K. R. Musgrave and J. Savory, *Proc. Chem. Soc.*, 113 (1961).

(37) M. Hauptschein and M. Braid, *J. Am. Chem. Soc.*, **83**, 2383 (1961).

(38) W. T. Miller, Jr., E. Bergman and A. H. Fainberg, *ibid.*, **79**, 4159 (1957).

(39) M. Hauptschein and A. V. Grosse, *ibid.*, **73**, 2461 (1951).

Pyridoxine and Pyridoxal Analogs. VI. Electronic Absorption Spectra of Schiff Bases[1]

BY DIETRICH HEINERT[2] AND ARTHUR E. MARTELL[2]

The electronic absorption spectra of the amino acid Schiff bases derived from 3-hydroxypyridine-4-aldehyde, 3-hydroxypyridine-2-aldehyde, salicylaldehyde and from the O-methyl derivatives of these aldehydes were obtained from solid state preparations and from their non-aqueous solutions. Analysis of the spectra confirms the presence of two tautomeric forms in the o-hydroxyaldehyde Schiff bases under these conditions. The equilibrium constants, K_x, between the "enol-imine" and the "keto-enamine" species of the two pyridinoid and the benzenoid series of compounds are determined.

In the preceding paper[3] an investigation of the infrared spectra of the amino acid Schiff bases of 3-hydroxypyridine-4-aldehyde (A, R = OH), 3-hydroxypyridine-2-aldehyde (B, R = OH), salicylaldehyde (C, R = OH) and their O-methyl derivatives (A, B, C, R = OCH_3) led to the assignment of the "keto-enamine" structure VIa–VIb to the o-hydroxyaldehyde Schiff bases. Presence of smaller amounts of the tautomeric "hydroxy-imine" species Va–Vb could not be excluded on the basis of the solid state infrared spectra.

The present work deals with an analysis of the electronic absorption spectra of the o-hydroxyaldehyde Schiff bases listed above, with the purpose of obtaining information on the structure of these compounds, and of the analogous pyridoxal derivatives, in solution.

Experimental

Materials.—The amino acid Schiff bases of o-hydroxy- and o-methoxypyridinealdehydes and of salicylaldehyde and o-methoxybenzaldehyde were synthesized as described earlier.[3] The o-hydroxy- and o-methoxypyridinealdehydes were synthesized according to procedures described previously,[4] and were purified by the method described in a subsequent paper.[5] The

spectro grade solvents employed usually required further purification before use. Dioxane and chloroform were purified successfully by a method described by Wohlleben.[6] All measurements in chloroform were carried out immediately after purification of the solvent. Spectro grade methanol was used directly and gave reproducible results.

Absorption Spectra.—The electronic absorption spectra in the visible and ultraviolet regions were recorded with a Cary model 14 spectrophotometer at 20°. For solution measurements a pair of 10-mm. quartz cells were used. Concentration of all compounds was 10^{-4} mole/liter. The solid state spectra were obtained from potassium bromide pellets of 1 mm. thickness, prepared from a mixture obtained by grinding 400 mg. of oven-dried spectro grade KBr with the weighed compound. Concentration of the compounds was adjusted to a level corresponding to 2 × 10^{-3} mole/liter assuming complete dispersion. The dispersion achieved by repeated regrinding and reprocessing of the pellets resulted in completely transparent and uniform pellets in all cases. All measurements were carried out with a 1-mm. blank potassium bromide pellet in the reference beam and in an atmosphere of dry nitrogen gas. The background absorption due to adsorption of water was almost completely eliminated with these precautions.

Results

Previous work in these laboratories has shown[7] that electronic absorption spectra of pyridine compounds of

(1) This investigation was supported by research grants A-1307 and A-5217 from the National Institute of Arthritis and Metabolic Diseases, U. S. Public Health Service.

(2) Department of Chemistry, Illinois Institute of Technology, Chicago 16, Ill.
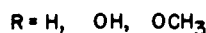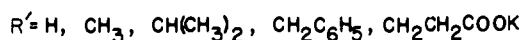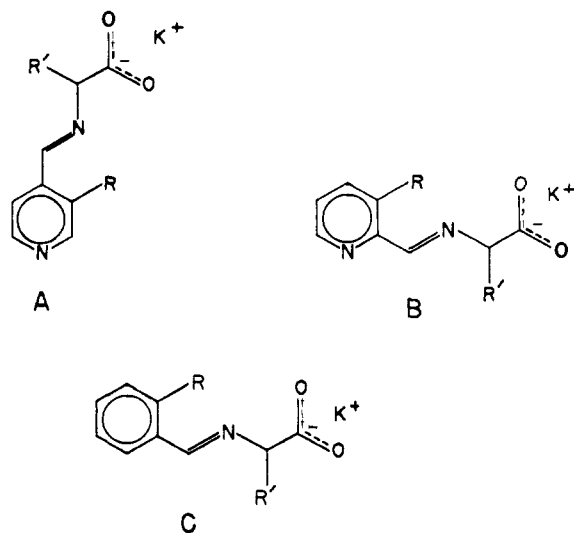
(3) D. Heinert and A. E. Martell, *J. Am. Chem. Soc.*, **84**, 3257 (1962).

(4) D. Heinert and A. E. Martell, *Tetrahedron*, **3**, 49 (1958).

(5) D. Heinert and A. E. Martell, *J. Am. Chem. Soc.*, **81**, 3933 (1959).

(6) G. Wohlleben, *Angew. Chem.*, **67**, 741 (1955); **68**, 752 (1956).

(7) K. Nakamoto and A. E. Martell, *J. Am. Chem. Soc.*, **81**, 5857, 5863 (1959).

R' = H, CH₃, CH(CH₃)₂, CH₂C₆H₅, CH₂CH₂COOK

R = H, OH, OCH₃

the type under investigation are characterized by two absorption bands, ascribed to the $\pi-\pi_1{}^*$- and the $\pi-\pi_2{}^*$-transitions (hereafter abbreviated as π_1- and π_2-bands, respectively).[8] The forbidden $n-\pi$ transitions due to carbonyl or imine groups result in absorbancy values of under 0.01 in the 10^{-4} molar solutions studied and therefore may be disregarded for the present discussion.

Difficulties in the interpretation of the absorption spectra of 3-hydroxypyridine derivatives, and in particular of the 3-hydroxypyridine-2- and -4-aldehydes, arise from the fact that even in neutral solutions a number of species is present, each of which produces $\pi-\pi_1{}^*$ and $\pi-\pi_2{}^*$ absorption bands.
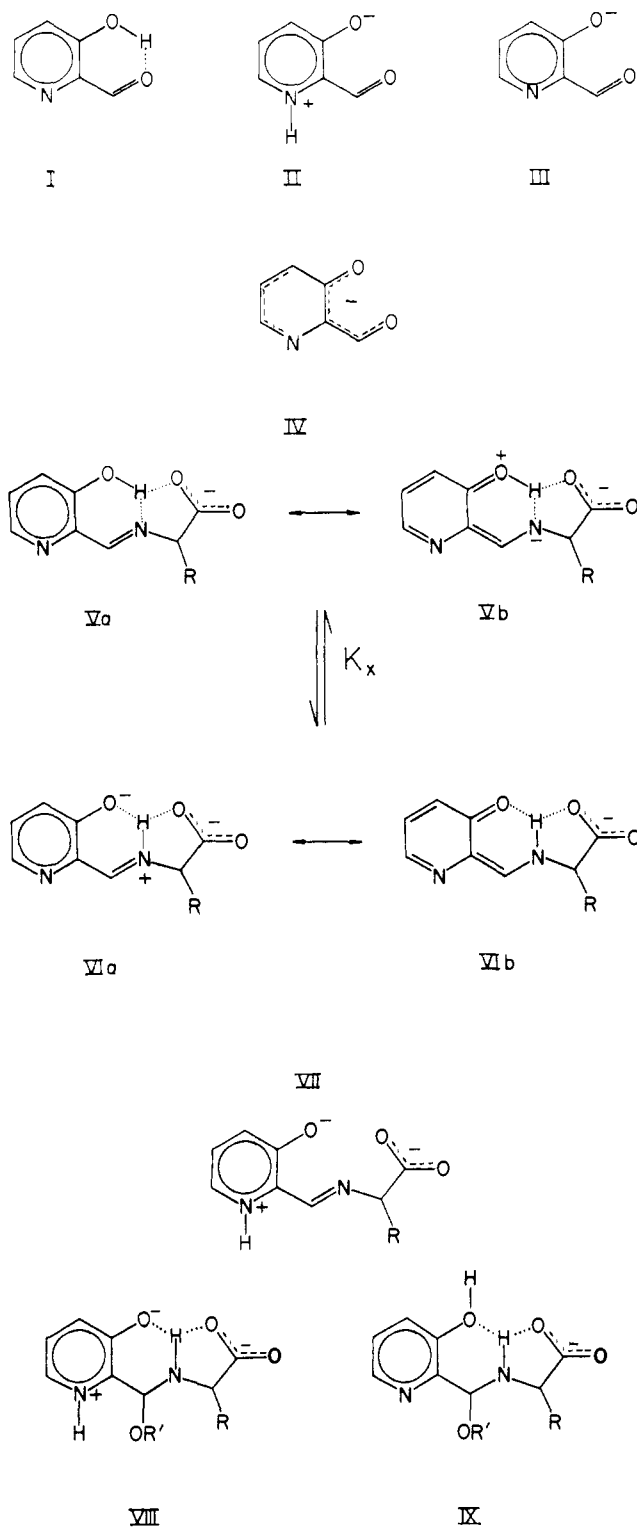
In the case of the imines, the possible formation of no less than three different tautomeric species (V, VI and VII) and of two hemiacetals (VIII and IX, R' = H) has to be considered for a neutral aqueous solution. An added complication is total hydrolysis of the Schiff base leading to formation of the free hydroxyaldehyde species and amino acid. Hydrolysis was found to be complete and rapid if the pure Schiff base compounds were dissolved in water. Similarly, an aqueous solution of the components in 1:1 molar ratio shows no trace of Schiff base formation, and even in solutions containing large excesses of amino acid over the aldehyde (e.g., 10⁴:1 molar ratios) formation of the Schiff base may not be complete.

Elucidation of the Schiff base structure was attempted by two independent methods which eliminate the complications resulting from aqueous solution equilibria and hydrolysis: study of non-aqueous solutions and of solid state spectra.

Electronic Absorption Spectra in Non-aqueous Solution.—It has been shown in previous investigations[7,9] that 3-pyridol and other 3-hydroxypyridine derivatives in dioxane solution exist entirely in the form of the neutral, non-polar species. Therefore solvents such as dioxane and chloroform should be suitable for a

study of solution equilibria of Schiff bases. Unfortunately, of the sixteen compounds prepared by the authors[3] most are entirely insoluble in these solvents. A notable exception was found in the Schiff bases derived from valine, and to some extent from phenylalanine. Greater solubility of the valine derivatives (formula A, B, C; R' = CH(CH₃)₂) and of the phenylalanine derivatives (A, B, C; R' = CH₂C₆H₅) is probably due to the large hydrophobic groups R' that are present. The solubilities of the O-methyl Schiff bases (A, B, C; R = OCH₃) were greater than those of the hydroxy compounds (A, B, C; R = OH). The solutions in dioxane were more stable than the chloroform solutions. A series of measurements of dioxane solu-

---

(8) The $\pi-\pi_1{}^*$-transitions in pyridine and the pyridine derivatives under discussion are considered analogous to the charge transfer transition in benzene, also referred to as a K-Band or E-Band (Burawoy and Braude) or as a B-Band (Moser and Kohlenberg). The $\pi-\pi_2{}^*$-transitions in pyridine and in the compounds measured in this investigation are considered analogous to the $A_{1g} \rightarrow B_{2u}$ (or $O \rightarrow 1$) transition in benzene, also referred to as B-Bands (Burawoy and Braude) or C-Bands (Moser and Kohlenberg). $n-\pi$ transitions are also designated as R-Bands (Burawoy and Braude) or D-bands (Moser and Kohlenberg).

(9) D. E. Metzler and E. E. Snell, *J. Am. Chem. Soc.*, **77**, 2431 (1955).

TABLE I

ELECTRONIC ABSORPTION SPECTRA IN DIOXANE SOLUTION[a]

Compound	Transition[c]				Enamine, %	K_x
	$\pi-\pi_1^*$	$\pi-\pi_1^*$	$\pi-\pi_1^*$	$\pi-\pi_1^*$		
3-Methoxy-2-pyridinecarboxaldehyde	234(0.51)	......	307(0.50)	......	..	..
3-Hydroxy-2-pyridinecarboxaldehyde	240(.51)	......	316(.61)	......	..	..
N-(3-Methoxy-2-pyridylmethylene)-valine	233(.80)	......	312(.83)	......	..	..
N-(3-Hydroxy-2-pyridylmethylene)valine	253(.71)	265(0.62)[b]	319(.28)	404(0.94)	73.3	2.74
3-Methoxy-4-pyridinecarboxaldehyde	238(.60)	......	324(.42)	......	..	..
3-Hydroxy-4-pyridinecarboxaldehyde	238(.56)	......	330(.36)	......	..	..
N-(3-Methoxy-4-pyridylmethylene)-valine	255(.69)	......	310(.62)	......	..	..
N-(3-Hydroxy-4-pyridylmethylene)-valine	252(.70)[b]	270(0.62)[b]	323(.25)	425(0.39)	53.3	1.14
2-Methoxybenzaldehyde	251(1.07)	......	315(.48)	......	..	..
Salicylaldehyde	256(1.15)	......	326(.36)	......	..	..
N-(2-Methoxybenzylidene)-valine	256(1.17)	......	306(.67)	......	..	..
N-Salicylidenevaline	257(0.95)	278(0.81)	318(.25)	411(0.46)	50.6	1.02

[a] Wave lengths are given in mμ; numbers in parentheses give the absorbancy for a 1-cm. light path and 10^{-4} mole/l. The absorbancy times 10^4 gives the molecular extinction coefficient αM. [b] Shoulder. [c] For species assignment of the π_1 and π_2 absorption bands, cf. Results; also see footnote 8.

TABLE II

ELECTRONIC ABSORPTION SPECTRA IN SOLID STATE AND IN METHANOL SOLUTION[a]

Compound, N-(3-	Solvent	Absorption maxima			
Methoxy-2-pyridylmethylene)-valine	MeOH[b]	237(0.42)[c]		312(0.35)	
Methoxy-2-pyridylmethylene)-valine	KBr[d]	236(1.55)		314(1.33)	
Hydroxy-2-pyridylmethylene)-glycine	MeOH	242(0.66)	263(0.35)[c]	318(0.54)	391(0.45)
Hydroxy-2-pyridylmethylene)-glycine	KBr	247(.96)	......[c]	323(.34)	394(.77)
Hydroxy-2-pyridylmethylene)-alanine	MeOH	244(.65)	264(0.34)[c]	316(.58)	396(.49)
Hydroxy-2-pyridylmethylene)-alanine	KBr	251(1.32)	274(.87)[c]	323(.48)	400(1.32)
Hydroxy-2-pyridylmethylene)-valine	MeOH	245(0.65)	264(.37)[c]	318(.55)	395(0.52)
Hydroxy-2-pyridylmethylene)-valine	KBr	250(1.61)	......[c]	316(.65)	399(1.25)
Hydroxy-2-pyridylmethylene)-phenylalanine	MeOH	245(0.61)	265(0.33)[c]	318(.63)	398(0.41)
Hydroxy-2-pyridylmethylene)-glutamic acid	MeOH	245(.63)	268(0.30)[c]	317(.63)	398(0.43)
Methoxy-4-pyridylmethylene)-valine	MeOH	250(.97)		310(.63)	
Methoxy-4-pyridylmethylene)-valine	KBr	252(2.15)		313(1.38)	
Hydroxy-4-pyridylmethylene)-glycine	MeOH	244(0.82)	......[c]	322(0.30)	405(0.17)
Hydroxy-4-pyridylmethylene)-alanine	MeOH	246(.70)	......[c]	322(.27)	405(.14)
Hydroxy-4-pyridylmethylene)-valine	MeOH	250(.86)	......[c]	323(.34)	414(.20)
Hydroxy-4-pyridylmethylene)-valine	KBr	......[c]	......[c]	322(.86)	422(1.06)
Hydroxy-4-pyridylmethylene)-phenylalanine	MeOH	245(0.68)[c]	286(0.35)[c]	321(.34)	412(0.10)
Hydroxy-4-pyridylmethylene)-glutamic acid	MeOH	249(0.79)	......[c]	323(.32)	407(0.17)

[a] Wave lengths are given in mμ; numbers in parentheses give the absorbancy for a 1-cm. light path and 10^{-4} mole/l. The absorbancy times 10^4 gives the molecular extinction coefficient αM. [b] Considerable hemiacetal formation of this compound is indicated by the appearance of an additional band at 281 mμ (0.38), which is absent in $CHCl_3$ solution and in solid state. [c] Shoulder. [d] Due to variations in dispersion and background absorption as well as surface scattering, the absorbancy values for the solid state spectra have only relative significance. [e] Band invisible due to overlap.

tions of valine Schiff bases derived from a variety of aldehydes was therefore carried out. The results are compiled in Table I.

Assignments of Electronic Transitions of the Schiff Bases.—As is seen from the data in Table I, all Schiff bases derived from o-hydroxyaldehydes exhibit four absorption bands in the ultraviolet and visible regions of the spectra, indicating of two species. By contrast, all the remaining compounds—hydroxyaldehydes, methoxyaldehydes and O-methyl Schiff bases—reveal only two absorption maxima, or one species, in dioxane solution. One pair of bands found between 305 and 330 mμ and between 230 and 255 mμ, respectively, is common to all compounds listed. In the hydroxypyridinealdehydes, these absorption bands have been assigned to the π_1- and π_2-transitions of the uncharged species I. For the various methoxyaldehydes and O-methyl Schiff bases only one assignment is available: the π_1- and π_2-transitions of the uncharged[10] and unhydrated species indicated by structures I and V when –CH₃ replaces –H.

From this it is seen that aza replacement in the parent aldehydes does not cause any marked changes in the absorption spectrum. For instance, the average

(10) Throughout this paper the ionization state of each species is discussed without regard to the charge of the amino acid carboxylate group.
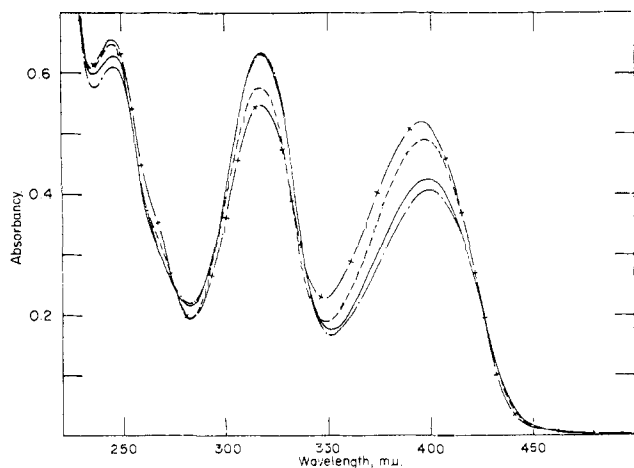
shift of the π_1-absorption band of the three o-methoxyaldehydes listed in Table I upon conversion to the imines is only −6 mμ. Consequently, transformation of the hydroxyaldehyde species I into the neutral "enol-imine" species V is expected to result in similar small shifts of the absorption bands. Indeed, the average shift observed between the π_1-absorptions of the hydroxyaldehydes and the band found in this region in their respective valine Schiff bases is only 6 mμ, while the π_2-transitions shift by approximately 9 mμ.

The effect of hydrogen bonding on electronic absorption spectra is known to result in a pronounced but small shift toward longer wave lengths. The π_1-absorption bands of the methoxyaldehydes under investigation, for example, experience an average red shift of only 9 mμ upon conversion to the intramolecularly hydrogen bonded hydroxyaldehyde structure I. Similarly, if the π_1- and π_2-absorptions of the methylated Schiff bases are compared with the absorptions found in these regions in the corresponding o-hydroxy Schiff bases, average shifts of +11 mμ and +6 mμ of the π_1- and π_2-bands are observed.

These results are the basis for the assignment of the 316–330 mμ absorptions to the π_1-transition, and of the 238–256 mμ absorptions to the π_2-transition of the Schiff base species V.

Fig. 1.—Electronic absorption spectra of $10^{-4} M$ N-(3-hydroxy-2-pyridylmethylene)-amino acid monopotassium salts in methanol solution: ———— + ————, -valine; — — — —, -alanine; ————, -glutamic acid (dipotassium salt); ———— · ————, -phenylalanine Schiff base.

The remaining pair of absorption bands found between 404 and 425 mμ, and between 265 and 280 mμ in the spectra of the hydroxyaldehyde Schiff bases are assigned to the π_1- and π_2-transitions of the tautomeric "keto-enamine" form, VI, of the Schiff base. The large red shift, especially of the π_1-bands, which shift an average of 93 mμ from their positions in the species V, becomes understandable in view of the description of species VI by the resonance forms VIa and VIb. Charge migration in the sense VIa → VIb is expected to be energetically favored over charge separation in the sense Va → Vb. This establishes the nature of species VI as that of an amide vinylog, and relates it to the merocyanine dyes[11a,b] and to the o-hydroxyazo-aromatic compounds,[12,13] which are known to have intense π_1-absorption bands in the visible region.

Tautomeric Equilibrium Constant, K_x.—In analogy to the equilibrium constant K_t used to describe keto-enol type equilibria, the enamine–enol equilibrium constant K_x may be defined as:

$$K_x = [\text{enamine}]/[\text{enol}] = [VI]/[V]$$

Since there are only two substances in the solutions studied, information on the concentration of one species at equilibrium is sufficient to determine K_x. Although the molar extinction coefficients of the species V and VI are not known, the absorbancy of the hydroxyaldehyde Schiff base V may be estimated from the absorbancy of the corresponding methoxyaldehyde Schiff base if the following assumption is made

$$\frac{\epsilon(o\text{-hydroxyaldehyde Schiff base})}{\epsilon(o\text{-methoxyaldehyde Schiff base})} = \frac{\epsilon(o\text{-hydroxyaldehyde})}{\epsilon(o\text{-methoxyaldehyde})}$$

Because they involve less overlap, the π_1-absorption bands rather than the π_2-absorptions were used for the calculations. The measurements were made for dioxane solutions at 20°. From the shape of the unsymmetrical π_1-absorption band of the Schiff base species VI, as well as that of most other species, exact wing corrections were computed by the method of Shimura and Tsuchida[14] for almost all absorption bands. The calculated percentages of enamine species and the equilibrium constants K_x determined in this manner for the three series of compounds are shown in Table I.

(11) (a) S. Hünig and H. Herrmann, *Liebigs Ann. Chem.*, **636**, 32 (1960); (b) H. A. Staab, "Einführung in die theoretische organische Chemie," Verlag Chemie, Weinheim, 1959.
(12) D. Hadzi, *J. Chem. Soc.*, 2143 (1956).
(13) A. Burawoy, A. G. Salem and A. R. Thompson, *ibid.*, 4793 (1952).
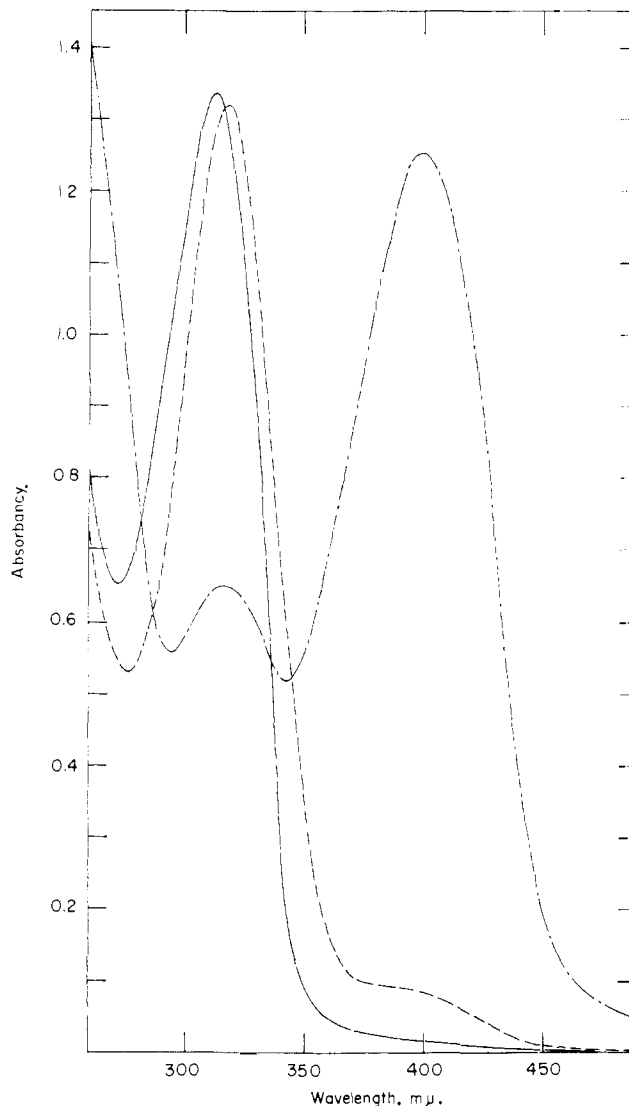(14) Y. Shimura and R. Tsuchida, *Bull. Chem. Soc. Japan*, **28**, 572 (1955).

Fig. 2.—Electronic absorption spectra in solid state (KBr pellets) of: N-(3-methoxy-2-pyridylmethylene)-valine, ————; N-(3-hydroxy-2-pyridylmethylene)-valine, ———— · ————; and 3-hydroxypyridine-2-aldehyde, — — — —.

It is seen that in the 3-hydroxypyridine-2-aldehyde Schiff bases the enamine species predominated (73%), while in the benzenoid Schiff bases and in those derived from 3-hydroxypyridine-4-aldehyde about equal proportions of the species V and VI are present.

Measurements in Other Solvents.—The absorption spectra of the Schiff bases were also investigated in a variety of other solvents and solvent mixtures. However, dioxane and chloroform were the only solvents found suitable for unequivocal assignments and determination of K_x. In dioxane–water mixtures, even at water concentrations as low as 10%, hydrolysis and hemiacetal formation of the Schiff bases was too rapid to allow evaluation of the spectra.

In methanol and ethanol solution, hydrolysis is excluded, but measurements of the hydroxypyridine-aldehydes and the O-methyl Schiff bases indicate that hemiacetal formation and conversion to dipolar species take place to an appreciable extent. The absorption characteristics in methanol for a number of Schiff bases are listed in Table II. Generally, the absorption spectra of the o-hydroxyaldehyde Schiff bases in methanol are similar to those in dioxane solution described above. However, as the spectra of four such Schiff bases shown in Fig. 1 indicate, the extinction of the 320 mμ bands increases, and that of the 400 mμ absorptions
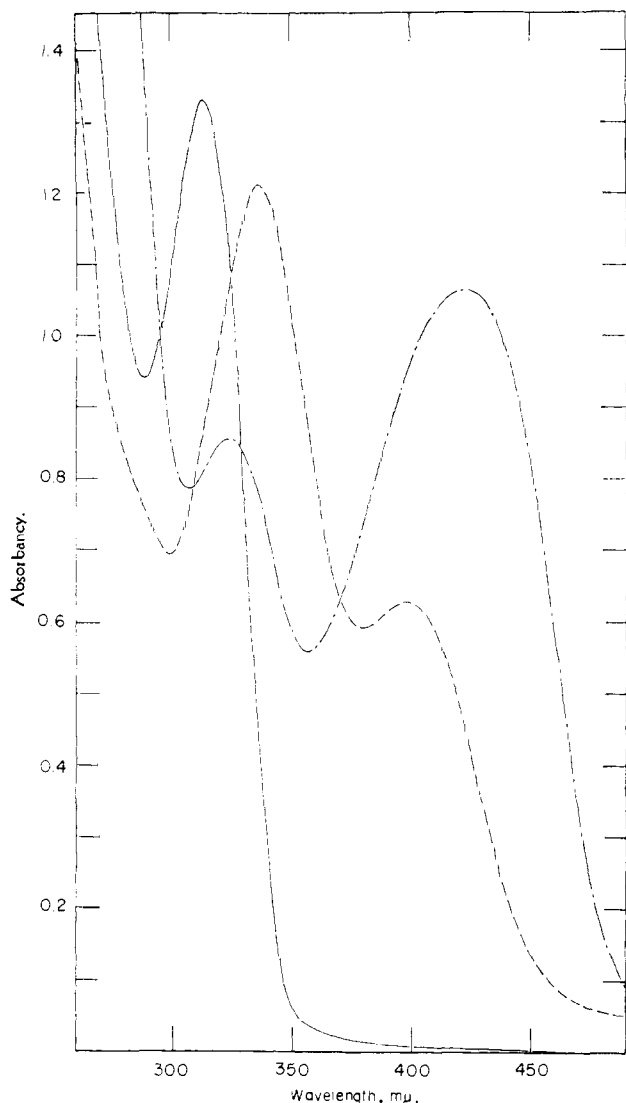
Fig. 3.—Electronic absorption spectra in solid state (KBr pellets) of: N-(3-methoxy-4-pyridylmethylen)-valine, ————: N-(3-hydroxy-4-pyridylmethylene)-valine, ———— · ————: and 3-hydroxypyridine-4-aldehyde, – – – –.

Fig. 4.—Electronic absorption spectra of 3-hydroxypyridine: ———— · ————, solid state, KBr pellet; ————, dioxane solution, 2×10^{-4} mole/l., – – – –, aqueous solution, pH 7, 2×10^{-4} mole/l.

decreases considerably. This is interpreted as caused by partial conversion of the imine species V and VI into the dipolar species VII and into the dipolar hemiacetal VIII (R' = CH₃). Thus the 400 mμ absorption band is assigned to the π_1-absorption of the remainder of species VI, overlapped by the π_1-absorptions of species VII. Similarly, the 320 mμ maximum consists of the overlapping π_1-absorptions of the remaining portion of species V and the dipolar hemiacetal species VIII. (Assignment of the hemiacetal species follows from comparison with the spectra of 3-pyridol and the hydroxypyridinealdehydes in aqueous solution.)[7] The π_1-transition of the neutral hemiacetal species IX, R' = CH₃, is expected to appear near 250–260 mμ.

Electronic Absorption Spectra of Solid Compounds.— In order to determine the structure of the o-hydroxy-aldehyde Schiff bases in crystalline state, and to establish a link to the results of the infrared measurements described earlier,[3] the absorption spectra of a number of Schiff bases and 3-hydroxypyridine derivatives in the solid state were measured, and the results are compiled in Table II.

The absorption spectra of crystalline N-(3-methoxy-2-pyridylmethylene)-valine and of N-(3-methoxy-4-pyridylmethylene)-valine are shown in Figs. 2 and 3
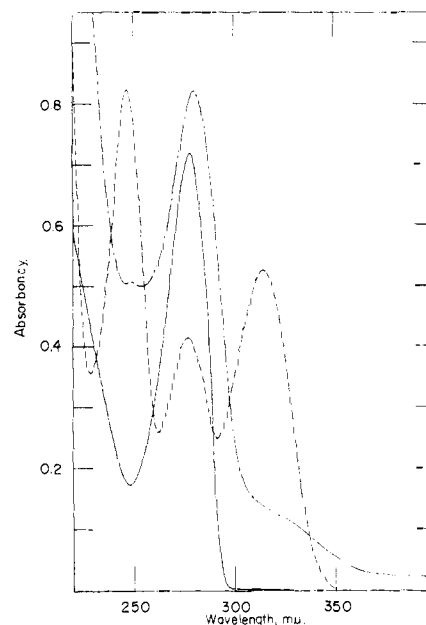
(solid lines). The positions of the single π_1-absorption bands are virtually identical with their respective locations in dioxane solution. Similarly, the shape of the solid state absorption curves of N-(3-hydroxy-2-pyridylmethylene)-valine and of N-(3-hydroxy-4-pyridylmethylene)-valine (dash-dotted traces in Figs. 2 and 3) resemble very closely the ones obtained in dioxane solution. The two major π_1-absorption bands in the vicinity of 400 mμ and 320 mμ, previously assigned to the tautomeric species VI and V of the Schiff base, are readily discernible and their relative extinction values reflect no large change with respect to dioxane solution. Thus, it may be concluded that in the solid hydroxy-pyridinealdehyde Schiff bases both tautomeric forms are indeed present, with the "keto-enamine" species VI in predominance. This confirms the infrared results obtained earlier.[3]

It is interesting to note that the o-hydroxypyridine-aldehydes in the solid state apparently contain a small amount of dipolar species II, as indicated by the broken lines in Figs. 2 and 3. This is indicated by the appearance of the characteristic absorption band near 380 mμ, along with the π_1-absorption of the neutral species I at 320–335 mμ.

A study of 3-hydroxypyridine further demonstrates the general validity of this result. In Fig. 4 are shown the absorption spectra of this compound in dioxane solution, aqueous solution and in the solid state. It is readily apparent that the crystalline preparation consists mainly of the neutral, nonpolar species, which is the only structure present in dioxane solution. The π_1-absorption band of this species appears near 275 mμ. On the other hand, the presence of a small fraction of the dipolar 3-pyridol species in the solid state is indicated by the weak absorptions near 313 and 246 mμ, which are characteristic of the π_1- and π_2-transitions of the dipolar species in aqueous solution[9] (Fig. 4). This information on the structure of 3-pyridol in KBr medium should end some of the uncertainties involved in the interpretation of the infrared spectra of this compound.[5]

In conclusion, the results of the solid state measurements seem to indicate the presence of two tautomeric species V and VI in the o-hydroxyaldehyde Schiff bases,

but the presence of smaller amounts of the dipolar species VII cannot be excluded.

Discussion

Ultraviolet Spectra.—An analogy to the large bathochromic shift from V to VI is found in the case of the parent hydroxypyridinealdehydes. Conversion of the neutral species I into any form incorporating the mesomeric structure IV causes a red shift of the π_1-absorption bands of over 50 mμ. Differences between individual species of this type, such as the dipolar form II and the anion III, are negligible. In similar fashion, the conversion of the hydroxyaldehydes into the dipolar imine species VII, or into the imine anion, might be expected to result in a red shift of the π_1-transitions to approximately 365–385 mμ. The Schiff base species VI shows a remarkable additional shift of about 30 mμ over this value because of intramolecular hydrogen bonding and its unique electron delocalization.

While the above arguments support the assignment of the 404–425 mμ band of the hydroxy Schiff bases to the "keto-enamine" species VI and not to the dipolar species VII, the correctness of this assignment is further supported by the nature of the spectra in more polar solvents. Thus, dioxane or chloroform solutions of the o-hydroxypyridinealdehydes show only two absorption bands corresponding to the π_1- and π_2-transitions of the neutral, non-polar species I, which appear near 320 and 240 mμ, respectively (Table I). The characteristic π_1- and π_2-absorption bands associated with the neutral, dipolar species II, found near 380 and 270 mμ in aqueous solutions and in dioxane–water mixtures, are completely absent under these conditions. From this, the absence of the dipolar species of the Schiff bases (as, for example, VII in the case of the 3-hydroxypyridine-2-aldimines) from dioxane or chloroform solutions of the Schiff base may be inferred with reasonable certainty. Since hydration (hemiacetal formation) as well as hydrolytic cleavage are also excluded, the species VIII and IX as well as free hydroxyaldehyde are also absent and the Schiff base may be fully described by V and VI. Confirming evidence for

this conclusion may be found in the spectrum of N-salicylidenevaline which is incapable of forming a dipolar species but exhibits four absorption bands, corresponding to two species, at wave lengths similar to the pyridine compounds.

Implications for the Chemistry of Pyridoxal.—The electronic absorption spectra of pyridoxal amino acid Schiff bases in aqueous solution have been studied by several investigators.[15,16] The possibility for the formation of tautomeric species has been recognized,[15] but no experimental evidence has thus far been obtained. The degree of validity of the results of this investigation for pyridoxal, and in particular for aqueous solutions, remains open. However, assignment of the 330 mμ absorptions to the dipolar species VII[16] appears inconsistent with the available information. Assignment to unreacted pyridoxal[15] or to the dipolar hemiacetal of the Schiff base[15] are definite possibilities, since the occurrence of the neutral, nonpolar species V in aqueous solution is unlikely. The presence of appreciable quantities of the pyridoxylideneimines in the "keto-enamine" tautomeric species VI, perhaps along with some proportion of the dipolar from VII, must be considered. If this should prove to be the case, a partial positive charge would be located at the imine nitrogen atom, which is in close proximity to the two carbon atoms involved in proton exchange during transamination and racemization reactions. If the positive nitrogen atom stabilizes the transition state in these reactions, their mechanism would not require the electron shift toward a positive charge at the pyridinium nitrogen formulated by Snell and co-workers.[17] Indeed, the occurrence of both transamination and racemization reactions at pH values up to 10 suggests such a possibility. Finally, the ease of transamination reactions in ethanol solution described by Matsuo[18] is readily understandable on the basis that the keto-enamine structure should be the predominant species in this solution.

(15) D. E. Metzler, *J. Am. Chem. Soc.*, **79**, 485 (1957).
(16) H. N. Christensen. *ibid.*, **80**, 99 (1958).
(17) D. E. Metzler, M. Ikawa and E. E. Snell. *ibid.*, **76**, 648 (1954).
(18) Y. Matsuo. *ibid.*, **79**, 2016 (1957).

Pyridoxine and Pyridoxal Analogs. VII. Acid–Base Equilibria of Schiff Bases[1]

BY DIETRICH HEINERT[2] AND ARTHUR E. MARTELL[2]

The electronic absorption spectra of N-salicylidenevaline and N-(3-hydroxy-4-pyridylmethylene)-valine have been studied in dioxane and methanol solutions in the presence of varying amounts of acid or base. Analysis of the spectra resulted in species and band assignments which allow the formulation of the complete solution equilibria of these compounds, and equilibrium constants are reported where possible.

Introduction

In the preceding paper[3] it was shown through an analysis of the electronic absorption spectra that the amino acid Schiff bases of o-hydroxypyridinealdehydes and of o-hydroxybenzaldehydes in neutral, non-aqueous solution constitute tautomeric equilibrium mixtures. This investigation has now been extended to a study of the absorption spectra of these compounds in non-aqueous solution under conditions of varying pH.

The objective of this work was to establish the nature of the reactions which take place, to measure these reactions quantitatively, and to provide evidence for the origin of certain band groups in the π_1- and π_2-transitions of specific species. The elucidation of these objectives is desirable because the various forms in which these Schiff bases exist, depending on hydrogen ion concentration and the solvent medium, would be expected to vary considerably in their involvement in the transamination and similar reactions. It was also hoped to gain at least qualitative information on the relative proton affinities of the various species of these compounds, even though the exact determination of acid dissociation constants would not be feasible because