2. From the intense band near 1100 cm^{-1} observed in all the $d\alpha$ crystals, it is concluded that Td symmetry of sulfate anion still holds in the $d\alpha$ form. The different magnitude in splitting of the sulfate band among the $h\gamma$ crystals is interpreted in terms of the removal of vibrational degeneracy of υ_3, as a result of interaction of a sulfate anion with a complexing agent.

3. The spectral differences arising from polymorphism are shown in the cases between the $d\alpha$ and $d\beta$ forms and between the $h\gamma$ and $h\delta$ forms.

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171. Kozo Nagano, Hisashi Kinoshita, and Zenzo Tamura : Metal Complexes of Isonicotinoylhydrazine and Related Compounds. III.*1 Consecutive Formation Constants for Various Metal Ions by the pH Titration Method.

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In order to determine formation constants of metal complexes, pH measurements have been frequently used as the most accurate and reliable method. Bjerrum devised a comparatively simple method of determining consecutive formation constants for metal amine complexes.[1] Schwarzenbach provided the more general method of analysis considering the existence of "Hydrogenkomplexe" and "Mehrkernige Komplexe" and using some approximations.[2] But his method was not so useful in analysing such equilibria concerning various species of complexes in ligand excess solutions as in the case of isonicotinoylhydrazine (INH). The authors improved the method more complete in order to determine consecutive formation constants of metal complexes of

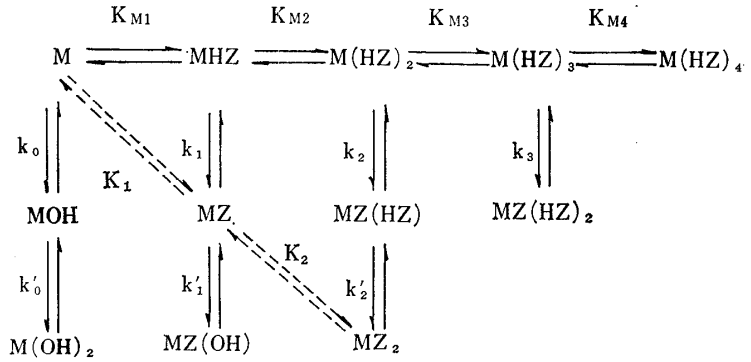

Chart 1.

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*1 A part of this work was lectured by M. Ishidate in Feigl Anniversary Symposium, Birmingham, England, 1962. Part II : This Bulletin, **11**, 797 (1963).

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1) J. Bjerrum : "Metal Ammine Formation in Aqueous Solution," 24 (1957), Haase & Son, Copenhagen.

2) G. Schwarzenbach : Helv. Chim. Acta, **33**, 947 (1950).

INH and related compounds. This method consisted of iterative approximation by the use of rapidly converging equations without omission. An electronic computer was used for this purpose.

Since INH and related compounds were capable to form complicated metal complexes, the authors assumed the reaction routes shown in Chart 1. Here M denotes a hydrated metal ion, and HZ an electrically neutral molecule of each compound.*1 HZ changes according to the following reaction pathway :

$$H_3Z \underset{Ka_1}{\rightleftharpoons} H_2Z \underset{Ka_2}{\rightleftharpoons} HZ \underset{Ka_3}{\rightleftharpoons} Z$$

MHZ, $M(HZ)_2$, $M(HZ)_3$, and $M(HZ)_4$ are consecutively formed complexes, which, in this case, do not have any chelate ring in their structures, while MZ is a 1:1 chelate. In Chart 1, complexes with coordination numbers larger than 4, polynuclear complexes and complexes with ligand having more than one proton were omitted; and this omission was verified by the preliminary calculations.

Equilibrium constants, K_{M_i}, k_j, and Ka_n are defined as follows.

$$\left.\begin{aligned} K_{M_1}&=\frac{[MHZ]}{[M][HZ]}, \quad K_{M_2}=\frac{[M(HZ)_2]}{[MHZ][HZ]}, \\ K_{M_3}&=\frac{[M(HZ)_3]}{[M(HZ)_2][HZ]}, \quad K_{M_4}=\frac{[M(HZ)_4]}{[M(HZ)_3][HZ]} \end{aligned}\right\} \quad (1)$$

$$k_0=\frac{a_H[MOH]}{[M]}, \quad k_0'=\frac{a_H[M(OH)_2]}{[MOH]} \quad (2)$$

$$\left.\begin{aligned} k_1&=\frac{a_H[MZ]}{[MHZ]}, \quad k_1'=\frac{a_H[MZ(OH)]}{[MZ]}, \quad k_2=\frac{a_H[MZ(HZ)]}{[M(HZ)_2]}, \\ k_2'&=\frac{a_H[MZ_2]}{[MZ(HZ)]}, \quad k_3=\frac{a_H[MZ(HZ)_2]}{[M(HZ)_3]} \end{aligned}\right\} \quad (3)$$

$$Ka_1=\frac{a_H[H_2Z]}{[H_3Z]}, \quad Ka_2=\frac{a_H[HZ]}{[H_2Z]}, \quad Ka_3=\frac{a_H[Z]}{[HZ]} \quad (4)$$

The method of calculation was as follows. As to a total ligand concentration $[Z]_T$, a total proton concentration $[H]_T$ and a total metal ion concentration $[M]_T$, the following relations hold :

$$\begin{aligned}[Z]_T=&[H_3Z]+[H_2Z]+[HZ]+[Z]+[MHZ]+[MZ]+[MZ(OH)]+2[M(HZ)_2]\\&+2[MZ(HZ)]+2[MZ_2]+3[M(HZ)_3]+3[MZ(HZ)_2]+4[M(HZ)_4] \quad (5)\end{aligned}$$

$$\begin{aligned}[H]_T-c_H+c_{OH}=[Z]_T\cdot g=&-[MOH]-2[M(OH)_2]+3[H_3Z]+2[H_2Z]+[HZ]+[MHZ]\\&-[MZ(OH)]+2[M(HZ)_2]+[MZ(HZ)]+3[M(HZ)_3]+2[MZ(HZ)_2]\\&+4[M(HZ)_4] \quad (6)\end{aligned}$$

$$\begin{aligned}[M]_T=&[M]+[MOH]+[M(OH)_2]+[MHZ]+[MZ]+[MZ(OH)]+[M(HZ)_2]\\&+[MZ(HZ)]+[MZ_2]+[M(HZ)_3]+[MZ(HZ)_2]+[M(HZ)_4] \quad (7)\end{aligned}$$

g in (6) is defined by the following equation.*1

$$g=3-a+\frac{c_{OH}-c_H}{[Z]_T} \quad (8)$$

Here a group of brief symbols is introduced : namely,

$$A=[Z]_T, \quad B=[Z]_Tg, \quad C=[M]_T, \quad m=[M], \quad h=[HZ] \quad (9)$$

$$\left.\begin{aligned} a_0&=(Ka_1Ka_2)^{-1}a_H^2+Ka_2^{-1}a_H+1+Ka_3a_H^{-1}, \\ b_0&=3(Ka_1Ka_2)^{-1}a_H^2+2Ka_2^{-1}a_H+1, \\ c_0&=1+k_0a_H^{-1}+k_0k_0'a_H^{-2}, \quad b_0'=k_0a_H^{-1}+2k_0k_0'a_H^{-2} \end{aligned}\right\} \quad (10)$$

$$\left.\begin{aligned} &D_1=K_{M_1},\quad D_2=K_{M_1}k_1,\quad D_3=K_{M_1}k_1k_1',\quad D_4=K_{M_1}K_{M_2},\\ &D_5=K_{M_1}K_{M_2}k_2,\quad D_6=K_{M_1}K_{M_2}k_2k_2',\quad D_7=K_{M_1}K_{M_2}K_{M_3},\\ &D_8=K_{M_1}K_{M_2}K_{M_3}k_3,\quad D_9=K_{M_1}K_{M_2}K_{M_3}K_{M_4}\end{aligned}\right\} \quad (11)$$

$$\left.\begin{aligned} &a_1=1,\quad a_2=a_H^{-1},\quad a_3=a_H^{-2},\quad a_4=2,\quad a_5=2a_H^{-1},\\ &a_6=2a_H^{-2},\quad a_7=3,\quad a_8=3a_H^{-1},\quad a_9=4\end{aligned}\right\} \quad (12)$$

$$c_1=1,\ c_2=a_H^{-1},\ c_3=a_H^{-2},\ c_4=1,\ c_5=a_H^{-1},\ c_6=a_H^{-2},\ c_7=1,\ c_8=a_H^{-1},\ c_9=1 \quad (13)$$

From (1), (2), (3), (4), (9), (10), (11), (12), and (13), equations (5), (6), and (7) are rewritten as follows :

$$\begin{aligned} A=h\{&a_0+(a_1D_1+a_2D_2+a_3D_3)m+(a_4D_4+a_5D_5+a_6D_6)mh\\ &+(a_7D_7+a_8D_8)mh^2+a_9D_9mh^3\} \end{aligned} \quad (14)$$

$$\begin{aligned} B=-b_0'm+h\{&b_0+(D_1-D_3a_H^{-2})m+(2D_4+D_5a_H^{-1})mh\\ &+(3D_7+2D_8a_H^{-1})mh^2+4D_9mh^3\} \end{aligned} \quad (15)$$

$$\begin{aligned} C=m\{&c_0+(c_1D_1+c_2D_2+c_3D_3)h+(c_4D_4+c_5D_5+c_6D_6)h^2\\ &+(c_7D_7+c_8D_8)h^3+c_9D_9h^4\} \end{aligned} \quad (16)$$

From (13), (15), and (16), the following equation is obtained :

$$\begin{aligned} E=h\{&e_0+(e_1D_1+e_2D_2+e_3D_3)m+(e_4D_4+e_5D_5+e_6D_6)mh\\ &+(e_7D_7+e_8D_8)mh^2+e_9D_9mh^3\} \end{aligned} \quad (17)$$

where,

$$\left.\begin{aligned} &E=Bc_0+Cb_0',\quad e_0=b_0c_0,\quad e_1=c_0+b_0',\quad e_2=b_0'a_H^{-1},\\ &e_3=(-c_0+b_0')a_H^{-2},\quad e_4=2c_0+b_0',\quad e_5=(c_0+b_0')a_H^{-1},\\ &e_6=b_0'a_H^{-2},\quad e_7=3c_0+b_0',\quad e_8=(2c_0+b_0')a_H^{-1},\quad e_9=4c_0+b_0'\end{aligned}\right\} \quad (18)$$

From (14) and (17), the next equation is derived :

$$F=(f_1D_1+f_2D_2+f_3D_3)m+(f_4D_4+f_5D_5+f_6D_6)mh+(f_7D_7+f_8D_8)mh^2+f_9D_9mh^3 \quad (19)$$

where,

$$F=Ae_0-Ea_0,\quad f_i=Ea_i-Ae_i\ (i=1,\ 2,\ \cdots\cdots,\ 9) \quad (20)$$

Elimination of h and m from three independent equations, (14), (15), and (16), or, (14), (16), and (19), will lead to one equation, in which the observed values of nine points on titration curves will be substituted; and if the simultaneous equations were solved, all formation constants would be obtained in principle. The simultaneous equation will be, however, of high degree and very intricate, and solution of them will be enormously troublesome. Accordingly, the authors conquered this difficulty by using an electronic computer, by applying iterative approximation to (14), (16), and (19), and by selecting suitable experimental conditions.

By an electronic computer, coefficients, A, a_i ($i=0, 1, 2, \cdots\cdots, 9$), C, c_i ($i=0, 1, 2, \cdots\cdots, 9$), F and f_i ($i=1, 2, \cdots\cdots, 9$), of the general equations, (14), (16), and (19), are calculated from a titrated volume of alkaline solution, V, a measured value, mv, an initial value of a total ligand concentration, $(A)_0$, an initial value of a total metal ion concentration, $(C)_0$, and a set of all necessary constants according to the flow diagram shown in Fig. 1, and stored.

According to Schwarzenbach, some kinds of ionic species can be neglected in a solution of a certain ratio of ligand to metal ion. In order to determine all constants, D_i ($i=1, 2, \cdots\cdots, 9$), successively from the coefficients stored, the following steps are taken.

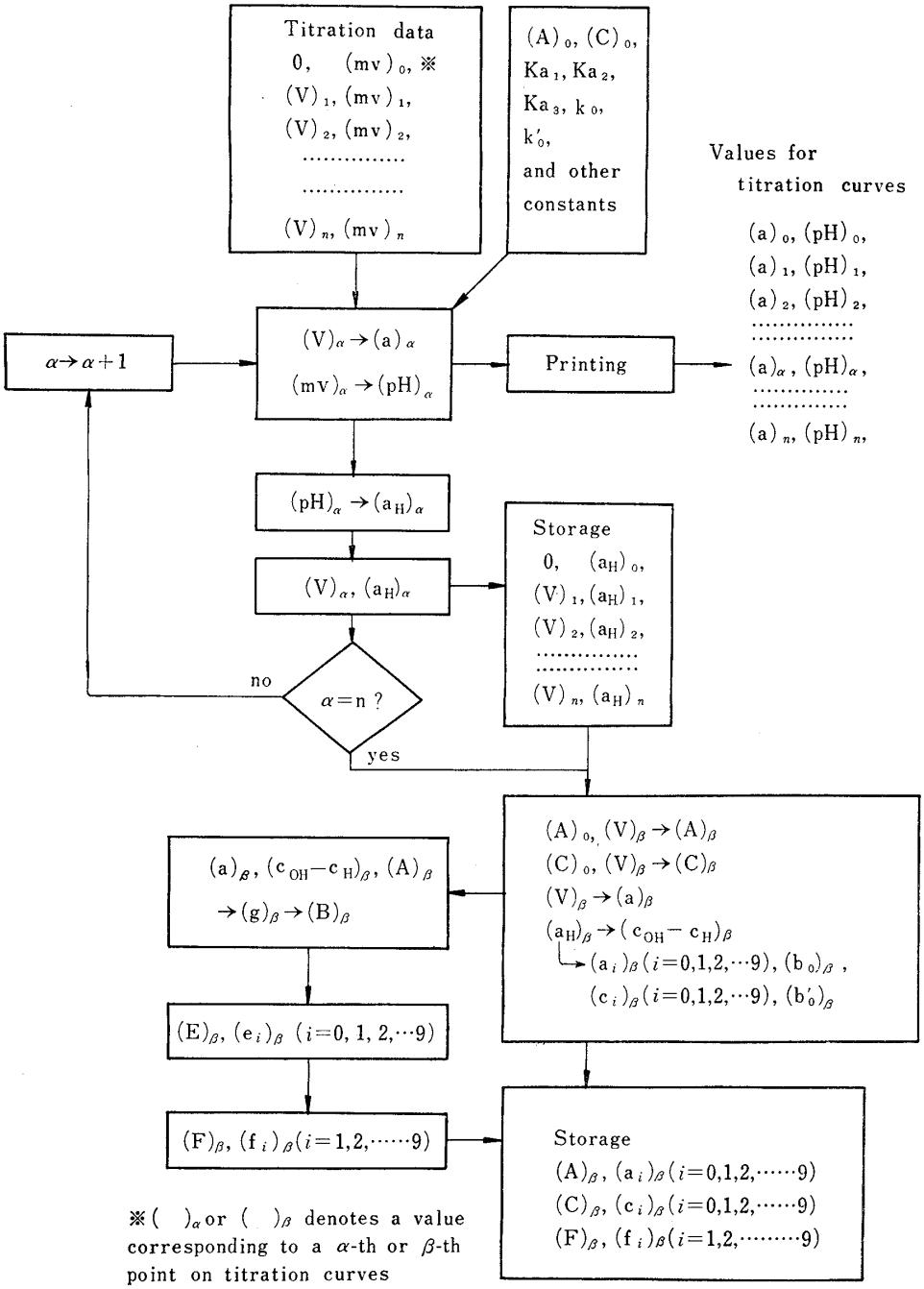


Fig. 1. Flow Diagram 1

(i) Metal ion excess solution : In this case, the concentration of free neutral ligand, h, is very small, and others than 1:1 species can be neglected. Then, (14), (15), (16), (17), and (19) become

$$A = h\{a_0 + (a_1D_1 + a_2D_2 + a_3D_3)m\} \tag{14-1}$$

$$B = -b_0'm + h\{b_0 + (D_1 - D_3a_H^{-2})m\} \tag{15-1}$$

$$C = m\{c_0 + (c_1D_1 + c_2D_2 + c_3D_3)h\} \tag{16-1}$$

$$E = h\{e_0 + (e_1D_1 + e_2D_2 + e_3D_3)m\} \tag{17-1}$$

$$F = (f_1D_1 + f_2D_2 + f_3D_3)m \tag{19-1}$$

In order to determine D_1, D_2, and D_3 correctly from (15-1) or (17-1), h and m must be previously calculated from (14-1) and (16-1) accurately. But, inversely, it requires

correct values of those constants. In the case of metal ion excess solutions, even if the initially assumed values of those are not so correct, the estimated value of m will be successfully near to the correct value, while that of h will be far from the correct one. Consequently, (19-1) will give more approximate values of those constants and, when the calculation is repeated, will converge more rapidly than (15-1) or (17-1). As m is near to C, C is substituted for m in (19-1) at first. Temporary values of D_1, D_2, and D_3 are obtained by solving simultaneous equations from three points, $(\ )_\alpha$, $(\ )_\beta$, and $(\ )_\gamma$, on titration curves. These temporary constants are substituted in (14-1) and (16-1), from which with the more reasonable values of m and h are obtained by the application of iterative approximation. This value of m is substituted in (19-1), and the more reasonable values of D_1, D_2, and D_3 are obtained. This procedure is repeated until the values of these constants converge. The iteration is the more significant, the nearer a ratio of ligand to metal ion to 1:1. The flow diagram of the calculation is illustrated in Fig. 2. When it becomes known that $D_j (j=1$, or 2, or 3) is zero within the range of experimental errors, the calculation will become much simpler. When D_4, D_5, etc. are too large to be neglected, D_1, D_2, and D_3 should be re-calculated after

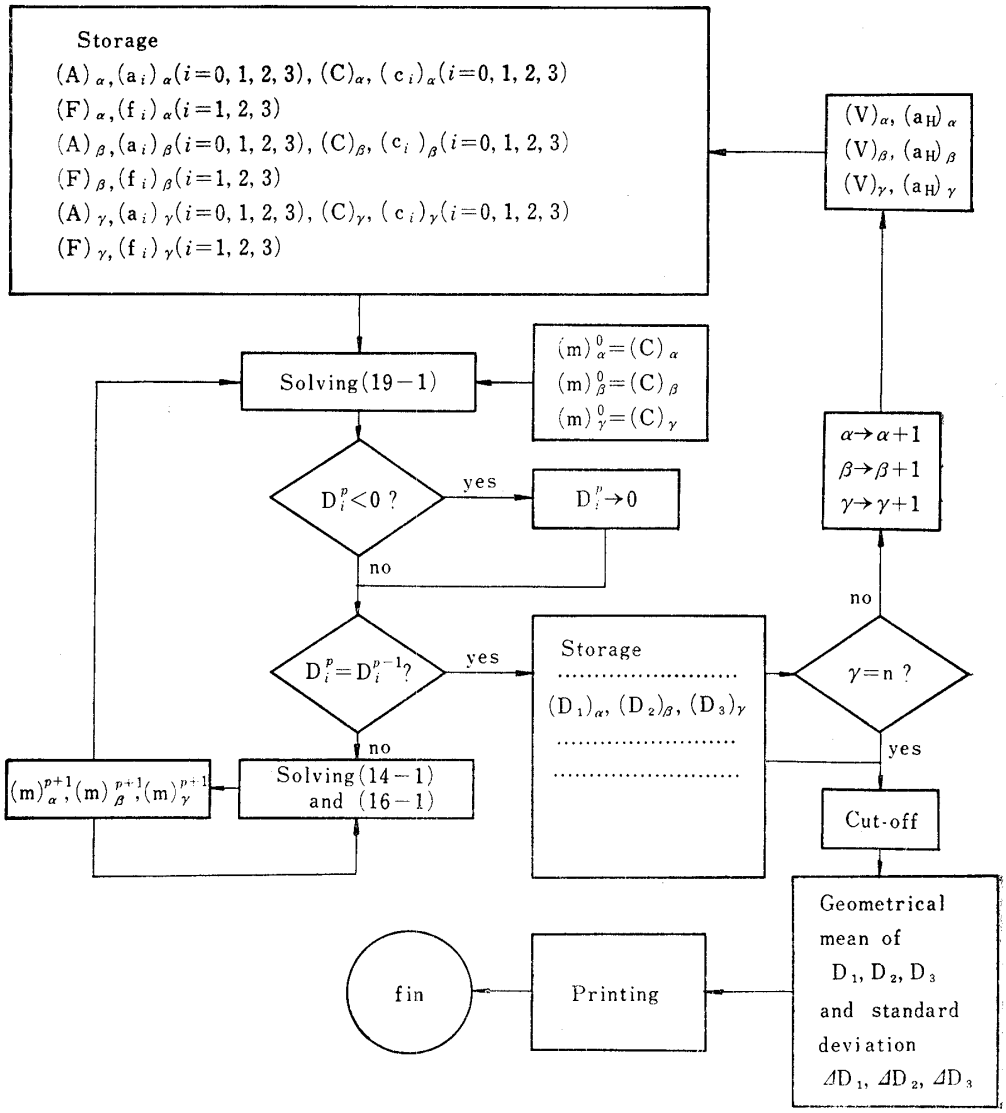


Fig. 2. Flow Diagram 2
Metal Ion Excess Solutions

D_4, D_5, etc. are determined from ligand excess solutions and substituted in (14), (16), and (19).

(ii) Ligand excess solutions : Here, D_1, D_2, and D_3 are already determined. In the case of ligand excess solutions, even if the initailly assumed values of D_4, D_5, ····· D_9 are not so correct, the estimated value of h will be near to the correct value, while that of m will be far from the correct one. Accordingly, it is profitable to use an equation in which m is eliminated in order to determine D_i ($i=4, 5, \cdots\cdots 9$). The following equation is derived from (16) and (19) :

$$L=\sum_{i=4}^{9} l_i D_i \tag{21}$$

where,

$$\left.\begin{aligned} &L=F\{c_0+(c_1D_1+c_2D_2+c_3D_3)h\}-C(f_1D_1+f_2D_2+f_3D_3),\\ &l_i=(Cf_i-Fc_ih)h\ (i=4, 5, 6),\quad l_j=(Cf_j-Fc_jh)h^2\ (j=7, 8),\\ &l_9=(Cf_9-Fc_9h)h^3 \end{aligned}\right\} \tag{22}$$

At first, assumed values of the constants to be determined are substituted into (14) and (16), and a comparatively reasonable value of h is obtained by the use of iterative approximation, and substituted into (22). Then, D_4 is sought from the titration data of solutions containing a comparatively small quantity of ligand by the use of the following equation :

$$D_4=L/l_4 \tag{23}$$

Here, the existence of ionic species corresponding to D_j ($j\geqslant 5$) is neglected. When calculated values of D_4 are negative, or dispersed about zero, or rapidly decreasing or increasing with increasing pH, $M(HZ)_2$ is considered to be negligible in the solution. On the contray, when calculated values of D_4 are reproducible within a range of experimental errors over a wide pH region, the exstence of the complex is inferred. The calculated value of D_4 is substituted in (14) and (16), and the process above mentioned is repeated until the value converges. Unreasonable values are cut off, and the geometrical mean of the values which are reproducible over a certain pH region is calculated and substituted in (14) and (16). In the same way, D_5, D_6, etc. are calculated successively from the titration data of solutions containing a larger quantity of ligand by the use of the following equation :

$$D_i=\left(L-\sum_{j=4}^{i-1} l_jD_j\right)\Big/ l_i\ (i=5, 6, \cdots\cdots, 9) \tag{24}$$

About genuine values of D_i ($i=1, 2, \cdots\cdots, 9$), it seems reasonable to hold the following relations :

$$\left.\begin{aligned} &\log K_{M_1}>\log K_{M_2}>\log K_{M_3}>\log K_{M_4}\\ &pk_1>pk_2>pk_3,\quad pk_2<pk_2' \end{aligned}\right\} \tag{25}$$

The flow diagram of the calculation is illustrated in Fig. 3.

(iii) Hydrolysis constants of metal ions : Before determining these formation constants by the method above mentioned, it is necessary to obtain hydrolysis constants of metal ions. The method of calculation is described as follows.

The first hydrolysis constant k_0 and the second hydrolysis constant k_0' are defined by (2). Although k_0' used to be neglected, the authors thought that k_0 could be obtained more accurately if k_0' was introduced and both constants were calculated simultaneously. But, when pH becomes higher, polymerized olated metal ions $M_m(OH)_n$ appear

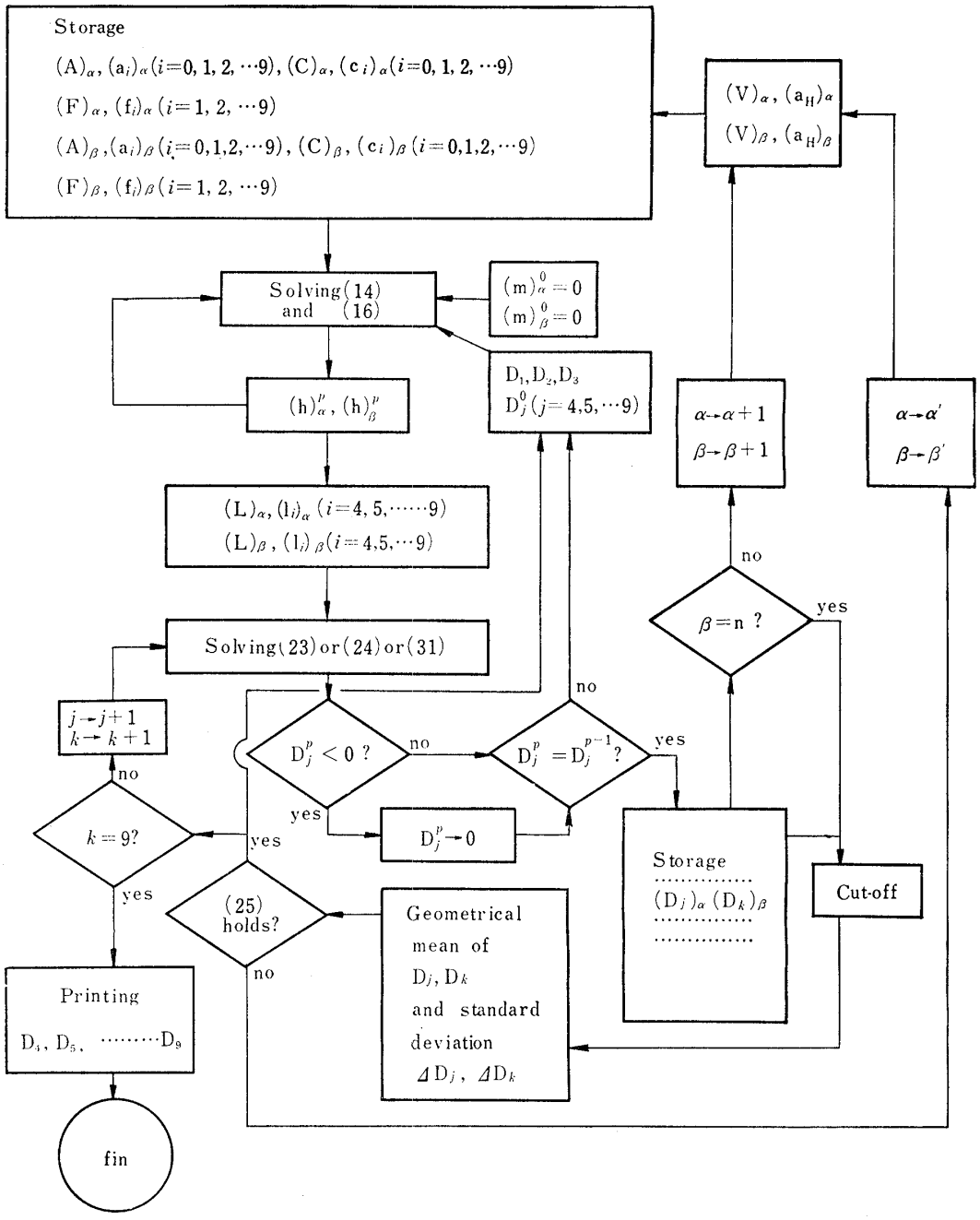


Fig. 3. Flow Diagram 3
Ligand Excess Solutions

and begin to deposit slowly. Accordingly, calculation of k_0 and k_0' is restricted within a pH range where calculated values of both constants are reproducible. In order to obtain such a pH range a solution of rich metal ion was titrated with a dilute alkaline solution. At first two functions of degree of neutralization a, $c^\circ_H(a)$ and $c^\circ_{OH}(a)$, are introduced. These represent molar concentrations of hydrogen ion and hydroxyl ion respectively when no metal ion is present, and can be obtained from the titration curve of a solution containing $2\times10^{-3}N$ HNO_3 and $1.0M$ KNO_3 with a solution of $5\times10^{-2}N$ NaOH and $0.95M$ KNO_3. In the presence of metal ions, $c_H(a)$ and $c_{OH}(a)$ deviate from $c^\circ_H(a)$ and $c^\circ_{OH}(a)$ respectively as a result of hydrolysis. Consequently, the following relation holds:

$$[M(OH)]+2[M(OH)_2]=c_H-c^\circ_H+c^\circ_{OH}-c_{OH}=X(a) \qquad (26)$$

Here X(a) is also a function of a. In acidic region, $c^{\circ}_{OH}-c_{OH}$ can be neglected, while, in alkaline region, $c_H-c^{\circ}_H$ can be neglected. From (2) and (9), (26) leads to

$$X=(k_0a_H^{-1}+2k_0k_0'a_H^{-2})m \tag{27}$$

On the other hand, as a total metal ion concentration $[M]_T$ is equal to the sum of each ionic species,

$$[M]_T=[M]+[M(OH)]+[M(OH)_2] \tag{28}$$

(28) can be rewritten by (2) and (9) as

$$C=(1+k_0a_H^{-1}+k_0k_0'a_H^{-2})m \tag{29}$$

From (27) and (29), the final equation is derived as

$$(X/C)+\{(X/C)-1\}a_H^{-1}k_0+\{(X/C)-2\}a_H^{-2}k_0k_0'=0 \tag{30}$$

In order to calculate k_0 and k_0' from (30), two points on the titration curve are connected with each other, and simultaneous equations are solved.

Experimental

Apparatus were the same as those used in Part II.*1

Materials——$Cu(NO_3)_2$, $Zn(NO_3)_2$, $Ni(NO_3)_2$, $Co(NO_3)_2$, $Cd(NO_3)_2$ and $Mn(NO_3)_2$ were all analytical grade and used without further purification. INH, nicotinoylhydrazine(NH), picolinoylhydrazine (PH),

Table I. The Composition of Sample Solution and Standard Solution

Ia. Solution for Hydrolysis Constants of Metal Ions

A:C[a]	Sample Solution: Ligand (*M*)	$M(NO_3)_2$ (*M*)	HNO_3 (*N*)	KNO_3 (*M*)	Standard Solution: NaOH (*N*)	KNO_3 (*M*)
	0	0	2×10^{-3}	1.0	5×10^{-2}	0.95
	0	2×10^{-2}	2×10^{-3}	1.0	5×10^{-2}	0.95

Ib. Solution for Consecutive Formation Constants of Cu(II) Complexes of INH and Related Compounds

A:C	Sample Solution: Ligand (*M*)	$Cu(NO_3)_2$ (*M*)	HNO_3 (*N*)	KNO_3 (*M*)	Standard Solution: NaOH (*N*)	KNO_3 (*M*)
1:20	1×10^{-3}	2×10^{-2}	2×10^{-3}	1.0	5×10^{-2}	0.95
1:1	1×10^{-3}	1×10^{-3}	2×10^{-3}	1.0	5×10^{-2}	0.95
2:1	2×10^{-3}	1×10^{-3}	4×10^{-3}	1.0	1×10^{-1}	0.9
2:1(PH)	2×10^{-4}	1×10^{-4}	4×10^{-4}	1.0(100 cc.)	1×10^{-1}	0.9
5:1	5×10^{-3}	1×10^{-3}	1×10^{-2}	1.0	2.5×10^{-1}	0.75
20:1	2×10^{-2}	1×10^{-3}	4×10^{-2}	1.0	1.0	0

Ic. Solution for Formation Constants of INH Complexes with Zn(II), Ni(II), Co(II), Cd(II) and Mn(II)

A:C	Sample Solution: INH (*M*)	$M(NO_3)_2$ (*M*)	HNO_3 (*N*)	KNO_3 (*M*)	Standard Solution: NaOH (*N*)	KNO_3 (*M*)
1:20	1×10^{-3}	2×10^{-2}	2×10^{-3}	1.0	5×10^{-2}	0.95
1:1	2×10^{-2}	2×10^{-2}	4×10^{-2}	1.0	1.0	0
20:1	2×10^{-2}	1×10^{-3}	4×10^{-2}	1.0	1.0	0

Id. Solution for D_7 of INH-Cd(II) Complexes

A:C	Sample Solution: INH (*M*)	$Cd(NO_3)_2$ (*M*)	HNO_3 (*N*)	KNO_3 (*M*)	Standard Solution: NaOH (*N*)	KNO_3 (*M*)
	4×10^{-1}	0	4×10^{-2}	1.0	1.0	0
20:1	4×10^{-1}	2×10^{-2}	4×10^{-2}	1.0	1.0	0

a) Ratio of a total ligand concentration to a total metal ion concentration. See (9).

benzoylhydrazine (BH), *p*-nitrobenzoylhydrazine (PNBH), isonicotinamide (INA), 1-isonicotinoyl-1-methylhydrazine (N-Me-INH) and 1-isonicotinoyl-2-methylhydrazine (N'-Me-INH) were the same as those used in Part II.*[1]

Titrations——The composition of sample solution and standard solution are tabulated in Table I. In the case of INH-Cd(II) complexes, a ligand excess solution shown in Table Id was also titrated with N NaOH solution. At such a high concentration of INH, activity coefficient of each ionic species of INH seemed to change considerably, while that of neutral species will not so change. The apparent acid dissociation constants were therefore corrected from the titration data of a solution containing $4\times10^{-1}M$ INH, $4\times10^{-2}N$ HNO_3 and $1.0M$ KNO_3 with N NaOH solution. The following result

$$pKa_2 = 3.758\pm0.008 \quad (pH\ 4.70\sim 5.56)$$
$$pKa_3 = 11.058\pm0.009 \quad (pH\ 9.20\sim10.10)$$

was obtained. The result indicated that activity coefficients of H_2Z^+ and Z^- increased ca. 10% when a concentration of a neutral molecule INH increased from $2\times10^{-2}M$ to $4\times10^{-1}M$.

Computers——Calculations were carried out by the use of electric computers (Brunsviga 11 E: Brunsviga Maschinenwerke AG.; Blue Star 20-EA: Tokyo Electric Co.), an electronic computer with 512 words (pc-1: Takahashi Laboratory, Faculty of Science, University of Tokyo) or an electronic computer with 4,000 words (OKITAC-5090A: Oki Denki Co.) in accordance with complexity of calculation. Programing was carried out by one of the authors.

Results and Discussion

The titration curves of metal ions are shown in Fig. 4, and the calculated values of pk_0 and pk_0' are listed in Table II with the mean errors and the pH ranges used.

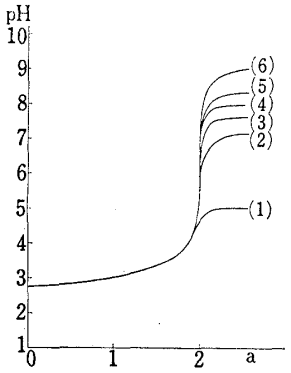


Fig. 4.

(1) $10Cu(NO_3)_2+HNO_3$
(2) $10Zn(NO_3)_2+HNO_3$
(3) $10Ni(NO_3)_2+HNO_3$
(4) $10Co(NO_3)_2+HNO_3$
(5) $10Cd(NO_3)_2+HNO_3$
(6) $10Mn(NO_3)_2+HNO_3$
Titrated with $0.05N$ NaOH

Table II. Hydrolysis Constants of Metal Ions

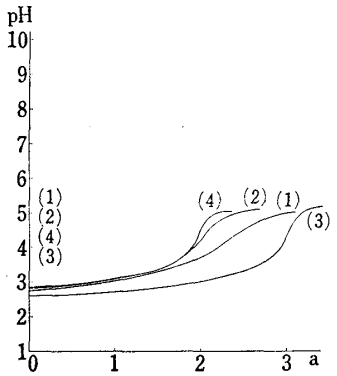
Metal Ion			Literature[3]
Cu(II)	$pk_0 = 7.80\pm0.05$	(pH 4.24~4·52)[a]	6.8[b]
	$pk_0' = 4.77\pm0.08$	(pH 4.59~4.79)	
Zn(II)	$pk_0 = 9.13\pm0.07$	(pH 4.47~6.70)	8.7
	$pk_0' = 7.49\pm0.23$	(pH 6.88~7.13)	
Ni(II)	$pk_0 = 9.45\pm0.36$	(pH 4.90~7.49)	9.4
	$pk_0' = 7.85\pm0.41$	(pH 7.56~7.65)	
Co(II)	$pk_0 = 10.18\pm0.13$	(pH 4.31~7.70)	8.9
	$pk_0' = 7.93\pm0.19$	(pH 7.80~7.94)	
Cd(II)	$pk_0 = 10.40\pm0.13$	(pH 6.94~7.47)	11.6
	$pk_0' = 8.41\pm0.44$	(pH 7.62~8.21)	
Mn(II)	$pk_0 = 10.65\pm0.11$	(pH 6.87~8.45)	10.6
	$pk_0' = 9.09\pm0.24$	(pH 8.55~8.90)	

a) The pH ranges used in calculation are indicated in parentheses.
b) $T=30$, $\mu=0.1$

3) S. Chaberek, Jr., R.C. Courtney, A.E. Martell: J. Am. Chem. Soc., **74**, 5057 (1952).

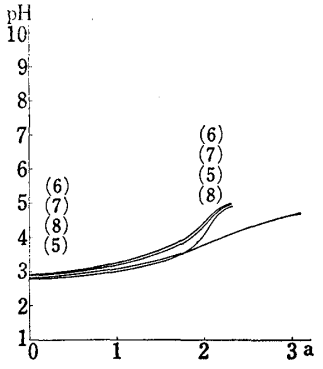
The titration curves of cupric ion excess solutions with INH and related compounds are shown in Figs. 5a and 5b. D_1 and D_2 values of all ligands except PH were obtained from these data, while D_3 values of all ligands could not be obtained. The titration curves of equimolar solutions are shown in Figs. 6a and 6b. D_1 and D_2 values of PH were calculated from the data of metal ion excess solution and equimolar solution. The titration curves of ligand excess solutions are shown in Figs. 7a, 7b and 7c (A:C 2:1), Figs. 8a and 8b (5:1) and Figs. 9a and 9b (20:1). D_4 values of INH, NH, PNBH, N-Me-INH, and N′-Me-INH were obtained from the data of 5:1 solution, while those of BH and INA from 20:1 solution. D_5 value of PNBH was obtained from 5:1 solution, while those of INH, NH, BH, and N′-Me-INH from 20:1 solution. D_6 values of INH, NH, and PH and D_7 value of N-Me-INH were obtained from 20:1 solution. D_4 and D_5 values of PH could not be obtained. D_6 and D_7 values of PNBH and N′-Me-INH were sure to exist but not obtained. In such cases, the following equation should be applied to the data of different A:C solutions and the simultaneous equations should be solved:

$$l_6D_6+l_7D_7=L-\sum_{j=4}^{5} l_jD_j \qquad (31)$$



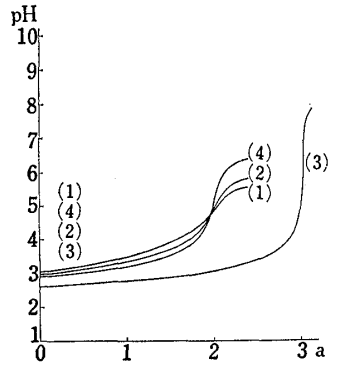
(1) $INH+20Cu(NO_3)_2+2HNO_3$
(2) $NH+20Cu(NO_3)_2+2HNO_3$
(3) $PH+20Cu(NO_3)_2+2HNO_3$
(4) $BH+20Cu(NO_3)_2+2HNO_3$
Titrated with 0.05*N* NaOH

Fig. 5a.



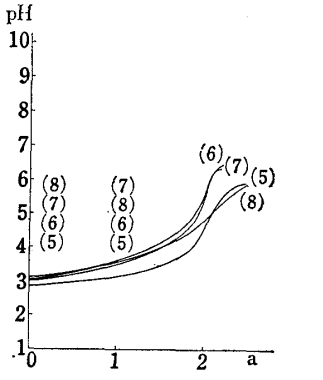
(5) $PNBH+20Cu(NO_3)_2+2HNO_3$
(6) $INA+20Cu(NO_3)_2+2HNO_3$
(7) $N\text{-}Me\text{-}INH+20Cu(NO_3)_2+2HNO_3$
(8) $N'\text{-}Me\text{-}INH+20Cu(NO_3)_2+2HNO_3$
Titrated with 0.05*N* NaOH

Fig. 5b.



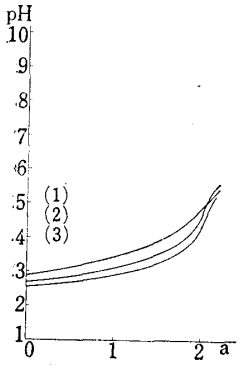
(1) $INH+Cu(NO_3)_2+2HNO_3$
(2) $NH+Cu(NO_3)_2+2HNO_3$
(3) $PH+Cu(NO_3)_2+2HNO_3$
(4) $BH+Cu(NO_3)_2+2HNO_3$
Titrated with 0.05*N* NaOH

Fig. 6a.



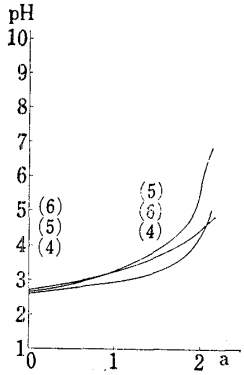
(5) $PNBH+Cu(NO_3)_2+2HNO_3$
(6) $INA+Cu(NO_3)_2+2HNO_3$
(7) $N\text{-}Me\text{-}INH+Cu(NO_3)_2+2HNO_3$
(8) $N'\text{-}Me\text{-}INH+Cu(NO_3)_2+2HNO_3$
Titrated with 0.05*N* NaOH

Fig. 6b.



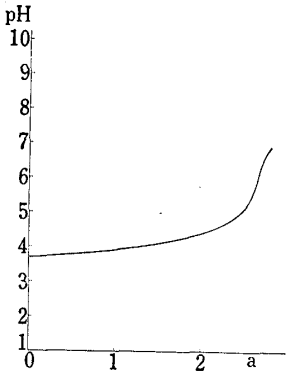
(1) $2INH+Cu(NO_3)_2+4HNO_3$
(2) $2NH+Cu(NO_3)_2+4HNO_3$
(3) $2BH+Cu(NO_3)_2+4HNO_3$
Titrated with 0.1*N* NaOH

Fig. 7a.



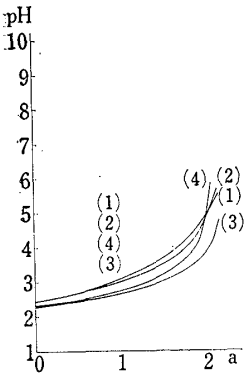
(4) $2PNBH+Cu(NO_3)_2+4HNO_3$
(5) $2N\text{-}Me\text{-}INH+Cu(NO_3)_2+4HNO_3$
(6) $2N'\text{-}Me\text{-}INH+Cu(NO_3)_2+4HNO_3$
Titrated with 0.1*N* NaOH

Fig. 7b.



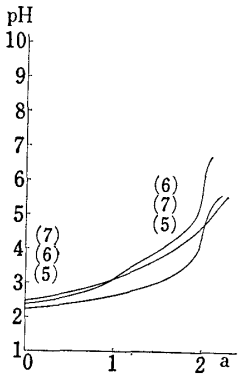
$2PH+Cu(NO_3)_2+4HNO_3$
Titrated with 0.1*N* NaOH

Fig. 7c.



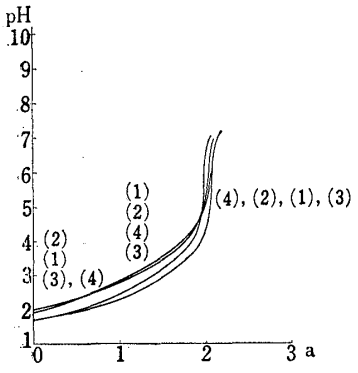
(1) $5INH+Cu(NO_3)_2+10HNO_3$
(2) $5NH+Cu(NO_3)_2+10HNO_3$
(3) $5PH+Cu(NO_3)_2+10HNO_3$
(4) $5BH+Cu(NO_3)_2+10HNO_3$
Titrated with 0.4*N* NaOH

Fig. 8a.



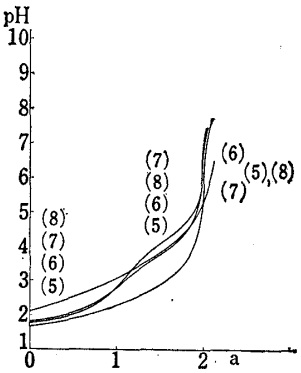
(5) $5PNBH+Cu(NO_3)_2+10HNO_3$
(6) $5N\text{-}Me\text{-}INH+Cu(NO_3)_2+10HNO_3$
(7) $5N'\text{-}Me\text{-}INH+Cu(NO_3)_2+10HNO_3$
Titrated with 0.4*N* NaOH

Fig. 8b.



(1) $20INH+Cu(NO_3)_2+40HNO_3$
(2) $20NH+Cu(NO_3)_2+40HNO_3$
(3) $20PH+Cu(NO_3)_2+40HNO_3$
(4) $20BH+Cu(NO_3)_2+40HNO_3$
Titrated with *N* NaOH

Fig. 9a.



(5) $20PNBH+Cu(NO_3)_2+40HNO_3$
(6) $20INA+Cu(NO_3)_2+40HNO_3$
(7) $20N\text{-}Me\text{-}INH+Cu(NO_3)_2+40HNO_3$
(8) $20N'\text{-}Me\text{-}INH+Cu(NO_3)_2+40HNO_3$
Titrated with *N* NaOH

Fig. 9b.

The calculated values of log D_i ($i=1, 2, \cdots\cdots, 9$) are listed in Table IIIa and compared with the values obtained by Albert in Table IIIb.[4] The confidence limits of these constants were not calculated but will be obtained in the same way when upper or under limits of confidence intervals of pH, V, pKa_i, pk_j, and other constants used in calculation are substituted in the computation process.

Table IIIa. log D_i ($i=1, 2, \cdots\cdots, 9$) Values of Cu(II) Complexes of INH and Related Compounds

Ligand	log D_1	log D_2	log D_3	log D_4	log D_5	log D_6	log D_7	log D_8	log D_9
INH	3.15	−1.01	—	5.08	2.83	−1.12			
NH	3.09	−1.97	—	6.30	4.60	0.20			
PH	3.72	2.38	—	—	—	3.43			
BH	3.99	−1.50	—	6.16	1.69	—			
PNBH	3.31	−1.41	—	5.55	1.97				
INA	2.33	—	—	3.38	—	—			
N-Me-INH	3.02	—	—	5.89	—	—	7.96		
N′-Me-INH	3.54	−0.82	—	7.08	4.59				

Table IIIb. log K_1 and log K_2 Values of Cu(II) Chelates of INH, NH, PH, BH, PNBH and N′-Me-INH

			Literature[4]	
Ligand	log K_1[a]	log K_2[b]	log K_1	log K_2
INH	10.02	10.94?	8.0	precipitate
NH	9.52	13.66?	8.7	7.5
PH	14.63	13.30	12.4	9.1
BH	11.03	—	9.0	precipitate
PNBH	9.87			
N′-Me-INH	10.14			

a) $K_1=\frac{[MZ]}{[M][Z]}=D_2Ka_3^{-1}$ *b*) $K_1K_2=\frac{[MZ_2]}{[M][Z]^2}=D_6Ka_3^{-2}$

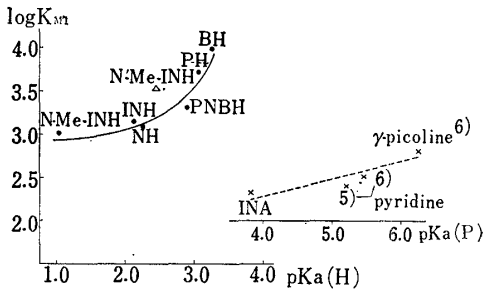
Values of log K_{M_i} and pk_j of Cu(II) complexes of INH and related compounds with values of their pKa(H), pKa(P) and pKa(A_2), definition of which were described in Part II,*1 are listed in Table IV.

Table IV. log K_{M_i} and pk_j Values of Cu (II) Complexes of INH and Related Compounds and Their Values of pKa (H), pKa (P) and pKa (A_2)

Ligand	pKa (H)	pKa (P)	pKa (A_2)	log K_{M_1}	pk_1	log K_{M_2}	pk_2	pk_2'	log K_{M_3}	log K_{M_4}
INH	2.13	3.81	11.03	3.15	4.16	1.93	2.25	3.95		
NH	2.26	3.63	11.49	3.09	5.06	3.21	1.70	4.40		
PH	3.07	1.26	12.25	3.72	1.34 ($\log K_{M_2}k_2k_2'=-0.29$)					
BH	3.27	—	12.53	3.99	5.49	2.17	4.47	—		
PNBH	2.90	—	11.28	3.31	4.72	2.24	3.58			
INA	—	3.82	15<	2.33	—	1.05	—	—		
N-Me-INH	1.03	4.17	—	3.02	—	2.87	—	—	2.07	
N′-Me-INH	2.46	4.04	10.96	3.54	4.36	3.54	2.49			
Pyridine[5]	—	5.21	—	2.41	—	1.88	—	—	1.14	0.60
〃 [6]	—	5.45	—	2.52	—	1.86	—	—	1.31	0.85
γ-Picoline[6]	—	6.26	—	2.82	—	2.15	—	—	1.61	1.16

When values of log K_{M1} of seven hydrazides are plotted against pKa(H) and those of INA, pyridine[5,6] and γ-picoline[6] against pKa(P), Fig. 10 is obtained. Fig. 11 is similarly obtained about the relation between pk_1 and pKa(A_2). The affinity of each

4) A. Albert: Experientia, **9**, 370 (1953); Nature, **177**, 525 (1956).
5) J. Bjerrum, E. J. Nielsen: Acta Chem. Scand., **2**, 316 (1948); J. Bjerrum: Chem. Rev., **46**, 381 (1950).
6) R. J. Bruehlmann, F. H. Verhoek: J. Am. Chem. Soc., **70**, 1401 (1948).



• : Ar-CO-NRNH$_2$(R=H or CH$_3$)
△ : Ar-CO-NHNHCH$_3$
× : -R′ (R′=H or CONH$_2$)

Fig. 10. The Relation between log K_{M_1} and pKa (H) (or pKa (P))

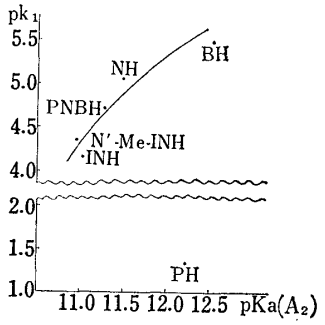
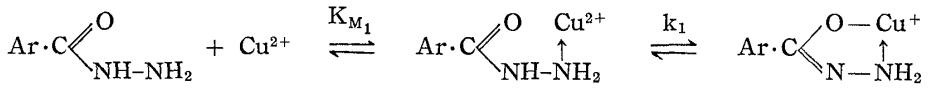


Fig. 11. The Relation between pk_1 and pKa (A_2)

hydrazide for cupric ion (log K_{M1}) is increasing in Fig. 10 with the affinity of terminal nitrogen for proton (pKa (H)), and falls in a range between 3 and 4, while that of INA is considerably small and similar to that of pyridine and γ-picoline though the affinity of pyridine nitrogen for proton (pKa (P)) is generally larger than that of terminal nitrogen of hydrazide (pKa (H)). This fact indicates that INH, NH, N-Me-INH, and N′-Me-INH form addition complexes more probably to terminal nitrogens similarly to BH and PNBH, and that INA forms an addition complex to pyridine nitrogen. On the other hand, each value of pk_1 is smaller than half of the corresponding pKa (A_2). Furthermore, the larger the acid dissociation ability of amide nitrogen of each hydrazide except PH is, the larger is that of the resultant complex. Consequently, Fig. 11 indicates that dissociation of a proton from amide nitrogen is facilitated by cupric ion associated to terminal nitrogen, and that it also depends upon the electronic structure of the hydrazide itself. From these considerations, the process of chelate formation of INH, NH, BH, PNBH, and N′-Me-INH with cupric ion may be concluded to consist of the following two steps :



The first step depends on the basicity of terminal nitrogen, and the second step on the acidity of amide nitrogen. N-Me-INH cannot take a chelate form since it does not possess any proton at amide nitrogen.

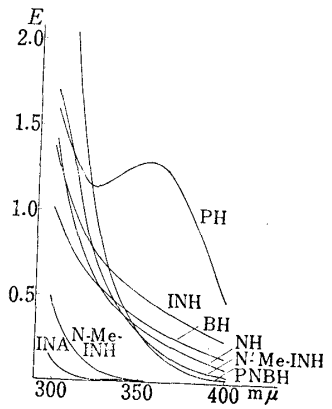
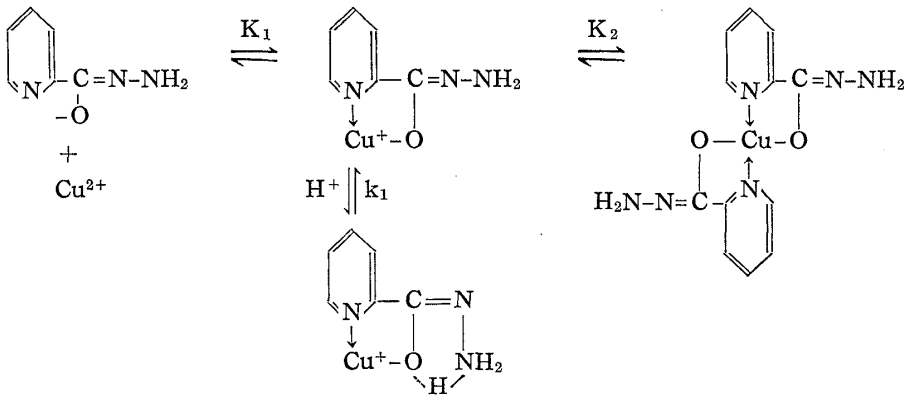
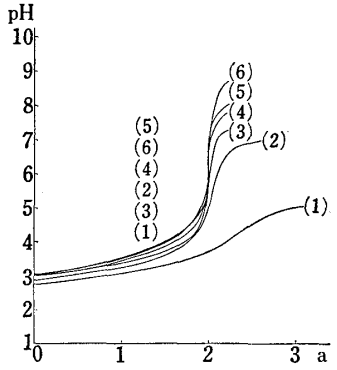


Fig. 12. Absorption Spectra of the Mixed Solution of Ligand and Cu^{2+}
[Ligand] = $2.5 \times 10^{-3} M$
[$CuNO_3$] = $2.5 \times 10^{-3} M$

*3 Part IV : This Bulletin, to be published.

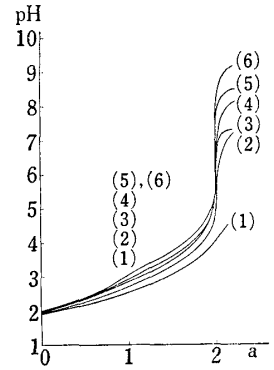
In the case of PH-Cu(II) complexes, values of log K_1 and log K_2 are very large and value of pk_1 is exceptionally small, while values of log D_4 and log D_5 are not obtained. Considering that picolinic acid the excellent chelating reagent for transition metal ions, pyridine nitrogen of PH seems to be used for the chelate ring formation. This thought is supported by the absorption spectral data of the solution containing $2.5\times10^{-3}M$ ligand and $2.5\times10^{-3}M$ cupric nitrate, shown in Fig. 12. On the other hand, from the infrared spectral data of PH-Cu(II) complex crystal,*3 it is inferred that carbonyl group of PH contributes to the formation of chelate ring. Consequently, the process of chelate formation of PH with cupric ion can be considered as follows*4 :





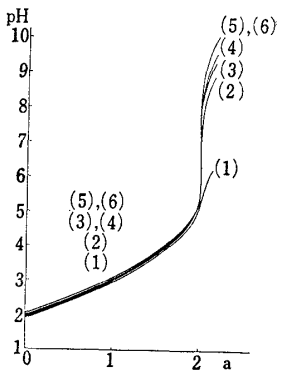
(1) INH+20Cu$(NO_3)_2$+2HNO_3
(2) INH+20Zn$(NO_3)_2$+2HNO_3
(3) INH+20Ni$(NO_3)_2$+2HNO_3
(4) INH+20Co$(NO_3)_2$+2HNO_3
(5) INH+20Cd$(NO_3)_2$+2HNO_3
(6) INH+20Mn$(NO_3)_2$+2HNO_3
Titrated with 0.05N NaOH

Fig. 13.



(1) INH+Cu$(NO_3)_2$+2HNO_3
(2) INH+Ni$(NO_3)_2$+2HNO_3
(3) INH+Zn$(NO_3)_2$+2HNO_3
(4) INH+Co$(NO_3)_2$+2HNO_3
(5) INH+Cd$(NO_3)_2$+2HNO_3
(6) INH+Mn$(NO_3)_2$+2HNO_3
Titrated with N NaOH

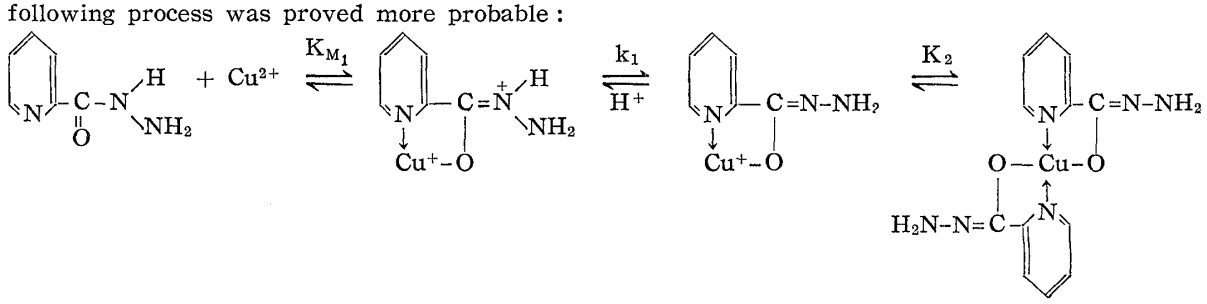
Fig. 14.



(1) 20INH+Cu$(NO_3)_2$+40HNO_3
(2) 20INH+Ni$(NO_3)_2$+40HNO_3
(3) 20INH+Zn$(NO_3)_2$+40HNO_3
(4) 20INH+Co$(NO_3)_2$+40HNO_3
(5) 20INH+Cd$(NO_3)_2$+40HNO_3
(6) 20INH+Mn$(NO_3)_2$+40HNO_3
Titrated with N NaOH

Fig. 15.

*4 From the later investigation of the infrared spectral data of PH-Cu(II) complex crystal,*3 the following process was proved more probable :



The titration curves for INH complexes with zinc, nickel, cobaltous, cadmium and manganous ions are shown in Fig. 13 (A:C, 1:20), Fig. 14 (1:1), and Fig. 15 (20:1).

The calculated values of log K_{M_i} and pk_j are tabulated in Table V, from which it is recognized that the sequence of magnitude of those constants agrees neither with each other nor with that of hydrolysis constants.

Table V. log K_{M_1}, pk_1 and log K_1 Values of INH Complexes with Cu(II), Zn(II), Ni(II), Co(II), Cd(II) and Mn(II)

Metal Ion	log K_{M_1}	pk_1	log K_1	pk_0	Literature[4] log K_1
Cu(II)	3.15	4.16	10.02	7.80	8.0
Zn(II)	1.86	5.71	7.18	9.13	5.4
Ni(II)	2.59	8.00	5.62	9.45	5.5
Co(II)	1.64	8.11	4.56	10.18	4.8
Cd(II)	1.09	8.69	3.43	10.40	
Mn(II)	1.04	7.93	4.14	10.65	

In the case of INH-Cd(II) complexes,

$$\log K_{M1}=1.09 \qquad \log K_{M2}=1.10 \qquad \log K_{M3}=0.53$$
$$pk_1=8.69 \qquad pk_1'=8.34$$

was obtained. The titration curve for log K_{M3} is shown in Fig. 16.

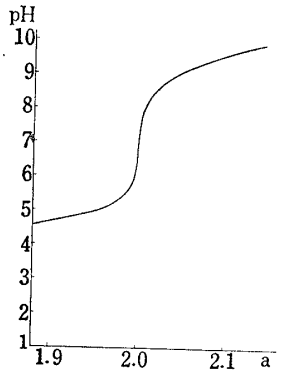


Fig. 16.
20INH+$Cd(NO_3)_2$+2HNO_3
Titrated with *N* NaOH

The authors express their deep gratitude to Professor Emeritus M. Ishidate for his continuous encouragement throughout this work. They are also indebted to members of kihara laboratory and those of Takahashi laboratory, Faculty of Science, University of Tokyo, for their pertinent advice about the method of programming, and to members of Computation Centor, University of Tokyo, for numerical computations.

Summary

Consecutive formation constants of metal complexes of isonicotinoylhydrazine (INH) and related compounds were determined by the pH titration method. The calculation was performed by an electronic computer applying the iterative approximation method from the data of titration curves of various ratio of ligand to metal ion, pKa values of ligands, and hydrolysis constants of metal ions which were also determined by pH titration. The constants thus obtained for 1:1 complexes and chelates were plotted against the pKa values, and some interesting relationship suggesting the reaction mechanism of complex formation were found.

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*1 A part of this work was read at the 12th Symposium on Co-ordination Chemistry, Tokyo, 1962.