

Studies on Phthalein Complexone
Separation and Acid Equilibria of Phthalein Complexone
and Alkaline Earth Metal Complexes
with Phthalein Complexone

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Abstract

The purification of the metallochromic indicator Phthalein Complexone, the potentiometric investigation of the acid equilibria and the formation constants of alkaline earth metal complexes with PC are described. PC was purified with both a cellulose column and a precipitation method. The purity of the product was nearly 100%. The acid formation constants of PC and the metal chelate formation constants of four alkaline earth metals, Mg(II), Ca(II), Sr(II) and Ba(II), with PC have been calculated. These metals form four 1:1 complex species, MH_3L , MH_2L , MHL and ML , and two 2:1 complex species, M_2HL and M_2L , in an aqueous solution ($\mu=0.1$). The stability order for the ligand is $Mg(II) > Ca(II) > Sr(II) > Ba(II)$.

Introduction

Phthaleine Complexone, 3, 3'-bis-[*N*, *N'*-di(carboxymethyl)aminomethyl]-*o*-cresolphthalein, PC, was introduced and purified by Schwarzenbach.¹⁾ PC is the excellent metallochromic indicator especially for alkaline earth metals.^{2),3)} The acid formation constants of PC and the chelate formation constants of Mg (II), Ca (II) and Ba (II) complexes with PC have been already determined by Schwarzenbach.¹⁾ Although there have been a few reports⁴⁻⁶⁾ of the investigation of PC, the purity of the reagent have not been shown clearly. It is assumed that the mono-substituted product 3[*N*, *N'*-di(carboxymethyl)aminomethyl]-*o*-cresolphthalein may be contained in the product of PC like other metallochromic indicators such as XO⁷⁾ and MTB.⁸⁾

In this work, the purification carried out with both a cellulose column and a precipitation method. The purity of the product was nearly 100%. Using the pure PC, the acid formation constants and the formation constants of Mg (II), Ca (II), Sr (II) and Ba (II) complexes with PC were determined with better accuracy from the potentiometric data. The calculations were performed by the successive approximation method.

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Experimental

Reagents

A 0.1 M standard carbonate free hydroxide solution. A saturated solution of sodium hydroxide was set aside about for a week at a room temperature in a 500 ml Erlenmyer flask. The supernatant fluid was diluted with demineralized water free from carbonate to be 0.1 M solution. The resulting solution was stored in a 500 ml polyethylene bottle with sodalime tube to protect from the atmosphere. The sodium hydroxide solution was standardized by the volumetric titration with a standard solution of sulfuric acid.

The 0.01 M stock solutions of metal ions. The 0.01 M stock solutions of metal ions were prepared by dissolving the solid salts of the nitrate in water and standardized by the EDTA titration.

Synthesis of PC

PC was synthesized by the Mannich condensation.^{1),5),8)} Six grams of *o*-cresolphthalein and 9.7 g of iminodiacetic acid were dissolved sufficiently stirring in the mixed solvent consisting of 26 ml of methyl alcohol, 10 ml of pure water and 20 ml of 30% sodium hydroxide, and added 8.3 ml of 37% formaldehyde under cooling. The mixture was kept at 68°C through 8 hours stirring in the reflux condenser. The progress of the reaction was followed by the paper chromatography with *n*-butanol saturated with 15% ammonia water. R_f of the sodium salt of PC was 0.1, of the presumed mono-substituted compound, 0.45 and of the unreacted *o*-cresolphthalein, 0.95–1.0.

Separation and purification of PC

After the reaction, the solvent was distilled off under the reduced pressure. The residue, dissolved in a little of water, was placed on a cellulose column 30 mm in diameter and 100 mm long and eluted with the top layer of *n*-butanol saturated with 15% ammonia water. Three fractions were obtained as the result of this separation procedure: the first containing mainly *o*-cresolphthalein, the second presumed mono-substituted product and the third PC and sodium iminodiacetate. This separation of the cellulose column was repeated several times until the first and the second fraction band disappeared. The elute containing PC was excluded perfectly by repeating the distillation under the reduced pressure. The residue was dissolved in 100 ml of water, and added 5 M hydrochloric acid gradually until the pH value of the solution changed to about 7, simultaneously a deep purple of the solution vanished. Under cooling, the resulting solution was added 1 M hydrochloric acid drop by drop from the burette fully stirring. PC began to precipitate below pH 2.6, and was obtained maximum amount at pH 1.9. The precipitation was filtered with the NO. 4 glass filter, washed with the cooled water several times. The gained white

precipitation was dried in a vacuum desiccator to constant weight. The product was the free acid form of PC (mp 201–204°C (decomp.)). Found: C, 58.34%; H, 4.98%; N, 4.95%. Calcd for $C_{32}H_{32}O_{12}N_2 \cdot H_2O$: C, 58.71%; H, 5.24%; N, 4.28%.

Potentiometric measurements

A Toadenpa Model HM-8 pH meter was used to measure pH values. The titration vessel was 200 ml glass flask containing four necks sealed into the periphery to accommodate a Metrohm Model E-274 piston burette, glass and calomel electrodes, gas inlet and outlet. The potentiometric titration of hexa basic PC was carried out with the sodium hydroxide solution in the absence and the presence of alkaline earth metal at 1:2, 1:1 and 4:1 molar ratios of metal to ligand. The concentration of the ligand was approximately $1 \times 10^{-3}M$ and the volume of the experimental solution was 50 ml. The temperature of the solution was maintained at $25 \pm 0.1^\circ C$ by circulation of water thermostated at this temperature through outer jacket of the potentiometric vessel. The ionic strength was maintained at 0.1 by addition of potassium nitrate to the solution. All experiments were performed under the nitrogen atmosphere.

Calculation

Acid formation constants of PC

The acid formation constant is more suitable than the acid dissociation constant for discussion over a wide pH range. The constants are calculated by the same methods as the previous work.⁷⁾

Formation constants of the complexes

The calculations of the various equilibrium constants for the alkaline earth metal complexes with PC were carried out in two parts. Recognizing that only the 1:1 complex species exist in a 1:1 curve and 2:1 complex can be negligible, a successive approximation method was employed to determine the values of the formation constants of the 1:1 complexes. These constants were then used to calculate the formation constants of the 2:1 complexes. The equations can be derived by modifying Schwarzenbach's⁹⁾ and Martell's.^{10),11)} In the mathematical treatment of data, the symbols used are the following: T_M = total analytical concentration of ligand in all forms; T_L = total analytical concentration of metal ion in all forms; a = number of moles of base added per mole of ligand; k_i = acid formation constant of ligand, $k_i = [H_iL]/[H_{i-1}L][H]$; $K_{MH_iL_j}^M$ = formation constant of complex, $K_{MH_iL_j}^M = [M_iH_jL]/[M][M_{i-1}H_jL]$; $K_{M_iH_jL}^H$ = acid formation constant of complex, $K_{M_iH_jL}^H = [M_iH_jL]/[M_iH_{j-1}L][H]$.

Formation constants of 1:1 complexes. For system of ligand H_6L and metal ion M , where complexes MH_iL ($i=0, 1, \dots, N$) are formed, equations describing the total analytical concentration of ligand, total metal ion concentration and

electroneutrality can be written as follows.

$$T_L = \sum_{i=0}^6 [\text{H}_i\text{L}] + \sum_{i=0}^N [\text{MH}_i\text{L}] \quad (1)$$

$$T_M = [\text{M}] + \sum_{i=0}^N [\text{MH}_i\text{L}] \quad (2)$$

$$(6-a)T_L = [\text{H}] - [\text{OH}] + \sum_{i=1}^6 i[\text{H}_i\text{L}] + \sum_{i=1}^N i[\text{MH}_i\text{L}] \quad (3)$$

Equations (1), (2) and (3) are written with the terms $[\text{MH}_n\text{L}]$, $[\text{H}_n\text{L}]$ and $[\text{M}]$ as follows.

$$T_L = A_n[\text{H}_n\text{L}] + B_n[\text{MH}_n\text{L}] \quad (4)$$

$$T_M = [\text{M}] + B_n[\text{MH}_n\text{L}] \quad (5)$$

$$T_H = C_n[\text{H}_n\text{L}] + D_n[\text{MH}_n\text{L}] \quad (6)$$

where

$$A_n = \sum_{i=0}^6 [\text{H}]^i K_i / [\text{H}]^n K_n, \quad B_n = \sum_{i=0}^N [\text{H}]^i K_i^1 / [\text{H}]^n K_n^1$$

$$C_n = \sum_{i=1}^6 i[\text{H}]^i K_i / [\text{H}]^n K_n, \quad D_n = \sum_{i=0}^N i[\text{H}]^i K_i^1 / [\text{H}]^n K_n^1$$

$$T_H = (6-a)T_L - [\text{H}] + [\text{OH}], \quad K_i = k_1 k_2 \cdots k_i \quad (K_0 = 1)$$

$$K_i^1 = K_{\text{MHL}}^{\text{H}} K_{\text{MH}_2\text{L}}^{\text{H}} \cdots K_{\text{MH}_i\text{L}}^{\text{H}} \quad (K_0^1 = 1).$$

Equations (4), (5) and (6) can be solved simultaneously for the quantities $[\text{MH}_n\text{L}]$, $[\text{H}_n\text{L}]$ and $[\text{M}]$, and the formation constant of the complex MH_nL are given by equation (7).

$$K_{\text{MH}_n\text{L}}^{\text{M}} = \frac{[\text{MH}_n\text{L}]}{[\text{M}][\text{H}_n\text{L}]} = \frac{(B_n C_n - A_n D_n)(C_n T_L - A_n T_H)}{(B_n T_H - D_n T_L)(A_n B_n T_H + B_n C_n T_M - A_n D_n T_M - B_n C_n T_L)} \quad (7)$$

The value for $K_{\text{MH}_n\text{L}}^{\text{M}}$ was obtained by means of successive approximation. Equation (7) involves N acid formation constants of complexes, $K_{\text{MH}_i\text{L}}^{\text{M}}$ ($i = 1, 2, \dots, N$). For a set of some assumed values for $K_{\text{MH}_i\text{L}}^{\text{H}}$, corresponding value for $K_{\text{MH}_n\text{L}}^{\text{M}}$ was calculated at any point along the titration curve in a certain range of a values where the complex MH_nL assumed to predominate. The value for constant $K_{\text{MH}_n\text{L}}^{\text{M}}$ was determined when the deviation of any $K_{\text{MH}_i\text{L}}^{\text{M}}$ value at the points along the curve was most minimized for the set of the unique values for $K_{\text{MH}_i\text{L}}^{\text{H}}$.

Formation constants of 2:1 complexes. For system of ligand H_6L and metal ion M , where the 1:1 complex MH_iL ($i=0, 1, \dots, N$) and the 2:1 complex M_2H_iL ($i=0, 1, \dots, M$) are formed, equations describing the analytical concentration of ligand, metal ion concentration and electroneutrality can be written as follows.

$$T_L = \sum_{i=0}^6 [H_iL] + \sum_{i=0}^N [MH_iL] + \sum_{i=0}^M [M_2H_iL] \quad (8)$$

$$T_M = [M] + \sum_{i=0}^N [MH_iL] + 2 \sum_{i=0}^M [M_2H_iL] \quad (9)$$

$$(6-a)T_L = [H] - [OH] + \sum_{i=1}^6 [H_iL] + \sum_{i=1}^N [MH_iL] + \sum_{i=1}^M [M_2H_iL] \quad (10)$$

Equations (8), (9) and (10) are written with the terms $[M]$, $[MH_nL]$ and $[M_2H_nL]$ as follows.

$$T_L = U_n[MH_nL]/[M] + V_n[MH_nL] + W_n[M_2H_nL] \quad (11)$$

$$T_M = [M] + V_n[MH_nL] + 2W_n[M_2H_nL] \quad (12)$$

$$T_H = X_n[MH_nL]/[M] + Y_n[MH_nL] + Z_n[M_2H_nL] \quad (13)$$

where

$$U_n = \sum_{i=0}^6 [H]^i K_i / [H]^n K_n K_{M_2H_nL}^M, \quad V_n = \sum_{i=0}^N [H]^i K_i^1 / [H]^n K_n^1$$

$$W_n = \sum_{i=0}^M [H]^i K_i^2 / [H]^n K_n^2, \quad X_n = \sum_{i=1}^6 i [H]^i K_i / [H]^n K_n K_{M_2H_nL}^M$$

$$Y_n = \sum_{i=1}^N i [H]^i K_n^1 / [H]^n K_n^1, \quad Z_n = \sum_{i=1}^M i [H]^i K_n^2$$

$$K_i^2 = K_{M_2HL}^H K_{M_2H_2L}^H \dots K_{M_2H_iL}^H (K_0^2 = 1).$$

Simultaneous equations (11), (12) and (13) may be solved in usual way for the quantities $[M]$, $[MH_nL]$ and $[M_2H_nL]$, and the successive formation constant of the complex M_2H_nL is given by equation (14).

$$K_{M_2H_nL}^M = \frac{[M_2H_nL]}{[M][MH_nL]} \quad (14)$$

The value for $K_{M_2H_nL}^M$ was obtained by the same successive approximation method as that the formation constant of the 1:1 complex was determined. The value for the constant $K_{M_2H_nL}^M$ was determined when the deviation of any $K_{M_2H_nL}^M$ value at the points along the curve in a certain range of a values where the complex M_2H_nL assumed to be formed, was most minimized for the set of the unique values for $K_{M_2H_iL}^H$ ($i=1, 2, \dots, M$).

Results and Discussion

The purification of PC

The removal of the mono-substituted compound, Semi-PC, from impure PC is difficult by means of recrystallization. *o*-Cresolphthalein and Semi-PC

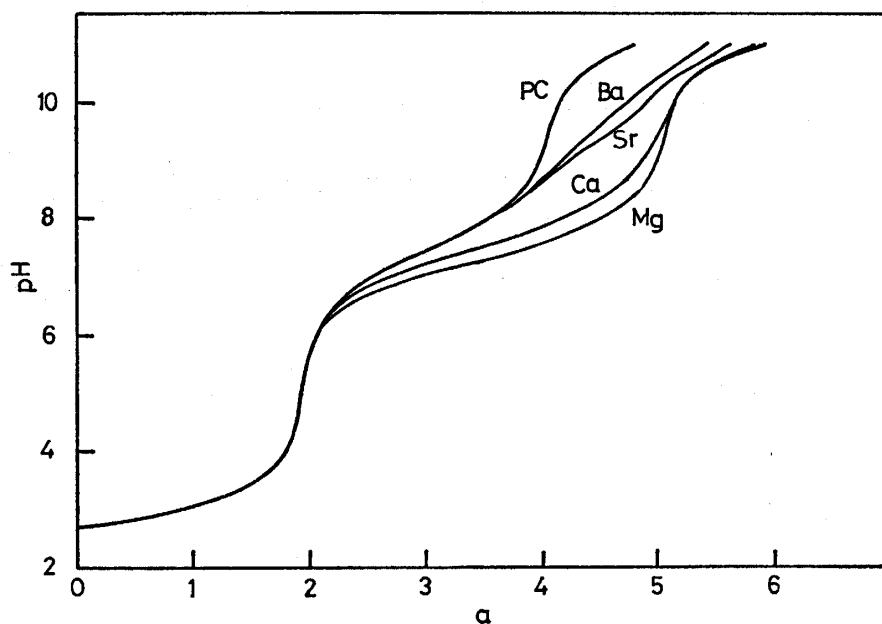


Fig. 1. Potentiometric titration curves for PC only and for 1:1 molar ratios of metal ions to PC at 25°C in 0.1M KNO₃, *a*— moles of base added per mole of ligand, $T_M=1 \times 10^{-3}M$, $T_L=1 \times 10^{-3}M$.

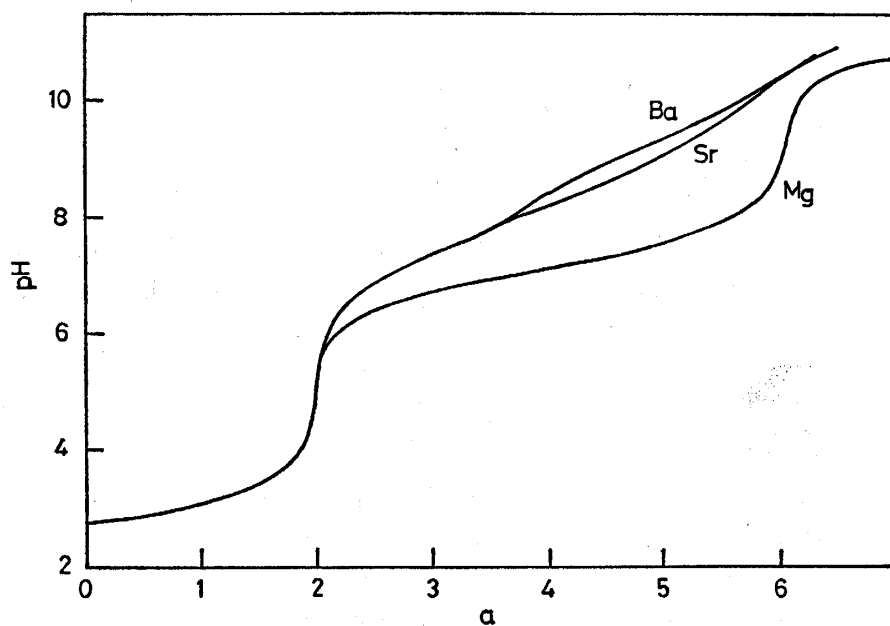


Fig. 2. Potentiometric titration curves for 4:1 molar ratios of metal ions to PC at 25°C in 0.1M KNO₃, *a*— moles of base added per mole of ligand, $T_M=4 \times 10^{-3}M$, $T_M=1 \times 10^{-3}M$.

were separated on a cellulose column from the sodium salts of PC, and PC and iminodiacetic acid were separated by the precipitation method. The purity of the product was established by elemental analysis, potentiometric titration, paper chromatography and NMR spectrum.

The acid equilibria and acid formation constants of PC

The potentiometric titration curve of PC is shown in Fig. 1. The curve shows the acid form of PC to be H_6L as might be expected. Since there are well-defined inflection points and no overlapping of the buffer regions, equilibria of acid species existing in a buffer region might be neglected in the other regions. Each equilibrium formation constant in a buffer region was calculated separately from the other regions.

Between $a=0$ and $a=2$, two protons per ligand molecule dissociate, and $\log k_6$ and $\log k_5$ were calculated. The values are similar to that of the carboxyl group of iminodiacetic acid, indicating two protons dissociation from position 1 and 2 of ligand form I in Fig. 3. At middle pH, two protons dissociate between

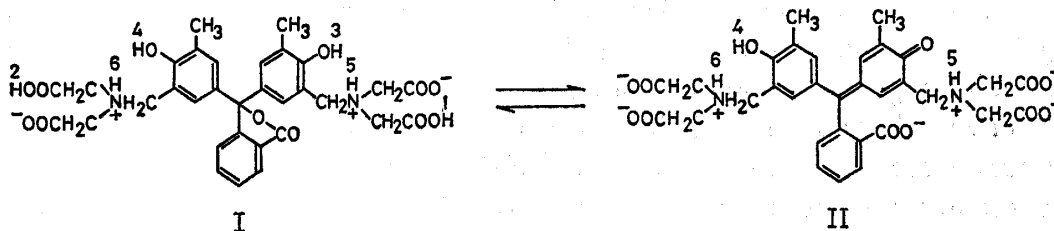


Fig. 3.

$a=2$ and $a=4$, accompanied by the color change from colorless to deep purple. The reaction involves the dissociation of the protons 3 and 4 of the hydroxyl

Table 1. Acid formation constants of PC at 25°C, $\mu=0.1(KNO_3)$

Equilibrium constants	Log of equilibrium constants for PC, H_6L
$k_1 = \frac{[HL]}{[H][L]}$	12.12
$k_2 = \frac{[H_2L]}{[H][HL]}$	11.30
$k_3 = \frac{[H_3L]}{[H][H_2L]}$	7.84
$k_4 = \frac{[H_4L]}{[H][H_3L]}$	7.12
$k_5 = \frac{[H_5L]}{[H][H_4L]}$	3.02
$k_6 = \frac{[H_6L]}{[H][H_5L]}$	2.31

group, and PC converts to form II from form I. For these equilibria, $\log k_4$ and $\log k_3$ were calculated. Above $a=4$, two more protons dissociate, and $\log k_2$ and $\log k_1$ were calculated. Values of $\log k_2$ and $\log k_1$ are similar to that of amino proton of iminodiacetic acid, so that these dissociation correspond to protons in position 5 and 6. The acid formation constants calculated are listed in Table 1. The equilibrium constants of PC obtained by Schwarzenbach are slightly different from ours but similar only to $\log k_1$. These constants are based on the protonation of the carboxyl and amino groups. This shows that their sample might have contained a small amount of iminodiacetic acid and Semi-PC.

The formation constants of alkaline earth metal complexes with PC

Equilibrium potentiometric titration curves for 1:1 and 4:1 molar ratios of Mg (II), Ca (II), Sr (II) and Ba (II) to PC are presented in Figs. 1 and 2. In all cases, curves are quite identical to that of ligand alone between $a=0$ and $a=2$. This exhibits alkaline earth metals do not form chelate compound with form I of PC. The positions of the potentiometric curves indicate the following relative stabilities; Mg (II) > Ca (II) > Sr (II) > Ba (II).

The 1:1 curves for Mg (II) and Ca (II) are almost similar, consisting of a long buffer region at the middle pH terminated by a sharp inflection at $a=5$ and indicating the reasonably stable protonated metal chelate species. In the cases of Sr (II) and Ba (II), there are not clearly visible inflection at high pH, and curves are almost identical to that of ligand alone up to $a=4$. It turns out that it is necessary to assume the formation of three protonated species MH_3L^- , MH_2L^{2-} , MHL^{3-} and a single complex ML^{4-} in order to calculate the equilibrium constants from experimental data.

When 4 moles of metal per ligand is present in a solution, the titration curves parallels that of the corresponding 1:1 mole ratio and all of the available protons of the ligand are neutralized in a single step with the formation of binuclear chelates. It is assumed that two 2:1 complex species M_2HL^- and M_2L^{2-} are formed.

Table 2. Formation constants of Mg(II), Ca(II), Sr(II) and Ba(II) complexes with PC at 25°C, $\mu=0.1(KNO_3)$

	Mg	Ca	Sr	Ba
$\log K_{ML}^M$	7.75	7.15	5.39	4.92
$\log K_{MHL}^M$	7.24	6.41	4.91	4.21
$\log K_{MH_2L}^M$	3.30	2.73	2.09	1.86
$\log K_{MH_3L}^M$	2.06	2.19	1.85	1.49
$\log K_{MHL}^H$	11.51	11.38	11.64	11.61
$\log K_{MH_2L}^H$	7.36	7.60	8.48	8.95
$\log K_{MH_3L}^H$	6.60	7.30	7.60	7.48
$\log K_{M_2L}^M$	6.3		4.4	4.3
$\log K_{M_2HL}^M$	1.48		3.4	2.5
$\log K_{M_2HL}^H$	6.7		9.61	9.76

Table 3. Formation constant $K_{\text{MH}_3\text{L}}^{\text{M}}$ values at points along titration curve

Assumed $K_{\text{MH}_2\text{L}}^{\text{H}}$ value: $\log K_{\text{MH}_3\text{L}}^{\text{H}}=6.60$; $\log K_{\text{MH}_2\text{L}}^{\text{H}}=7.36$; $\log K_{\text{MHL}}^{\text{H}}=11.51$.
 $T_{\text{M}}=1.99 \times 10^{-3}\text{M}$, $T_{\text{L}}=1.02 \times 10^{-3}\text{M}$.

pH	$\log K_{\text{MH}_3\text{L}}^{\text{M}}$
6.696	2.059
6.805	2.060
6.904	2.068
6.995	2.066
7.093	2.067
7.191	2.065
7.287	2.060
7.381	2.061
7.480	2.056
7.581	2.067
7.691	2.062
av. 2.062 ± 0.006	

Table 4. Formation constant $K_{\text{M}_2\text{HL}}^{\text{M}}$ values at points along titration curve

Assumed $K_{\text{M}_2\text{HL}}^{\text{H}}$ value=6.7.
 $T_{\text{M}}=3.98 \times 10^{-3}\text{M}$, $T_{\text{L}}=9.89 \times 10^{-4}\text{M}$.

pH	$\log K_{\text{M}_2\text{HL}}^{\text{M}}$
7.660	1.461
7.759	1.470
7.858	1.486
7.961	1.500
8.057	1.490
8.300	1.496
8.390	1.492
8.505	1.480
8.649	1.468
8.739	1.461
av. 1.48 ± 0.02	

The formation constants of the complexes stated above were calculated and listed in Table 2. Tables 3 and 4 show the results of the successive approximation method for constants $K_{\text{MH}_3\text{L}}^{\text{M}}$ and $K_{\text{M}_2\text{HL}}^{\text{M}}$ of Mg (II) complexes. The relative stabilities of each complex species are similar to the assumption from the titration curves. The steric consideration leads to the assumption that in a complex ML^{4-} , metal cation combines with iminodiacetate group and phenolate oxygen and the protons of the complexes MHL^{3-} and MH_2L^{2-} are bound to nitrogen of iminodiacetate. In a triprotonated complex MH_3L^- , it is obvious three protons

are implied to phenolate group and nitrogen of iminodiacetate groups. Binuclear complex M_2HL^- may be formed by dissociation of proton from one of the protons bound to nitrogen of iminodiacetate groups in a complex MH_2L^{2-} .

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