



The Equilibrium Chemistry of Chelate Compounds in Aqueous Medium Analyzed with the help of SCOGS and ORIGIN

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Abstract

Solution study of chelate compounds of 2-Amino-3-(4-hydroxyphenyl) propanoic acid (2-AHPPA) and 5-methyluracil (5-MU) with bivalent heavy metal ions Cd (II) and Pb (II) have been completed potentiometrically at a fixed ionic strength $I = 0.1M NaNO_3$ and $37 \pm 1^\circ C$ temperature at silver-silver chloride electrode in biologically relevant conditions. The analysis of stability constant ($\log \beta_{pqrs}$) and stability order of investigated metal chelates were done by a specific computer programme SCOGS. The ORIGIN 4.0 deduced the formation of various metal chelate species by sketching the speciation curves for all species separately.

Keywords: Stability Constants, Metal Chelates, SCOGS and Speciation Curves

Introduction

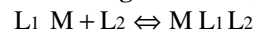
The study in aqueous medium has kinetic as well as thermodynamic aspects. In these investigations, the kinetic aspects refers to the speed of a complex species transformation leading to the attainment of the equilibrium while the thermodynamic aspects concern with the extent to which this species will form or be transformed into another species. Under certain conditions, when the system has attained equilibrium the work is reported in the field of equilibrium chemistry. Evaluation of the solution properties which changes as a result of simply chelate formation said to have chelation or complexation can give information of the stability and existence of different species. Chelates are the results of the sharing of electrons between a metal and a ligand and were used to designate such cyclic structures which arise from the union of metallic ions with organic or inorganic ligands. An immense amount of equilibrium data is available in different volumes published by Martell and Smith¹⁻³. Akhtar Shazia, Iram Shazia and Ul Hassan Mahmood reported effect of chelating agents on heavy metal extraction⁴. The chelation plays a vital role in cure of cancer and many other fields⁵⁻⁷. We know that insoluble compounds as well as the metallic forms often exhibit negligible toxicity and this is possible by the aid of suitable chelating agents. The 2- Amino-3-(4-hydroxyphenyl) propanoic acid (2-AHPPA) is a non-essential amino acid with a polar side group having the condons UAC and UAU. It is a precursor to neurotransmitters, increases plasma neurotransmitter levels and for various industrial and pharmaceutical applications. A number of studies have found that it would be useful during conditions of stress, cold, fatigue loss of a loved one such as in death or divorce, prolonged work and sleep deprivation⁸. 5-methyluracil is one of the four nucleobases in the nucleic acid of DNA found in all eukaryotic and prokaryotic cells as a part of DNA to flow of genetic information (excepting in RNA

viruses). It could also be a target for actions of 5-fluorouracil (5-FU) in cancer treatment. 5-FU can be a metabolic analog of 5-methyluracil (in DNA synthesis) or 2,4-dihydroxypyrimidine (in RNA synthesis).

Material and Methods

It is the fact to know, when any specified kind of metal ion interacted with any specified kind of ligands the relative and absolute concentration of all the kinds of ligands were totally responsible. The relevant formation constant or stability constants ($\log \beta$) and pH of the solution also responsible for complex formation through metal – ligand interaction. Formation of complex in solution proceeds by the stepwise addition of the ligands to the metal ion, a number of successive equilibria can be formulated. The formation of ternary and quaternary complexes may takes place as:

Mixed - ligand ternary systems: $L_1 + M + L_2 \rightleftharpoons M L_1 L_2$



Overall stability constant ($\log \beta$) is given as:

$$\beta_{ML_1L_2} = \frac{[ML_1L_2]}{[L_1][M][L_2]} \quad (1)$$

$$\beta_{ML_1L_2} = \frac{[ML_1L_2]}{[L_1M][L_2]} \quad (2)$$

Multi metal-multi ligand quaternary systems completed in two ways: $L_1 M_1 L_2 + M_2 \rightleftharpoons M_1 M_2 L_1 L_2$

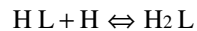
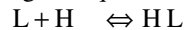


Now the overall stability constant ($\log \beta$) will be given as:

$$\beta_{M_1M_2L_1L_2} = \frac{[M_1M_2L_1L_2]}{[L_1M_1L_2][M_2]} \quad (3)$$

$$\beta_{M_1M_2L_1L_2} = \frac{[M_1M_2L_1L_2]}{[L_1][M_1][L_2][M_2]} \quad (4)$$

The protonation of the ligand L may consider following proton ligand equilibria:



Finally overall proton ligand stability constant β_3^H , is determined as:

$$\beta_3^H = \frac{[H_3L]}{[H_2L][H]} \quad (5)$$

pH- Metric Titration: This paper concerned with the study of equilibrium chemistry of mixed - ligand ternary and multi metal-multi ligand quaternary chelates by potentiometric technique of analysis in aqueous medium using Bjerrum's method modified by Irving and Rossotti⁹⁻¹¹. Here we studied the formation of complexes through metal - ligand interaction of Cd (II) and Pb(II) metal ions with 2-Amino-3-(4-hydroxyphenyl) propanoic acid (2-AHPPA) used as primary ligand (A) and 5-methyluracil (5-MU) used as secondary ligand (B). The pH measurements were done by an electric digital pH meter (Eutech 501) having reproducibility of ± 0.01 pH and calibrated with (4.0) and (9.2) pH buffer solutions working on 220V/50 cycles. An ultra thermostat type U₁₀ (VEB MLW Sitz, Freital, Germany) was used to maintain a constant temperature and SONAR magnetic stirrer 2 MLH was used for constant stirring of the solution mixtures throughout the experiment. All the metal salts used were of A R Grade and were standardized volumetrically by titration with the disodium salt of EDTA¹². The following solution mixtures were prepared in double distilled water for analytical study and were titrated against a carbonate free sodium hydroxide solution until the solution becomes turbid.

Acid Solution: 5 ml NaNO₃ (1.0 M) + 5ml HNO₃ (0.02M) + 40 ml water.

Ligand Solution: 5ml NaNO₃ (1.0M) + 5ml HNO₃ (0.02M) + 5ml A (2-AHPPA) / B (5-MU) (0.01M) + 35 ml. water.

Binary system(1: 1) (M: A) / (M: B): 5 ml NaNO₃ (1.0 M) + 5ml HNO₃ (0.02M) + 5ml A (2-AHPPA) / B (5-MU) (0.01M) + 5 ml M (II) (0.01M) Cd (II) / Pb (II) + 30 ml water.

Mixed ligand ternary system (1: 1: 1) (M:A: B) : 5 ml NaNO₃ (1.0 M) + 5ml HNO₃ (0.02M) + 5ml A (2-AHPPA) (0.01M) + 5 ml M (II) (0.01M) Cd(II) / Pb(II) + 5 ml B (0.01M) (5-MU) + 25 ml water.

Multi metal – multi ligands quaternary system (1: 1: 1: 1) (M₁: M₂: A: B): 5 ml NaNO₃ (1.0 M) + 5ml HNO₃ (0.02M) + 5ml A (0.01M) (2-AHPPA) + 5 ml M₁ (II) (0.01M) Cd (II) + 5ml B (0.01M) (5-MU) + 5ml M₂ (II) (0.01M) Pb (II) + 20 ml water

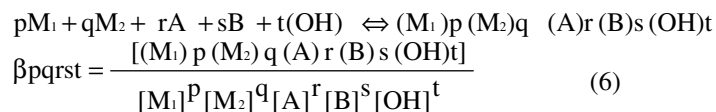
The equilibrium constants of complexes were evaluated by

using SCOGS similar to those as described in our earlier research articles¹³⁻¹⁶. Chaudhary Rakhi and Shelly reported synthesis spectral and pharmacological study of Cu (II), Ni (II), Co (II) coordination complexes¹⁷. Gazala Mohamed reported ternary complexes of cobalt (II) involving NTA and some biologically active ligands¹⁸. Shaesta Quyoomb reported the studies of some mixed ligand ternary complexes of N acetyl cysteine with Zn (II) and Ni (II) metal ions¹⁹. Mrinalini L. and A.K. Manihar Singh reported mixed ligands Co (II) complexes study²⁰. Butturs N.H. and Mohamed S.M studied the Ni²⁺ Cu²⁺ Zn²⁺ complexes with benzoxazole-2- thionate, diphenyl phosphinomethane and iodine²¹.

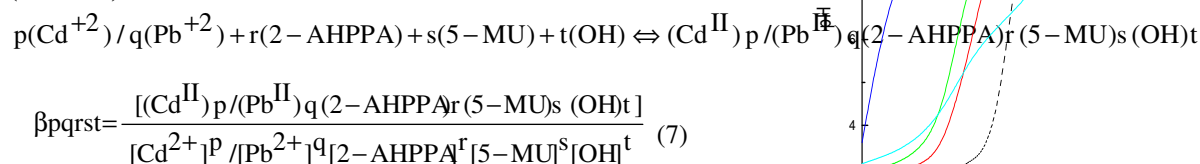
Calculation of Formation or Stability Constant: The importance of Irving and Rossotti's method lies in fact that the same set of experiments were utilized for the evaluation of acid dissociation constants (protonation constants) of the ligand and stability constant or formation constant of the complexes. To start with, firstly we determined the stability constants of binary system under our present experimental conditions and match it with literature values then we proceed for ternary and quaternary systems. Various computer programs for the treatment of equilibria in aqueous medium have been developed for calculating the stability constants of metal complexes, from pH titration data. Anderegg published a program that could deal with protonated, hydrolysed or polynuclear metal complexes, hydrolysed metal ions and protonated ligands. The program MINQUAD has been used to evaluate formation constants of species in solution equilibria from data obtained only by potentiometric titration. I.G.Sayce developed a new computer program named as SCOGS (Stability constant of generalized species) which employs the conventional non linear least square approach²²⁻²⁴. The program is written in FORTRAN IV. It is capable of calculating simultaneously or individually, association constants for any of the species formed in the system containing up to two metals and two ligands, provided that the degree of complex formation is pH-dependent. Thus, SCOGS may be utilized to analyse appropriate pH titration data to yield metal-ion hydrolytic constants, stability constants of simple complexes (MA, MB and MA₂ etc.). SCOGS may also be used to calculate constants for "mixed" complexes containing two different metals and two different ligands resulting the formation of MAB and M₁M₂ AB types of complexes. The main program deals with input of data, the setting up and solution of the least-squares equations and output of the results and used successfully in the refinement of ternary and quaternary system's data studied in the present work.

Results and Discussion

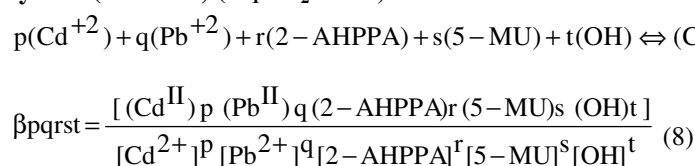
The above mentioned computer program SCOGS (Stability constant of generalized species) was used in the analysis of all binary, ternary and quaternary chelates. The overall stability constant (β_{pqrst}) of above chelates were evaluated with program as suggested by Sayce.



**Stability constant for mixed- ligand ternary system (1: 1: 1)
(M: A: B)**



Stability constant for multi metal –multi ligands quaternary system (1: 1: 1: 1) (M₁: M₂: A: B)



In above equation the p, q, r and s are either the zero or positive integer and t is a negative integer for a protonated species like H₃A, H₂A, HA and BH, positive integer for a hydroxo or a deprotonated species like [M(OH)⁺], [M(OH)₂] and zero for a neutral or normal species like [M A], [M B] and [M A B] and [M₁M₂ A B] etc.

Potentiometric Titration Curve: The pH titration curves for the binary, ternary and quaternary complexes were drawn by plotting pH Vs volume of alkali. A representative pH titration curves for the studied quaternary system given in figure. 1 which shows the binary, ternary and quaternary complexes by individual lines.

Speciation Curves: The speciation curves were obtained by plotting percent (%) concentration of the species obtained through SCOGS computer programme against pH. The pH titration curves and speciation curves are finally sketched by running the computer program ORIGIN 4.0. The detailed study of speciation curve of Pb AB ternary system and Cd Pb AB quaternary system is given here

Pb (II) - 2-AHPPA (A)- 5- MU (B) Ternary System: The species distribution curve figure.2 stated that protonated ligand species H₃A, H₂A and BH shows their remarkable presence. The binary complex of Pb B exist in good concentration ~ 98% at start of the titration and gradually decreases with increase in pH range while Pb A in very lower amount ~ 10 % at higher pH ~ 7.0. Ternary complex of Pb A B exist with higher value attaining maximum concentration ~ 98 % at higher pH ~ 9.5. The hydroxo species Pb(OH)₂ also seen in this system in good concentration. Formation of ternary complex follows the equilibria given as: Step wise process:

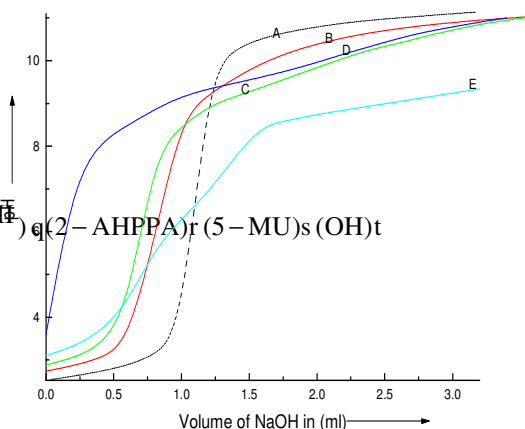


Figure-1
Titration Curves of 1:1:1:1 Cd(II)-Pb(II)- 2-AHPPA (A) -5-MU(B) system (A) Acid (B) Ligand (C) Cd (II)-2-AHPPA(D) Cd(II)- 2-AHPPA- 5-MU (E) Cd(II) -Pb(II)- 2-AHPPA - 5-MU

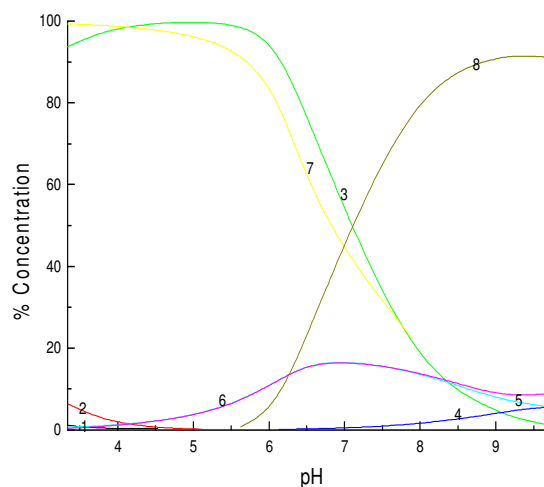
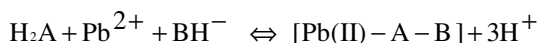
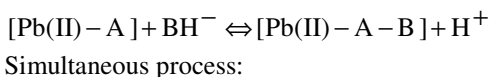
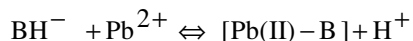
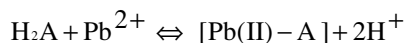


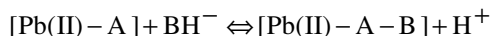
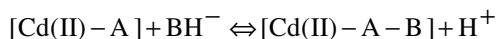
Figure-2
Speciation Curves of 1:1:1 Pb (II)-2-AHPPA (A)-5-MU (B) System Pb²⁺ (2) H₃A (3) H₂A (4) BH (5) Pb (OH)₂ (6) Pb A (7) Pb B (8) Pb AB

Cd (II) Pb (II) - 2-AHPPA (A)- 5- MU (B) Quaternary System: The distribution diagram or speciation curve for present system is represented in figure.3. in which Cd²⁺, Pb²⁺, H₃A, H₂A, HA, Cd(OH)₂, Cd(OH)⁺, Pb(OH)₂, PbA, Pb B, Cd AB, Pb AB and Cd Pb AB species existed. It is clearly evident from species distribution diagram that the protonated ligand species H₃A, H₂A, HA are found to be in decreasing manner with increase in pH range. H₂A attain the maximum concentration ~97% at start

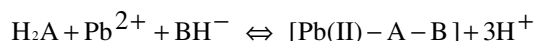
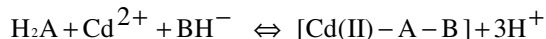
of titration and goes till ~ 5.5 pH, after then it gradually decreases as the pH raised and other ligand species also follows the decline trend to increase in pH. The coordination of both the metal ions with the protonated ligand species may be concluded on the basis of appearance and gradual increase in binary, ternary and quaternary complex species. The free metal ion Cd^{2+} attains the maximum concentration ~90% at the very start of titration which decreases with increase in pH. Binary complex of Pb A have lower amount but Pb B complex attain the maximum concentration ~91% at the very start of titration showing decline pattern that of increase in pH. Cd A and Cd B shows their no existence. The binary complexes show their remarkable presence according to following equilibria:



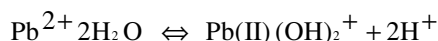
Ternary complexes of Cd AB existed with maximum concentration ~6.0% at the ~ 9.4 pH while the PbAB existed with maximum concentration ~18% at the ~ 9.3 pH. The formation of both ternary complexes takes place in two ways, stepwise and simultaneous. In stepwise complex formation at first it undergoes to binary complexation and then goes for ternary complexation according to following equilibria:



When the complex formation takes place simultaneously then it may be explained as per equilibria:

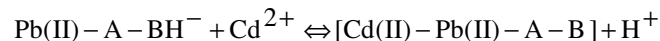
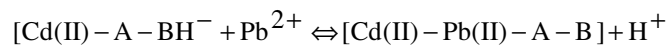


Hydroxo species Cd $(OH)_2$ shows very well existence in this system having maximum concentration ~32% at the ~ 9.5 pH. Other hydroxo species existed with trace amount and their formation can be understood according to given equilibria:



The quaternary complex of Cd Pb AB attains the maximum concentration ~83% at the ~ 8.2 pH. The formation of this multi - metal multi - ligand quaternary complex start at ~ 5.3 pH which gradually increases with increase in pH value and goes to ~ 8.2pH attaining the maximum concentration ~83.% which is the major species. Here both the ternary complexes Cd AB and Pb AB gradually decreases as the pH raised and their presence provide the environment to more involvement in the formation of quaternary complex species. This formation may takes place in two ways, stepwise formation of mixed - ligand ternary complex and then addition of bivalent metal ions M_2

according to following equilibrium:



Another way of formation of Cd Pb AB complex is simultaneous way where addition is in the $L_1 + M_1 + L_2 + M_2$ manner and follow the following equilibrium:

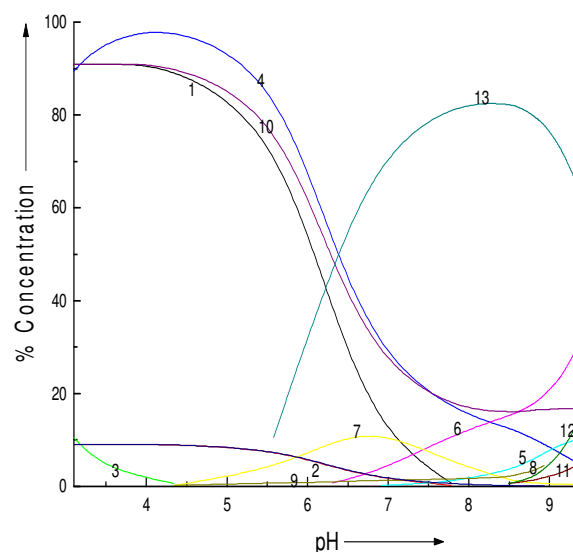
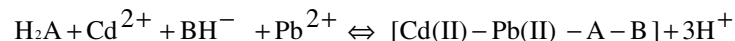


Figure. 3
Speciation Curves of 1:1:1:1Cd (II) - Pb (II)-2-AHPPA (A)-5-MU(B) System Cd²⁺ (2) Pb²⁺ (3) H₃A (4) H₂A (5) HA (6) Cd (OH)₂ (7) Cd(OH)⁺ (8) Pb(OH)₂ (9) Pb A (10) Pb B (11) Cd AB (12) Pb A B (13) Cd Pb AB

Table-1
Overall Stability Constants (Log β_{pqrst}) of Investigated Complexes

Proton-ligand formation constant (log β_{00r0t}/ log β_{000st}) of 2-AHPPA - 5-MU at 37 ± 1°C I = 0.1 NaNO₃

Complex	log β _{00r0t} / log β _{000st}
H ₃ A	21.35
H ₂ A	19.18
HA	10.14
BH	9.94

Hydrolytic constants (log β_{p000t}/ log β_{0q00t}) M²⁺ (aq.) ions

Complex	Cd	Pb
M(OH) ⁺	-6.89	-9.84
M(OH) ₂	-14.35	-15.54

Metal-Ligand constants ($\log\beta_{p0r00}/\log\beta_{0qr00}/\log\beta_{p00s0}/\log\beta_{0q0s0}$)
Binary System

Complex	Cd	Pb
MA	3.57	4.14
MB	11.33	13.33

Metal-Ligand constants ($\log\beta_{p0rs0}/\log\beta_{0qrs0}$): Ternary System
(1:1:1)

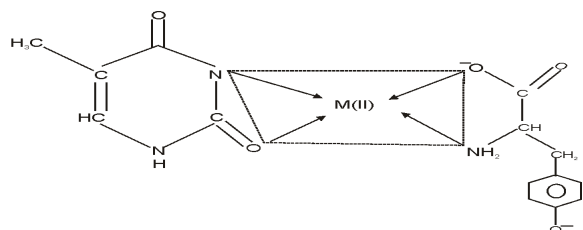
Complex	Cd	Pb
MAB	16.95	17.05

Metal-Ligand constants ($\log\beta_{pqrst}$): Quaternary System (1:1:1:1)

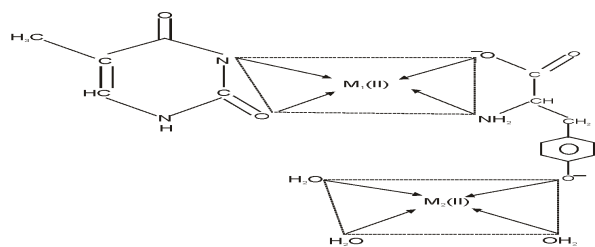
Complex	Cd-Pb
$M_1 - M_2 - A - B$	26.62

Stability Order of Complex Species: Cd (II) -2-AHPPA (A) - 5-MU (B) > Pb (II)- 2-AHPPA (A) - 5-MU (B) > Cd (II)-2-AHPPA (A) - 5-MU (B) > Pb (II) 5-MU (B) > Cd (II)-5-MU (B) > Pb (II) - 2-AHPPA (A) > Cd (II)-2-AHPPA (A)

Proposed Structure of Investigated Complexes



Scheme - 1
M (II)-2- AHPPA-5-MU



Scheme - 2
M₁(II) . M₂ (II)-2- AHPPA - 5- MU

Conclusion

It is very well clear that the present work provides an effective and accurate method for the study of equilibrium chemistry of binary, ternary and quaternary metal chelates having a great importance in human life. The metals form a large number of coordination compounds in which the electron donating anions or neutral molecules bind single metal ion and form a heterocyclic ring structure, it is said to be a chelating ligand and the complex compound formed as the results of the sharing of

electrons between metal and ligand termed as metal chelate having high stability which can be explained on the basis of increased number of fused rings and the extra stabilization caused by ligand-ligand interactions. The chelating ligand must be of low toxicity and not metabolized so as to persist on changes in the biological system to perform their scavenging functions due to their interaction with metal ions to form metal chelates or dislodging the bound metals and excreting these as soluble chelates from the system. The $\log\beta$ values of complexes depend on the denticities of both ligands and coordination number of metal ions. The program SCOGS used in this study concern with the input of data, their setting up and solution of the least-squares equations and output of the results and finally provide exact stability constant value of chelate compounds and their exact stability order which is essential for understanding of various vexed problems of biological and chemical sciences.

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