Qualitative analysis of elements important in terms of biology and toxicology

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1. Introduction

Medicine branches use many analytical methods in the specialized laboratories (clinical biochemistry, molecular biology et al.).

Chemical analysis is a series of operations, which are carried out with analysed (tested) material, to discover:

1. Its chemical composition – **qualitative analysis**, proofs of particular components (elements)
2. Amount of particular components – **quantitative analysis**

Qualitative analysis nearly always goes before quantitative analysis. Average sample is taken away from tested material. This sample is assessed by preliminary analysis in dry way for (appearance (design), colour of sample, behaviour during pyroreaction - flame annealing, colouration of flame et al.) and wet way (proof of chemical compounds in water solutions).

Almost all of inorganic compounds in water solutions dissociate to ions – positively charged cations and negatively charged anions. Precipitate analytical reactions are often used for proofs of particular ions (cations, or anions) in solutions. These reactions are binary replacement (conversion) of ions during rise of slightly soluble product of given ionic compound, white or colour precipitate. The other ions remain almost without change in mother solution above precipitate. Slightly soluble ionic compounds are not absolutely insoluble in water; rather, there are only quantitative differences in their solubilities, which however can be very high. Detailed values of solubility of inorganic compounds are shown in literature, in many chemicals tables. Examples of approximate solubilities of ionic compounds are shown in Table 1. Solubility is connected with the term solubility product of ionic compounds (Chapter 5. and Table 2). Reactions that give rise to coloured, soluble, less dissociated coordinative compounds, complexes are described in Chapter 6. These reactions are used for proofs of particular ions too. Table 3 shows examples of some inorganic compounds important in medicine and toxicology.

Various systematic methods are used for determination of particular cations and anions in mixed samples. We can use reactions with **group reagents**, which divide particular ions in **analytical classes**. Specific ions are determined by special targeted reactions after previous gradual separation of the other cations and anions. The most known analytical way to determination of cations is sulphane way (previous hydrogen sulphide way). These systematic ways are much laborious and time consuming and that is why they are being replaced with free and goal seeking combinations of group and selective reactions at present. Analysis is adapted to individual nature of sample.

2. Group reagents

Group reagents that are used very often and that serve to rapid preliminary **determination of cations:** hydrochloric acid HCl, sulphuric acid H_2SO_4, saturated solution of sulphane H_2S in acid media, white ammonium sulphide $(NH_4)_2S$, alkaline hydroxides NaOH, KOH, ammonia NH_3, NH_4OH, ammonium carbonate $(NH_4)_2CO_3$, alkaline iodide KI, hydrolytic reactions (lowering of acidity in solution by dilution water, addition of sodium acetate).

Group reagents for **determination of anions** are: solution of baric salt $Ba(NO_3)_2$, silver salt $AgNO_3$, oxidative reactions with MnO_4^-, and I_2, reduction with I^-.

3. Determination of cations

Cations are divided into 5 analytical classes according to the sulphane way:

I. class

Ag^+, Pb^{2+}, Hg_2^{2+}. Group reagent is HCl. Chlorides of these cations are insoluble in water, their sulphides as well, see Table 2, solubility products

II.a class

Cu^{2+}, Hg^{2+}, Bi^{3+}. Group reagent is sulphane **H_2S** from acid media (negligible concentration S^{2-} is enough to precipitate sulphides of these cations). Chlorides of these cations are insoluble in water, sulphides are insoluble in diluted acids, ammonium hydroxide NH_4OH and in yellow ammonium sulphide $(NH_4)_2S_x$.

II.b class

As^{3+}. Sulphides are soluble in yellow ammonium sulphide $(NH_4)_2S_x$.

III. class

Zn^{2+}, Fe^{2+}, Fe^{3+}. Group reagent is white ammonium sulphide **$(NH_4)_2S$** (its complete dissociation guarantees high concentration S^{2-} needed to precipitate sulphides of these cations). Sulphides are already soluble in diluted acids; by hydrolysis are degraded to sulphane and relevant metal hydroxide.

IV. class

Ca^{2+}, Ba^{2+}. Group reagent is ammonium carbonate **$(NH_4)_2CO_3$**. Sulphides of these cations are soluble in water, carbonates form white precipitates that dissolve in diluted and strong acids, with concomitant release of gaseous carbon dioxide.

V. class

Mg^{2+}, Li^+, Na^+, K^+, NH_4^+. Group reagent does not exist; each cation is tested by special reactions. There are colour flame reactions for some cations as well.

4. Determination of anions

Anions are divided, by the same way as cations, into three analytical classes according to their reactions with baric and silver salts, as well as according to further reactions and behaviour of compounds rising with other reagents. Some literature classifies anions into four classes (SO_4^{2-}, F^- form a separate class).

I. class

CO_3^{2-}, PO_4^{3-}, SO_3^{2-}, CrO_4^{2-}, SO_4^{2-}, F^-. These anions are precipitated by baric and silver nitrate.

II. class

Cl^-, I^-, CN^-, S^{2-}, HS^-, NO_2^-. These anions are precipitated by silver nitrate.

III. class

NO_3^-, ClO_4^-, MnO_4^-. These anions are not precipitated with any group reagent.

5. Solubility product

Solubility product is derived from the relationship for equilibrium constants, which characterize equilibrium of chemical reactions in heterogeneous systems. Precipitation reactions in water solutions, used in qualitative analysis, have established the equilibrium between unreacted ions in solution above precipitate and solid phase of sediment. For example: for slightly soluble compound (precipitate) Ag_2CrO_4, rising according to equation

$$Ag_2CrO_4 \rightleftharpoons 2Ag^+ + CrO_4^{2-}$$

For equilibrium state applies

$$K = \frac{[\mathrm{Ag}^+]^2 \cdot [\mathrm{CrO}_4^{2-}]}{[\mathrm{Ag}_2\mathrm{CrO}_4]} .$$

Because solution of insoluble compound is saturated during precipitation and substance concentration of insoluble compound is constant, product of equilibrium constant and concentration of insoluble compound will be constant as well.

We get the relationship

$$K_s = K \cdot [\mathrm{Ag}_2\mathrm{CrO}_4] = [\mathrm{Ag}^+]^2 \cdot [\mathrm{CrO}_4^{2-}]$$

Generally, the solubility product K_s is given as product of equilibrium concentrations ions in solution above sediment (precipitate), exponentiated by stoichiometric coefficients of given chemical reaction. The values of solubility products of various substances are tabulated.

According to the solubility product it is possible to assess and calculate solubility of substances under various conditions. Solubility depends on temperature, pH and presence of other outside ions in solution. This fact is possible to use in qualitative analysis; precipitation of slightly soluble compounds can be affected in order to aid their better separation and proofs.

6. Complex compounds

Complex compounds, coordination compounds (complexes) can be molecules or ions that contain as a central particle an atom or ion onto which ligands are bonded by **coordination covalent bond.** Central particles are almost always atoms or ions of transition elements with unoccupied valence orbitals, which can receive electrons, free electron pairs; they are acceptors of electrons. The elements in sequence: d-elements, p-elements, s-elements form the best nucleus of complex. Ligands (donors) can be anions, for example Cl^- – chloro, Br^- – bromo, CN^- – cyano, OH^- – hydroxo, or neutral molecules, which have atom with free electron pair, for example H_2O – aqua, NH_3 – ammine, NO – nitrosyl, CO – carbonyl. Maximal number of univalent ligands around central particle is named **coordination number** of compounds, most often it is number 6, 4, 8, 2. Coordination compounds can contain a complex cation, anion or both.

Complex compounds are almost always soluble in water, less dissociative and differ from its original component in colour and solubility owing to coordinate bonds. They have therefore a broad use in analytical chemistry. Equilibrium that sets up in solution of complex compounds is possible to write by this way

$$Cu^{2+} + 4NH_3 \rightleftharpoons [Cu(NH_3)_4]^{2+}$$

$$K_k = \frac{[Cu(NH_3)_4]^{2+}}{[Cu^{2+}] \cdot [NH_3]^4}$$

K_k is constant stability of complex. A higher value of K_k means a more stable complex and vice versa.

Chelate complexes (chelate compounds) are subgroup of complex compounds. An organic compound is the ligand in this complex; it can occupy at once even more coordinative sites around the central atom and contains more free electron pairs. Chelatometric reagent is an organic compound that gives at least two free electron pairs to give rise dative bonds. Some of these reagents are used in analytical chemistry for titration determination, for example chelatometric reagent EDTA (ethylenediaminetetraacetate acid and its salts), biuret etc. Number of chelatometric reagents is used in medicine at acute poisoning by cations of some bivalent and trivalent metals to get them off and remove from the organism. Chelate structures are physiologically important for many enzymes, and also in haemoglobin, chlorophyll and others biological pigments.

TAB. 1 APPROXIMATE SOLUBILITIES OF IONIC COMPOUNDS

Type of compound	**Freely soluble**	**Sparingly soluble**	**Insoluble**
Salts of alkaline metals (Li^+, K^+, Na^+) and ammonium salts (NH_4^+)	All	no	no
perchlorates (ClO_4^-), chlorates (ClO_3^-), nitrates	the others	$KClO_4$, CH_3COOAg	no

(NO_3^-), acetates (CH_3COO^-)			
chlorides (Cl^-), bromides (Br^-), iodides (I^-)	the others	$PbCl_2$, $PbBr_2$	Cu^+, Ag^+,Hg_2^{2+},HgI_2, BiI_3, PbI_2
sulphates (SO_4^{2-})	the others	Ca^{2+}, Ag^+	Sr^{2+}, Ba^{2+}, Pb^{2+}
hydroxides (OH^-)	alkaline metals and alkaline earths	Ca^{2+}	the others
carbonates (CO_3^{2-}), phosphates (PO_4^{3-}), arsenates (AsO_4^{3-})	alkaline metals, NH_4^+	$MgCO_3$	the others
sulphides (S^{2-})	ions with structure of inert gas (alkaline metals, alkaline earths, NH_4^+, Al^{3+} etc.)		the others
oxides (O^{2-})	alkaline metals, Ca^{2+}, Ba^{2+}, Sr^{2+}		the others

It generally applies that salts of weak acids are soluble in solutions of strong acids, weak acids rise from them. Analogously salts of weak bases are soluble in solutions of strong bases, weak bases rise from them. Compounds that contain hydrogenanions in molecule are more soluble.

Tab. 2 Solubility products of ionic compounds

Compounds	**Temperature (°C)**	**Solubility product K_s**
AgBr	25	$6.3\cdot 10^{-13}$
AgCl	25	$1.6\cdot 10^{-10}$
Ag_2CrO_4	25	$4\cdot 10^{-12}$
AgI	25	$1.5\cdot 10^{-16}$
Ag_2S	18	$1.6\cdot 10^{-49}$
Ag_2SO_4	25	$7.7\cdot 10^{-5}$

$Al(OH)_3$	25	$6 \cdot 10^{-33}$
As_2S_3	20	$4 \cdot 10^{-29}$
$BaSO_4$	25	$1 \cdot 10^{-10}$
Bi_2S_3	18	$1.6 \cdot 10^{-72}$
$CaCO_3$	25	$8.7 \cdot 10^{-9}$
CaC_2O_4	20	$3.9 \cdot 10^{-9}$
$Ca(OH)_2$	25	$4.3 \cdot 10^{-6}$
$CaSO_4$	25	$6.1 \cdot 10^{-5}$
$Ca_3(PO_4)_2$	25	$1.8 \cdot 10^{-26}$
$Cu(OH)_2$	25	$5.6 \cdot 10^{-20}$
CuS	18	$8 \cdot 10^{-36}$
$Fe(OH)_3$	18	$3.8 \cdot 10^{-38}$
$Fe(OH)_2$	18	$4.8 \cdot 10^{-16}$
FeS	25	$5 \cdot 10^{-18}$
Hg_2Cl_2	25	$2 \cdot 10^{-18}$
Hg_2I_2	25	$1.2 \cdot 10^{-28}$
HgS	20	$4 \cdot 10^{-53}$
Hg_2S	25	$1 \cdot 10^{-45}$
$Mg(OH)_2$	25	$2.6 \cdot 10^{-11}$
$PbCl_2$	25	$2 \cdot 10^{-5}$
$Pb(OH)_2$	25	$3 \cdot 10^{-16}$
PbS	18	$3.4 \cdot 10^{-28}$
$PbSO_4$	25	$1.5 \cdot 10^{-8}$
$Sn(OH)_2$	25	$5 \cdot 10^{-26}$
$Sn(OH)_4$	18	$1 \cdot 10^{-56}$
SnS	18	$1 \cdot 10^{-28}$

$Zn(OH)_2$	25	$1.5 \cdot 10^{-16}$
ZnS	25	$1.1 \cdot 10^{-24}$

Tab. 3 Examples of some inorganic compounds important in medicine and toxicology

Ag	silver	colloidal silver, bactericidal effects, disinfection of water well, Sagen, dental amalgams
$Al(OH)_3$	aluminium hydroxide	antacid
As_2O_3	arsenous oxide	strongly toxic, arsenical
$BaSO_4$	barium sulphate	use in X-ray examination, Intestibar
$CaCl_2$	calcium chloride	supplementation in calcium deficiency
$CaSO_4$	calcium sulphate	gypsum
CO	carbon monoxide	toxic gas, poisonings by coal-gas
CO_2	carbon dioxide	buffering system of blood, saturated beverages
FeI_2	iron diiodide	supplementation in iron deficiency
HCO_3^-	hydrogen carbonate anion	buffering system of blood
H_3BO_3	boric acid	boric acid, disinfection, part of eye drops
H_2O_2	hydrogen peroxide	disinfection solution
HCl	hydrochloric acid	included in gastric juice
Hg	mercury	stomatology, amalgams
Hg_2Cl_2	mercurous chloride	calomel, specific electrode for pH measurement
$HgCl_2$	mercuric chloride	strong toxic
KCl	potassium chloride	supplementation in potassium deficiency
KCN	potassium cyanide	strong toxic, cyancali
KI	potassium iodide	iodination of potable water and kitchen salt
$KMnO_4$	potassium permanganate	strong oxidizing reagent, disinfectants

KNO_2	potassium nitrite	antidote at poisonings by cyanides
Li_2CO_3	lithium carbonate	Psychiatric drug
$Mg(OH)_2$	magnesium hydroxide	antacid
$MgSO_4$	magnesium sulphate	laxative effects
Na_2HPO_4	sodium secondary phosphate	buffering system of blood and urine
$NaCl$	sodium chloride	physiological solution (saline)
$NaClO$	sodium hypochlorite	disinfectants, Savo
Na_2CO_3	sodium carbonate	softening agent of water (soda), regulator of acidity in foods
NaF	sodium fluoride	fluoridation of water, tooth pastes, toxic in high dose
Na_2PO_3F	sodium phosphate-fluoride	tooth pastes
NaH_2PO_4	sodium dihydrogen phosphate	buffering system of blood and urine
$NaHCO_3$	sodium hydrogen carbonate	buffering system of blood, antacid, aerating baking powder
NH_4Cl	ammonium chloride	in preparation Salnatrex for salt-free diet, salmiac – dry-cells
NH_4HCO_3	ammonium hydrogen carbonate	aerating baking powder
$(NH_4)_2SO_4$	ammonium sulphate	used for the salt precipitation of proteins
Pb_3O_4 ($2PbO + PbO_2$)	lead monoxide-dioxide	toxic, minium, basic paint colour
SO_2	sulphur dioxide	toxic gas, air pollution
TiO_2	titanic oxide	titanium white
ZnO	zinc oxide	part of some salves

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