Chemistry and Materials Science: Second-round Sample Tasks for the Open Doors Maser's and Doctoral Track

This sample test comprises 35 tasks, including: 21 entry-level tasks with a single correct answer, each correct answer assigned 1 point; 5 intermediate-level tasks with multiple correct answers, each correct answer assigned 3 to 4 points; 6 intermediate-level tasks with a single answer, each correct answer assigned 3 points; 3 advanced-level tasks requiring a detailed answer, each answer assigned up to 15 points, depending on its correctness and completeness.
For advanced-level tasks requiring a detailed answer, assessment criteria and a standard answer are provided.

Field of Science 1. Inorganic and Nuclear Chemistry

Task 1
Entry level (1 point)

Which of the following substances is a double salt?

a) $Na_2IO_3(NO_3)$
b) PbFCl
c) $K_3Fe(CN)_6$
d) $K_2Mg(SO_4)_2 \cdot 6H_2O$

Answer: d.

Task 2
Entry level (1 point)

Which of the following aqueous saturated solutions of slightly soluble compounds will have the minimum concentration of anion?

a) silver iodide ($Ks = 8.3 \cdot 10^{-17}$)
b) thallium chloride (I) ($Ks = 1.7 \cdot 10^{-4}$)
c) calcium sulfate ($Ks = 2.5 \cdot 10^{-5}$)
d) barium carbonate ($Ks = 4.0 \cdot 10^{-10}$)

Answer: a.

Task 3
Entry level (1 point)

The interaction of sulfur (IV) oxide and chlorine in the presence of light yields:

a) sulfuryl chloride.
b) thionyl chloride.
c) sulfuric acid.
d) chlorosulfonic acid.

Answer: a.

Task 4
Intermediate level (3 points)

The ionization constant of ammonia in solution is $1.74 \cdot 10^{-5}$. To 100 mL of a 0.5 M ammonia solution, 5.35 g of ammonium chloride is added. By what factor has the concentration of hydroxonium ions increased? Neglect any change in the volume of the solution upon salt addition. Enter your answer as an integer.

Answer: 340.

Task 5
Intermediate level (3 points)

A hydrochloric acid solution has a mass of 433 g. The number of chlorine atoms in the solution is one-tenth the number of oxygen atoms. After introducing 32.5 g of zinc granules and allowing the reaction to complete, calculate the mass of a 20% sodium hydroxide solution that must be added to ensure the completion of all reactions. Enter your answer as an integer in grams.
Answer: 600.

Task 6
Advanced level (15 points)

The content of sodium thiosulfate pentahydrate in the preparation is quantitatively determined by direct iodometric titration. A 0.345 g sample of the drug is dissolved in 25 ml of water, transferred to a 100.0 ml volumetric flask, and the volume is brought to the mark with water. For titration, a 10.0 ml aliquot is taken, an indicator is added, and it is titrated with 0.05 M iodine solution until a color change occurs. A volume of 1.35 ml of titrant solution was used. Calculate the mass fraction (in %) of the crystallohydrate in the preparation.

Note: A complete solution must include your method and reasoning. Providing the final answer alone will not suffice.

Solution:

$2Na_2S_2O_3 + I_2 \rightarrow Na_2S_4O_6 + 2\ NaI$	3
Mass of sodium thiosulfate in the sample (aliquot fraction): $m\ (Na_2S_2O_3) = M(Na_2S_2O_3) \cdot 2 \cdot C\ (I_2) \cdot V\ (I_2)$ $m\ (Na_2S_2O_3) = 158 \cdot 2 \cdot 0.05 \cdot 0.00135 = 0.02133$ g	3
Mass of sodium thiosulfate in solution: $m\ (Na_2S_2O_3) = 0.02133 \cdot 100/10 = 0.2133$g	3
Weight of sodium thiosulfate crystallohydrate: $m\ (Na_2S_2O_3 \cdot 5H_2O) = 248 \cdot 0.2133/\ 158 = 0.3348$ g	3
Mass fraction: $\omega\ (Na_2S_2O_3 \cdot 5H_2O) = (0.3348 / 0.345) \cdot 100\% = 97.1\%$	3

Answer: 97.1

Field of Science 2. Organic Chemistry

Task 7
Entry level (1 point)

Which compound exhibits the strongest acidic properties?

a) phenol
b) 4-aminophenol
c) 3-aminophenol
d) 2,4-dinitrophenol

Answer: d.

Task 8

Entry level (1 point)

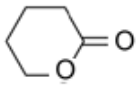
In which compound is a glycoside bond present?

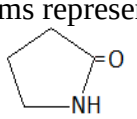
a) glucose
b) fructose
c) maltose
d) Mannose

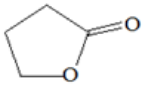
Answer: c.

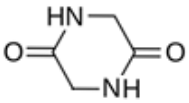
Task 9
Entry level (1 point)

Which of the following diagrams represents diketopiperazine?

a) 

b) 

c) 

d) 

Answer: d.

Task 10
Intermediate level (3 points)

Acetaldehyde was divided into two equal parts. The first part underwent croton condensation, yielding 12.25 g of croton aldehyde (butene-2-al) at 70% yield. The second part was oxidized to carboxylic acid, which reacted with 60% yield with a monatomic alcohol in the presence of sulfuric acid, producing 30.6 g of organic product. Determine the formula of the alcohol. Specify its molecular weight as an integer.

Answer: 60.

Task 11
Intermediate level (3 points)

A mixture of adenine and cytosine was burned in excess oxygen. The combustion products were passed through excess calcium hydroxide solution, resulting in a precipitate mass of 220 g. The volume of unabsorbed gas equals the volume of gas produced by the reaction of 93.1 g of sodium cyanide with sodium hypochlorite in aqueous solution. Determine the mass of adenosine-5-monophosphate from which the adenine in the initial mixture was isolated. Round your answer to one decimal place.

Answer: 69.4.

Field of Science 3. Analytical Chemistry

Task 12
Entry level (1 point)

Calculate the solubility in mol/L and the concentration of Ba^{2+} ions in g-ion/L in a solution of $Ba_3(PO_4)_2$ with solubility product equal to $6 \cdot 10^{-39}$.

a) $2.76 \cdot 10^{-6}$ mol/L, $1.8 \cdot 10^{-8}$ g-ion/L
b) $2.76 \cdot 10^{-6}$ mol/L, $2.7 \cdot 10^{-8}$ g-ion/L

c) $0.89 \cdot 10^{-8}$ mol/L, $2.7 \cdot 10^{-8}$ g-ion/L
d) $0.69 \cdot 10^{-6}$ mol/L, $0.89 \cdot 10^{-8}$ g-ion/L
Answer: c.

Task 13
Entry level (1 point)

The dissociation constant of formic acid HCOOH, which dissociates according to the equation $HCOOH = H^+ + HCOO^-$, is $2.1 \cdot 10^{-4}$. Calculate the degree of dissociation α and the concentration of $[H^+]$ for a 0.3 M solution of this acid.
a) $6.96 \cdot 10^{-4}$, $5.3 \cdot 10^{-3}$ g-ion/L
b) $2.64 \cdot 10^{-2}$, $7.9 \cdot 10^{-3}$ g-ion/L
c) $1.17 \cdot 10^{-2}$, $7.9 \cdot 10^{-3}$ g-ion/L
d) $2.64 \cdot 10^{-2}$, $1.25 \cdot 10^{-2}$ g-ion/L
Answer: b.

Task 14
Entry level (1 point)

Calculate the concentration of Ag^+ ions in a 0.1 M solution of $[Ag(NH_3)_2]NO_3$ with an excess of 1 mole of ammonia. The instability constant of the ion $[Ag(NH_3)_2]^+$ is $5.7 \cdot 10^{-8}$.
a) $0.5 \cdot 10^{-8}$ g-ion/L
b) $0.4 \cdot 10^{-6}$ g-ion/L
c) $0.6 \cdot 10^{-7}$ g-ion/L
d) $0.6 \cdot 10^{-8}$ g-ion/L
Answer: d.

Task 15
Intermediate level (3 points)

A transparent pink solution was submitted to a laboratory for testing. While conducting the study, a laboratory assistant carried out a series of tests on aliquots of the solution, yielding the following results:
a) Adding sodium hydroxide resulted in a mixture of white, blue, and pink colors.
b) Adding sulfuric acid and hydrogen peroxide solutions caused a portion of the solution to turn yellow-orange.
c) Adding ammonium thiocyanate solution in the presence of isoamyl alcohol caused the upper layer to turn bright blue.
d) Adding barium chloride solution produced a white precipitate.

Which ions does the unknown solution contain? Select all that apply.
a) Ni^{2+}
b) Fe^{3+}
c) Ti^{4+}
d) Cr^{3+}
e) Co^{2+}
f) SO_4^{2-}
Answer: c, e, f.

Task 16
Intermediate level (3 points)

A sample containing iron was submitted to a laboratory for testing. To determine the total iron content, a 1 g sample was dissolved in concentrated hydrochloric acid and reduced with metallic zinc. The resulting solution was diluted with distilled water to 100 ml in a volumetric flask. A 5 ml aliquot was transferred to a 100 ml conical flask. A mixture of sulfuric and phosphoric acids and 2–3 drops of diphenylamine indicator were added, followed by titration with 0.01 mol/l potassium dichromate solution until the indicator turned blue-violet. The volume of titrant used was 10.25 ml. Calculate the mass fraction of total iron (%) in the sample, assuming Mr(Fe) = 56. Provide your answer as an integer.
Answer: 69.

Field of Science 4. Physical Chemistry

Task 17
Entry level (1 point)

The change in enthalpy for the reaction is -145 kJ/mol. Calculate the equilibrium constant of the reaction at 700 K, given that the equilibrium constant at 650 K is 1000.

a) 147
b) 0.045
c) 6800
d) 3.5

Answer: a.

Task 18
Entry level (1 point)

Carbon tetrachloride boils at 76.8 °C. At this temperature, the enthalpy of vaporization at constant pressure is 29.82 kJ/mol. Calculate the entropy change for 1 mol at the boiling point of carbon tetrachloride.

a) 5.5 kJ /(K·mol)
b) 85.2 J/(K mol)
c) -16.5 J/(K·mol)
d) 32 J/(K·mol)

Answer: b.

Task 19
Entry level (1 point)

Calculate the Gibbs energy change for the isothermal compression of 0.003 m^3 of methane at 25 °C, when the pressure increases from 0.5×10^5 Pa to 2.0×10^5 Pa. Assume methane behaves as an ideal gas.

a) 103 J
b) 206 J
c) 10.3 J
d) 20.6 J

Answer: b.

Task 20
Intermediate level (3 points)

Which THREE statements are true for a 0.25 molal NaCl solution in water?

a) This is a solution of a strong electrolyte.
b) The freezing point of the solution is lower than that of the pure solvent.
c) The numerical value of the ionic strength of the solution is 0.25.
d) The NaCl solution conducts electric current less effectively than the solvent.
e) The NaCl activity coefficient for the specified solution is 0.
f) When diluted, the specific electrical conductivity of the solution will decrease.

Answer: a, c, f.

Task 21
Intermediate level (3 points)

Which THREE statements are true for a 0.1 molar solution of acetic acid in water?

a) This is a solution of a strong electrolyte.
b) If the resistivity of 0.1 molar acetic acid solution in water at 298 K is 1960 ohm cm, the molar electrical conductivity of the solution is 5 10^{-4} Cm · cm^2/mol.
c) If the value of the limiting mobility of acetic acid ions is $\lambda_{H} = 350 S \cdot cm^2/mol$, $\lambda_{CH_3COO} = 40{,}9 S \cdot cm^2/mol$, the degree of dissociation of 0.1 molar solution is 0.013.
d) The dissociation degree of acetic acid solutions does not depend on the degree of dilution.
e) The electrical conductivity of a 0.1 molar acetic acid solution increases with rising temperature.
f) The dissociation constant of 0.1 molar acetic acid solution is 1.71 10^{-5}.

Answer: c, e, f.

Task 22
Advanced level (15 points)

The following reaction takes place in a galvanic cell:

$$2FeCl_3 + Sn \leftrightarrow SnCl_2 + 2FeCl_2$$

1) Draw a diagram of the galvanic cell and specify the electrode processes occurring within it.
2) Calculate the standard EMF, ΔG°, and the reaction equilibrium constant at 25 °C.
E_{Sn} = -0.140 B, $E_{Fe^{3+Fe}}$ = 0.771 V.
3) Find the concentration of the $SnCl_2$ solution in a cell if the galvanic cell shows an EMF of 0.967 V, and the concentrations of $FeCl_3$ and $FeCl_2$ in another cell are both 0.005 mol/L (ion activity can be replaced with the corresponding concentrations).

Note: A complete solution must include your method and reasoning. Providing the final answer alone will not suffice.

Solution:

Galvanic cell notation:
$Sn \mid Sn^{2+} \parallel Fe^{3+}, Fe^{2+} \mid Pt$ — 2 points
Electrode processes:
Left electrode (anode): $Sn - 2e \rightarrow Sn^{2+}$ (oxidation) — 2 points
The right electrode (cathode): $Fe^{3+} + e \rightarrow Fe^{2+}$ (reduction) — 2 points
Calculation of the standard EMF.
$E° = E_{right}{}^0 - E_{left}{}^0 = 0.771 - (-0.140) = 0.911$ V — 1 point
$\Delta G^0 = -zFE^\circ = -2 \cdot 96485 \cdot 1.021 = -175796$ J — 2 points
$\ln K = E° \cdot z \cdot F/(R \cdot T) = 0.911 \cdot 2 \cdot 96485/(8.31 \cdot 298) = 71.0$

$K = e^{\wedge}79.6 = 6.76\ 10^{30}$ 2 points
$E_{right} = E_{right}^{0} - 8.31 \cdot 298/1/96485 \cdot \ln(0.005/0.005) = 0.771$ V
$E_{left} = E_{right} - E = 0.771 - 0.967 = -0.196$ V
$\ln(C(Sn^{2+})) = (E_{left} - E_{left}^{0}) \cdot z \cdot F/R/T = (-0.196 - (-0.140)) \cdot 2 \cdot 96485/8.31/298 = -4.36$
$C(Sn^{2+}) = 0.013$ mol / L 4 points

Field of Science 4. Crystallography

Task 23
Entry level (1 point)

Indicate the ratios of angles and translations in the unit cell of an orthorhombic crystal.

a) a=b=c, α=β=γ= 90°
b) a=b≠c, α=β=γ= 90°
c) a≠b≠c, α=β=γ≠ 90°
d) a≠b≠c, α=β=γ= 90°

Answer: d.

Task 24
Entry level (1 point)

The RbCl crystal corresponds to the B2 (Pm3m) structure type. Determine the number of atoms per unit cell in this crystal.

a) 2
b) 4
c) 6
d) 8

Answer: a.

Task 25
Entry level (1 point)

Which symmetry class does a crystal with the space group $I4_1/amd$ belong to?

a) 4mm
b) 4/m
c) $\frac{4}{m}\frac{2}{m}\frac{2}{m}$
d) $\frac{4}{m}3\frac{2}{m}$

Answer: c.

Task 26
Intermediate level (3 points)

Given the atomic radius of Ni (Fm3m) as 1.245 Å, calculate the lattice parameter and round the result to two decimal places (X.XX).

Answer: 3.52.

Field of Science 5. Metallurgy and Metallurgical Engineering

Task 27
Entry level (1 point)

Which of the following represents a first-order phase transition?

a) melting and condensation of matter
b) transition of a metal or alloy to a superconducting state
c) transition of liquid helium to a superfluid state
d) the transformation of a magnetic alloy from a ferromagnetic state to a paramagnetic state

Answer: a.

Task 28
Entry level (1 point)

Which of the following is the packing density of a BCC crystal?

a) 0.52
b) 0.74
c) 0.68
d) 0.34

Answer: c.

Task 29
Entry level (1 point)

Which of the following refers to the transition from the liquid state to the solid state?

a) recrystallization
b) melting
c) amorphization
d) crystallization

Answer: d.

Task 30
Intermediate level (3 points)

Due to the dimensional effect, nanoparticles of a given substance demonstrate greater solubility than the corresponding bulk phase. If the nanoparticle radius is known, which of the following characteristics are required to evaluate their solubility at a given temperature? Select all that apply.

a) bulk phase solubility
b) specific enthalpy of bulk phase melting
c) molar volume of the substance
d) surface tension of the substance at the solid–liquid boundary
e) surface tension of the substance at the solid–gaseous boundary
f) surface tension of the substance at the liquid–gaseous boundary

Answer: a, c, d.

Task 31
Advanced level (15 points)

Determine the number of atoms per an elementary cell of Au (structural type A1), given that its density is $\rho = 19.32$ g/cm^3, lattice period is $a = 4.078$ Å, $A_{Au} = 196.97$, and $1\ u = 1.66 \cdot 10^{-24}$ g.

Note: A complete solution must include your method and reasoning. Providing the final answer alone will not suffice.

Solution. Density $\rho = m / V$, where m is the mass of the unit cell, and V is the volume of the unit cell.

$m = N \cdot m_{av}$, where N is the number of atoms per unit cell, m_{av} is the average mass of a particle ($m_{av} = A \cdot 1.66 \cdot 10^{-24}$ (A is the atomic mass))

Structural type A1 has a cubic cell, therefore the volume of the unit cell is $V = a^3$.

Therefore:

$$\rho = (N \cdot A \cdot 1.66 \cdot 10^{-24}) / a^3; N = \rho \cdot a^3 / (A \cdot 1.66 \cdot 10^{-24}) = 19.32 \cdot (4.078 \cdot 10^{-8})^3 / 196.97 \cdot 1.66 \cdot 10^{-24} = 4$$

Answer: 4 atoms

Assessment criteria

Stating the density formula in terms of mass and volume is worth 3 points.
Stating the mass of the unit cell in terms of the number of atoms and their mass is worth 2 points.
Stating the expression for the average particle mass is worth 2 points.
Stating the unit cell volume formula for the given structural type is worth 2 points.
Deriving the final formula for the number of atoms per unit cell is worth 3 points.
Substituting numerical values into the formula is worth 1 point.
Recording the final answer as an integer is worth 2 points.

Field of Science 6. Materials Science: Evaluation and Testing

Task 32
Entry level (1 point)

Which of the following refers to the difference in properties depending on the direction of mechanical testing?

a) allotropy
b) isotropy
c) anisotropy
d) polymorphism

Answer: c.

Task 33
Entry level (1 point)

Which method of determining the hardness number uses the following formula?

$$HB = P / D^2 \left[\frac{2 / \pi}{1 - \sqrt{1 - (d / D)^2}} \right]$$

a) Brinell hardness
b) Vickers hardness
c) Rockwell hardness
d) micro hardness

Answer: a.

Task 34
Entry level (1 point)

Which of the following characterizes first-order phase transitions?

a) The first derivatives of the specific thermodynamic potentials for different phases are the same, and the second derivatives are different.

b) The first derivatives of the relevant thermodynamic potentials differ between phases.

c) There is a discontinuity in heat capacity, temperature coefficient of expansion, and compressibility of the substance.

d) The mass of the first phase decreases, and that of the second remains unchanged.

Answer: b.

Task 35
Intermediate level (4 points)

Which THREE characteristics can be obtained after tensile tests at room temperature?

a) endurance limit
b) tensile strength
c) yield stress
d) creep limit
e) elastic limit
f) ultimate strength

Answer: b, c, e