2022 WUCT: Individual Exam ANSWER KEY

This exam consists of 7 questions and is worth 100 points. You will have 1 hour to take the exam, followed by 10 minutes of upload time during which you cannot make changes to your exam. The only allowed resources for this exam are a calculator and the provided equation sheet. You may NOT use any other notes, books, people, or websites (other than Gradescope and HopIn). You must show your work and box your final answer to receive credit for a problem. Please write your answer in the designated space on the answer sheet. If you need additional space for a problem, you may use scratch paper, but make sure to clearly indicate in the problem's designated space where the rest of your work can be found. Dark pencil or pen is preferred so that your writing clearly shows on your submitted document in Gradescope.

Problem #1: ***(11 points)***

A rough estimate of the radius, *r*, of a nucleus is provided by the formula $r = kA^{1/3}$, where *k* is approximately 1.3×10^{-13} cm and *A* is the mass number of the nucleus.

a) Calculate the density of the nucleus of ^{192}Ir atom in grams per cubic centimeter. ^{192}Ir has a nuclear mass of 3.19×10^{-22} g. Volume of a sphere is given by the equation: $\frac{4}{3}\pi r^3$. ***(4 points)***

$\rho = \frac{m}{v} = \frac{3.19\times10^{-22}}{4/3\ \pi*(1.3*10^{-13}*(192)^{1/3})^3} = 1.8 \text{ x } 10^{14}$ g/cm^3

+1 points for using the correct density equation

+1 points for correct value substitution

+2 points for correct answer

b) Compare the density of the nucleus of a ^{192}Ir atom with solid iridium sample (22.65 g/cm^3). Which has a higher density? What does this say about the nucleus? Write your answer in 2 - 3 sentences. ***(4 points)***

Sample Answer: The density of the nucleus is greater than the density of solid iridium. This tells us that the mass of the atom is primarily concentrated in the nucleus and that electrons don't have much mass compared to protons and neutrons in the nucleus.

+2 points for indicating that the nucleus has a greater density

+2 points correct explanation

c) Iridium has two stable isotopes, one of which is iridium-191. The relative abundance of iridium-191 is 37.2%. Calculate the atomic mass of the second stable isotope of iridium. Report your answer in amu. ***(3 points)***

192.22 = 191 * 0.372 + x * 0.628

x = 192.94

+1 point for correct equation setup
+2 points for correct calculation of atomic mass

Problem #2: ***(10 points)***

When 3g of pure phenol, C_6H_5OH*(s)* goes through a combustion reaction as shown in the equation below, 97.47 kJ of heat is released. Using the information in the table below, answer the following equations.

$$C_6H_5OH(s) + 7\ O_2(g) \rightarrow 6\ CO_2(g) + 3\ H_2O(l)$$

Substance	Standard Heat of Formation, ΔH^o_f at 25°C (kJ/mol)
$H_2O(l)$	-285.85
$CO_2(g)$	-393.5

a) Calculate the molar heat of combustion of phenol in kJ/mol at 25°C. ***(5 points)***

Molar mass of phenol = 94.11g/mol

$\Delta H_{combustion} = \frac{-97.47kJ}{3g\ phenol} * \frac{94.11g\ phenol}{1\ mol}$ = -3058 kJ/mol

+2 points for calculating molar mass of phenol
+2 points for correct calculation of molar heat of combustion
+1 point for negative sign

b) Calculate the standard heat of formation, ΔH^o_f, of phenol in kJ/mol at 25°C. ***(5 points)***

$\Delta H_{combustion}$ = 6 * ΔH^o_f of CO_2 + 3 * ΔH^o_f of H_2O - ΔH^o_f of phenol

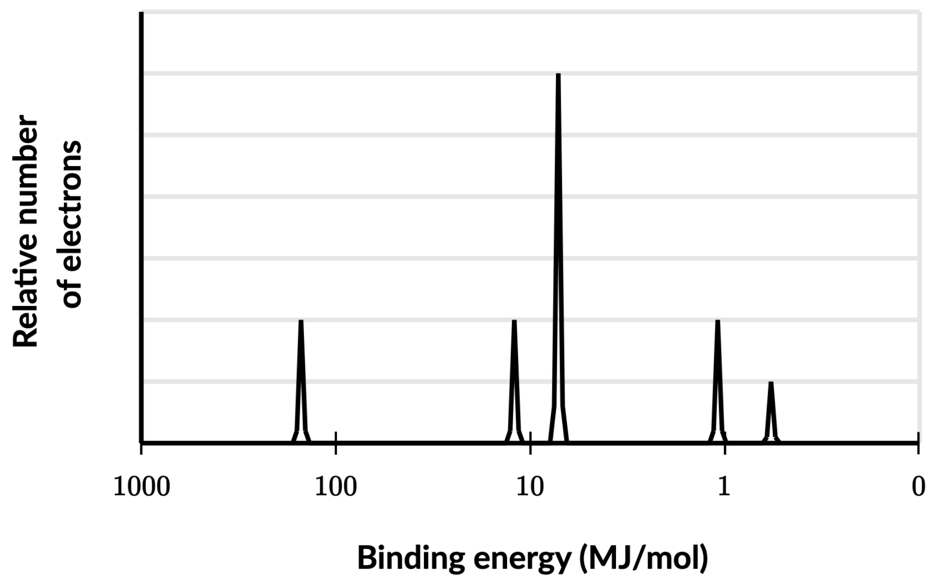
-3058kJ/mol = 6 * (-393.5) + 3 * (-285.85) - ΔH^o_f of phenol

ΔH^o_f of phenol = -160.6 kJ/mol

+2 points for correct $\Delta H_{combustion}$ equation
+2 points for correct calculations
+1 point for correct units

Problem #3: ***(16 points)***

The complete photoelectron spectrum of an element in its ground state is shown below.



a) Based on the spectrum,

1) write the full electronic configuration of this element. ***(3 points)***

$1s^2 2s^2 2p^6 3s^2 3p^1$ or $[Ne]3s^2 3p^1$

+3 points for correct electronic configuration

2) describe in words which peak on the spectrum above corresponds to the 2s shell of this element. ***(2 points)***

The 2nd peak from the left should be the 2s peak

+2 points for the correctly labeled peak

3) identify the element. ***(1 point)***

Aluminum

+1 point for correct element

b) The binding energy of the outermost electron was measured to be 3.3 x 10^{-19}J. Using the reference table below, identify the color of the electromagnetic radiation needed to remove the outermost electron from the valence shell of an atom of the element. ***(6 points)***

Color	Wavelengths
Red	620 - 750 nm
Orange	590 - 620 nm
Yellow	570 - 590 nm
Green	495 - 570 nm
Blue	450 - 495 nm
Violet	380 - 450 nm

E = hf where h = Plank's constant and f = frequency

$E = 3.3 * 10^{-19} J = 6.62 * 10^{-34} J*s * f$

$f = 4.98 * 10^{14} Hz$

$c = f\lambda$

$3*10^{8}\ m/s = 4.98 * 10^{14}\ Hz * \lambda$

$\lambda = 6.02 * 10^{-7} m = 602\ nm$ → Orange color light

+2 points for correct frequency calculations

+2 points for correct wavelength calculations

+2 points for correct color

c) The photoelectron spectroscopies of fluorine and oxygen were performed. Compare the placement of the 1s electron peak of fluorine to the 1s electron peak of oxygen. In other words, would the 1s electron peak of fluorine be positioned to the right or left of the 1s electron peak for oxygen? Briefly explain your reasoning in 1-2 sentences. ***(4 points)***

Sample Answer: The 1s electrons peak for fluorine would be positioned to the left of the 1s electrons peak for oxygen because the effective nuclear charge of fluorine (Z = 9) is greater than the effective nuclear charge of oxygen (Z = 8). Greater nuclear charge would bind the electrons more tightly, which means higher binding energy.

+2 points for identifying the correct positioning

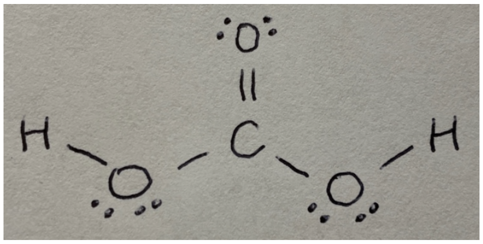
+2 points for correct reasoning

Problem #4: ***(15 points)***

For proper functioning of our body, it is critical that we maintain a constant blood pH that stays within a certain range at around 7.4. The carbonic acid (H_2CO_3) and bicarbonate ion (HCO_3^-) buffer system in our blood, modeled by the equation below, helps maintain that stable pH.

$$H_2CO_{3\ (aq)} \Leftrightarrow H^+_{(aq)} + HCO^-_{3\ (aq)} \qquad K_a = 4.3 * 10^{-7}$$

a) Draw the most preferred Lewis structure of carbonic acid (H_2CO_3). ***(2 points)***



+2 points for correct lewis structure

b) On the basis of the diagram you completed in part (b), can all six nuclei on carbonic acid lie in the same plane? Explain your answer in 1 - 2 sentences. ***(2 points)***

Sample Answer: Yes, the carbon is **sp^2 hybridized** so the carbon and the three oxygens will be in a trigonal planar conformation. The oxygens on both sides are sp^3 hybridized so it is possible for the **hydrogens to orient themselves** in a way that all six atoms on carbonic acid lie in the same plane.

+1 point for correct answer - Yes

+1 point for correct reasoning

c) Calculate the pKa of the blood buffer system. ***(2 points)***

$pK_a = -\log[K_a] = -\log[4.3 * 10^{-7}] = 6.37$

+2 points for correct pK_a

d) Write the equilibrium constant expression for the reaction. ***(2 points)***

$$K_a = \frac{[H^+][HCO_3^-]}{[H_2CO_3]}$$

+2 points for correct equilibrium-constant expression

e) Calculate the *pH* of a 0.00120M carbonic acid (H_2CO_3) aqueous solution and the equilibrium concentrations of the species H_2CO_3, HCO_3^-, and H^+. Use 3 significant figures in your final answers. Show all your work to receive full credit. ***(7 points)***

ICE Table	$H_2CO_{3\,(aq)} \Leftrightarrow H^+_{(aq)} + HCO_3^-{}_{(aq)}$		
Initial Concentration (M)	*0.0012M*	*0*	*0*
Change (M)	*-x*	*+x*	*+x*
Equilibrium Concentration (M)	*0.0012 - x*	*x*	*x*

$$K_a = 4.3 * 10^{-7} = \frac{[H^+][HCO_3^-]}{[H_2CO_3]} = \frac{x * x}{0.00120 - x} \approx \frac{x * x}{0.00120}$$

$$x = 2.25 * 10^{-5}$$

$$pH = -\log[H^+] = -\log[2.25 * 10^{-5}] = \mathbf{4.648 / 4.65}$$

Final Equilibrium Concentrations

H_2CO_3	HCO_3^-	H^+
*0.00118M = 1.18 * 10^-3M*	*0.0000225M = 2.25 * 10^-5M*	*0.0000225M = 2.25 * 10^-5M*

+1 point for using ICE tables
+1 point for using equilibrium constant from part (d)
+2 points for correct pH calculation
+2 points for correct final equilibrium concentration calculations
+1 point for correct significant figures

Problem #5: ***(15 points)***

The Haber process is used in manufacturing ammonia (NH_3) from nitrogen and can be modeled by the equation below:

$$N_2\,(g) + H_2\,(g) \rightarrow NH_3\,(g)$$

a) Write out the balanced equation of the Haber process by adding the correct coefficients below. ***(3 points)***

__1_ N_2 (g) + __3_ H_2 (g) → __2_ NH_3 (g)

+1 points for each correct coefficient (total 3 points)

Rate data was collected for the Haber process at a particular temperature as shown below:

Experiment	**N_2 (mol/L)**	**H_2 (mol/L)**	**Initial Rate (M/s)**
1	0.018	0.018	3.105×10^{-4}
2	0.036	0.018	1.242×10^{-3}
3	0.018	0.036	6.210×10^{-4}
4	0.036	0.036	2.484×10^{-3}

b) Write the rate-law expression for the Haber process. ***(3 points)***

Rate = $k[N_2]^2[H_2]$

+3 points for correct rate-law expression

c) Describe the order of the reaction with respect to each reactant and to the overall order. ***(2 points)***

Second order with respect to N_2, first order with respect to H_2 and third order overall.

+1 point for correct order of the reaction with respect to each reactant

+1 point for correct overall order

d) Calculate the value of the rate constant, *k*, with the correct units. ***(3 points)***

3.105×10^{-4} M/s = k(0.018 M)^2 (0.018 M)

k = 53.2 M^{-2} s^{-1}

+2 points for correct calculations

+1 point for correct units

e) From the perspective of collision theory, explain how increasing the temperature will result in an increase in the rate of reaction in 1 - 2 sentences. ***(2 points)***

Sample Answer: Increasing the temperature will increase the average kinetic energy of the molecules. Higher kinetic energy would increase the number of collisions and will increase the overall rate of the reaction.

Sample Answer: Higher kinetic energy means collisions are more likely to have enough energy for the molecules to react when the molecules collide

+2 points for correct reasonable explanation

f) Iron is often used as a catalyst to accelerate the Haber Reaction. Circle all of the answers that correctly finish the following sentence: Iron will… ***(2 points)***

a. lower the activation energy of the reaction
b. lower the equilibrium constant
c. be consumed up during the reaction
d. accelerate the rate of reaction
e. initiate the reaction
f. work best in any temperature

+1 point for each correct answer chosen (total 2 points max)

-1 point for each incorrect answer chosen (min: 0 points)

<u>Problem #6</u>: *(15 points)*

A titration is an analytical method used by chemists to determine the concentration of a substance by titrating, or mixing, the substance with a reagent of known concentration.

For example, a titration can be used to calculate the amount of citric acid ($C_6H_8O_7$) present in orange juice by adding the strong base, NaOH. When the citric acid interacts with NaOH, an acid-base reaction occurs.

a) Write the balanced net ionic equation of the acid-base reaction between citric acid and NaOH. Assume that citric acid is monoprotic. ***(2 points)***

$C_6H_8O_7 + OH^- \rightarrow C_6H_7O_7^- + H_2O$
+2 points for correct equation
+0.5 for each correct reactant/product

b) Suppose we start with a 100 mL sample of citric acid and titrate it with 1M NaOH. After 10 mL of NaOH have been added, how many moles of citric acid have been consumed, given that the equivalence point has not been reached yet? ***(2 points)***
mol NaOH added = 1M * 0.010L = 0.0100mol = mol citric acid consumed
0.01 moles of citric acid is consumed
+2 points for correct answer and units
(+1 for correct answer +1 for units)

c) The equivalence point is reached when 15.2 mL of NaOH has been added. Given this information, what was the concentration (in g/L) of citric acid in the original orange juice sample? ***(2 points)***
mol NaOH added = 1M * 0.01520L = 0.01520mol = mol citric acid consumed
molar mass of citric acid = 192.124g/mol
0.01520mol * 192.124g/mol = 2.92g citric acid consumed
original concentration = 2.92g/0.100L = 29.2g/L
+2 points for correct answer and units

d) The pKa of citric acid is 2.79. Using this information, calculate the pOH and pH of the solution at the equivalence point of the titration. ***(6 points)***

pKb = 14 - pKa = 14 - 2.79 = 11.21

Kb = $10^{-11.21}$ = 6.17 * 10^{-12}

$C_6H_7O_7^- + H_2O \rightleftharpoons C_6H_8O_7 + OH^-$

Kb = $[C_6H_8O_7][OH^-]/[C_6H_7O_7^-]$

$[C_6H_7O_7^-]$ = 0.01520mol/(0.100L + 0.01520L) = 0.132M

6.17 * 10^{-12} = x^2/0.132

x = [OH-] = 9.02 * 10^{-7}M

pOH = 6.04

pH = 14 - 6.04 = 7.96

+1 point for correct K_b

+1 point for correct dissociation equation

+1 point for correct substitution into equation

+1 point for correct [OH-] calculation

+2 points for correct final pOH and pH

e) Which of the following indicators is best suited for this titration? Explain your answer in 1 - 2 sentences. ***(3 points)***

Indicator	Approximate pH Range for Color Change	Color Change
Methyl Orange	3.2 - 4.4	Red to yellow
Bromocresol green	3.8 - 5.4	Yellow to blue
Bromothymol blue	6.0 - 7.5	Yellow to blue
Thymol blue	7.9 - 9.6	Yellow to blue

Thymol blue because it changes color at a pH closest to the equivalence point of our titration.

+2 points for correct indicator

+1 point for correct explanation

<u>Problem #7</u>: *(18 points)*

A chemist was given an aqueous acidic solution containing Ba^{2+} ions, Mn solid, Ga^{3+} ions, Ag solid, Cl^- ions, and Cu solid. The mixture was open to the air. They had a battery and two inert graphite electrodes: an anode and a cathode. After connecting the electrodes to a battery, they stuck them into the mixture. Use the Table of Standard Reduction Potentials given below for the following questions.

Standard Reduction Half-Reaction	Standard Reduction Potential (E°) (Volts)
$O_3\ (g) + 2H^+\ (aq) + 2e^- \rightarrow O_2\ (g) + H_2O\ (l)$	2.07
$H_2O_2\ (aq) + 2H^+\ (aq) + 2e^- \rightarrow 2H_2O\ (l)$	1.763
$Cl_2\ (g) + 2e^- \rightarrow 2Cl^-\ (aq)$	1.396
$MnO_2\ (s) + 4H^+ + 2e^- \rightarrow Mn^{2+} + 2H_2O\ (l)$	1.23
$O_2\ (g) + 4H^+\ (aq) + 4e^- \rightarrow 2H_2O\ (l)$	1.229
$Ag^+\ (aq) + e^- \rightarrow Ag\ (s)$	0.7996
$O_2\ (g) + 2H^+ + 2e^- \rightarrow H_2O_2$	0.695
$Cu^+\ (aq) + Cl^- + e^- \rightarrow CuCl\ (s)$	0.559
$Cu^+\ (aq) + e^- \rightarrow Cu\ (s)$	0.52
$O_2\ (g) + 2H_2O\ (l) + 4e^- \rightarrow 4OH^-$	0.401
$Cu^{2+}\ (aq) + 2e^- \rightarrow Cu\ (s)$	0.3419
$AgCl\ (s) + e^- \rightarrow Ag\ (s) + Cl^-\ (aq)$	0.2223
$2H^+\ (aq) + 2e^- \rightarrow H_2\ (g)$	0.000
$Ga^{3+} + 3e^- \rightarrow Ga\ (s)$	-0.56
$2H_2O\ (l) + 2e^- \rightarrow H_2\ (g) + 2OH^-\ (aq)$	-0.828
$Mn^{2+} + 2e^- \rightarrow Mn\ (s)$	-1.17
$Ba^{2+} + 2e^- \rightarrow Ba\ (s)$	-2.92

a) What products are most thermodynamically favored at the electrode sites? Make sure to include their phases. ***(2 points)***

Reaction at cathode: $O_2\ (g) + 4H^+\ (aq) + 4e^- \rightarrow 2H_2O\ (l)$ Ered=1.229 V

Reaction at anode: $Mn\ (s) \rightarrow Mn^{2+}\ (aq) + 2e^-$ Eox = -(-1.17) = 1.17 V

Products: $H_2O\ (l)$, $Mn^{2+}\ (aq)$

+2 points for correct products with correct phases

b) Write the net ionic equation of the complete reaction that takes place. ***(2 points)***

$2Mn\ (s) + O_2\ (g) + 4H^+\ (aq) \rightarrow 2H_2O\ (l) + 2Mn^{2+}\ (aq)$

+2 points for correct equation

c) Assuming that the reaction takes place while the reactants and products are in their standard states at a temperature of 25℃, what is the equilibrium constant of the reaction that takes place? If you were unable to solve parts (a) and (b), use the value E° = 3.00 V for the cell and assume that 3 moles of electrons were used in both the reduction and oxidation half-reactions. Leave the answer in exponential form. ***(4 points)***

$E^{\circ} = 1.229 + 1.17 = 2.399$ V

$\Delta G^{\circ} = -nFE^{\circ} = -(4\ \text{mol}\ e^-)(96,485\ C/mol\ e^-)(2.399\ \text{V}) = -925870.06$ J/mol

$K = e^{\frac{\Delta G^{\circ}}{-RT}} = e^{\frac{(-925870.06\ J/mol)}{-(8.31451\ J/mol\ K)\ (298.15\ K)}} = e^{373.49}$

+2 points for correct equations

+1 point for correct substitutions

+1 point for correct answer

If unable to solve parts (a) and (b): for E° = 3V and 3 mol electrons: $\Delta G^{\circ} = -nFE^{\circ} = -(3\ \text{mol}\ e^-)(96,485\ C/mol\ e^-)(3.00\ \text{V}) = -868365$ J/mol

$K = e^{\frac{\Delta G^{\circ}}{-RT}} = e^{\frac{(-868365\ J/mol)}{-(8.31451\ J/mol\ K)\ (298.15\ K)}} = e^{350.29}$

d) The hydrolytic cell was allowed to run for 5 hours. What was the current through the electrode wires during that time? Use the same assumptions as part (c) if you were unable to solve parts (a) and (b). ***(2 points)***

$I = \frac{(4\ mol\ e^-)(96{,}485.31\ C/mol\ e^-)}{(5\ hrs)(3600\ s/hr)} = 21.44118\ A$

+1 point for correct equation

+1 point for correct answer

If able to solve (a) and (b): for E° = 3V and 3 mol electrons:

$$I = \frac{(3\ mol\ e^-)(96{,}485.31\ C/mol\ e^-)}{(5\ hrs)(3600\ s/hr)} = 16.081\ A$$

e) The chemist removed the electrodes from the mixture. Does the reaction continue? Be sure to justify your answer. ***(2 points)***

The reaction **continues** because there is a negative free energy change, so this reaction will happen spontaneously in the direction written, without the use of electrodes. Also, the reaction continues until it reaches equilibrium.

+1 point for stating reaction continues

+1 point for stating correct reasoning

f) Assuming that ΔH° for the reaction that takes place is -571.6 kJ/mol when the reaction occurs at a temperature of 25℃, what is the standard molar entropy change of the reaction? Report your answer in J/mol K. ***(2 points)***

$$lnK = \frac{-\Delta H^{\circ}}{RT} + \frac{\Delta S^{\circ}}{R}$$

$$\Delta S^{\circ} = RlnK + \frac{\Delta H^{\circ}}{T}$$

$$\Delta H^{\circ} =- 571.6\ kJ/mol,\ K = e^{373.49},\ T = 25 + 273.15 = 298.15\ K$$

$$\Delta S^{\circ} = (8.31451\ J/mol\ K)ln(e^{373.49}) + \frac{-571600\ J/mol}{298.15\ K} = 1188.231\ J/mol\ K$$

+1 point for correct equation or other valid equation

+1 point for correct answer

If able to solve (a) and (b): for $K = e^{350.29}$

$$\Delta S^{\circ} = (8.31451\ J/mol\ K)ln(e^{350.29}) + \frac{-571600\ J/mol}{298.15\ K} = 995.334\ J/mol\ K$$

g) Another chemist has a mixture with the same exact materials but in non-standard state amounts. Using a voltmeter, they measure the potential of the cell to be 4.051 V. The temperature in the lab is a warm 29.3℃. Is the reaction at equilibrium? If not, which direction must the reaction go to reach equilibrium? If you were unable to solve parts (a) and (b), use the value E° = 3.00 V for the cell and assume that 3 moles of electrons were used in both the reduction and oxidation half-reactions. ***(4 points)***

$$\Delta E_{cell} = \Delta E^{0}_{cell} - \frac{RT}{nF} ln(Q)$$

$$\Delta E_{cell} = 4.051\, V,\ \Delta E^{0}_{cell} = 2.399\, V,\ R = 8.31451\, J/mol\, K,\ F = 96485.31\, C/mol,\ n = 4\, mol$$

$$T = 29.3 + 273.15 = 302.45\, K$$

$$\frac{-nF}{RT} (\Delta E_{cell} - \Delta E^{0}_{cell}) = ln(Q)$$

$$\frac{-(4\, mol)(96485.31\, C/mol)}{(8.31451\, J/mol\, K)(302.45\, K)} (4.051\, V - 2.399\, V) =- 253.537 = ln(Q)$$

$Q = e^{-253.537}$ vs. $K = e^{373.49}$

The reaction must go to the right.

+1 point for using Nernst equation

+1 point for correct substitution into Nernst equation)

+1 point for Q vs. K comparison

+1 point for correct answer

If able to solve (a) and (b): for n = 3 mol, E° = 3.00 V, K = $e^{350.29}$:

$$\frac{-(3\, mol)(96485.31\, C/mol)}{(8.31451\, J/mol\, K)(302.45\, K)} (4.051\, V - 3.00\, V) =- 120.975 = ln(Q)$$

$Q = e^{-120.975}$ vs. $K = e^{350.29}$

The reaction must go to the right.