03/14/2022

Honors General Chemistry (Chem H2B) Winter 2022
Final Exam

Instructions

- Answer the questions below in the spaces provided. For full credit, results must be *inside* the answer boxes, rounded exactly to the requested precision, and in the correct units.
- If you need additional space for your work, use separate sheets of paper (provided to you during the exam), and submit them together with the exam. Do not write on the back of any sheet.
- This exam is administered in person and closed book. You may use a calculator and a hand-written 4"×6" note card (with writing on both sides), but no other electronic devices, notes, or books are allowed.
- This exam comprises 11 problems on 7 pages (excluding the cover page).
- Constants, unit conversions, and useful identities are provided in the appendix.
- Please use only the molar masses provided in each problem and the exact values of the constants provided in the Appendix. Do not take atomic weights from the periodic table.
- Do not round intermediate results.
- Exam time is 120 minutes.

By submitting this exam, you certify under the penalty of an academic integrity violation that all results are your own and were obtained according to the rules above. You consent to be forthcoming to any subsequent questions about your results and how exactly they were obtained, and understand that you may not receive credit if you cannot give a satisfactory answer.

Problems

1. Ammonia Fuel Cell (4 credits)

Ammonia fuel cells use oxygen from the air to combust ammonia gas. In modern cells, the exhaust contains only dinitrogen and water.

a) Formulate the balanced chemical equation for the combustion reaction, including states.

Answer :

b) How many grams of ammonia are necessary to generate 1 kWh of electricity at standard conditions? Assume that the fuel cell operates at 99% efficiency. The standard free enthalpies of formation of ammonia gas and liquid water are −16.4 kJ/mol and −237.1 kJ/mol, respectively.

Answer (3 significant figures):

2. Hess's Law (4 credits)

Ethyne (a.k.a. acetylene, C_2H_2) is commonly used in welding. Ethyne gas may be synthesized by reaction of calcium carbide (CaC_2) with water.

You are given the following data:

$$\mathrm{CaO(s) + H_2O(l) \rightarrow Ca(OH)_2(s)} \qquad \Delta H_r^\circ = -65.3 \text{ kJ/mol}$$
$$\mathrm{2\ CaO(s) + 5\ C(s,graphite) \rightarrow 2\ CaC_2(s) + CO_2(g)} \qquad \Delta H_r^\circ = 753.1 \text{ kJ/mol}$$
$$\mathrm{CaC_2(s) + 2\ H_2O(l) \rightarrow Ca(OH)_2(s) + C_2H_2(g)} \qquad \Delta H_r^\circ = -126.2 \text{ kJ/mol}$$
$$\mathrm{C(s,graphite) + O_2(g) \rightarrow CO_2(g)} \qquad \Delta H_r^\circ = -393.5 \text{ kJ/mol}$$
$$\mathrm{2\ H_2O(l) \rightarrow 2\ H_2(g) + O_2(g)} \qquad \Delta H_r^\circ = 571.8 \text{ kJ/mol}$$

a) Write the chemical equation for the formation of C_2H_2 including states.

Answer :

b) Determine the standard enthalpy of formation of gaseous ethyne.

Answer (3 significant figures):

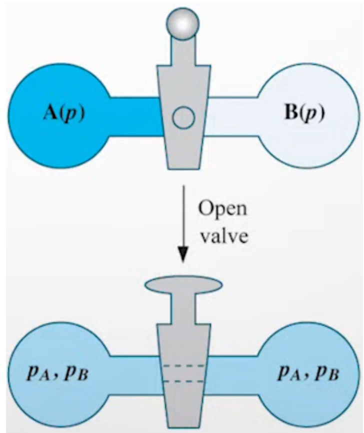


Figure 1: Two gases A and B separated into equal volumes.

3. Mixing Ideal Gass (6 credits)

At 25°C, equal volumes pure nitrogen dioxide and pure dinitrogen tetroxide are initially separated by a valve, see Figure 1. The initial pressure of both gases is 1.25 atm. The valve is then opened, allowing the gases to mix. Assume ideal gas behavior in the following.

a) Dinitrogen tetraoxide is in equilibrium with nitrogen dioxide. Formulate the balanced chemical equation including states.

Answer :

b) Determine the free energy of mixing ΔG_{mix}.

Answer (2 significant figures):

c) At 25°C, the equilibrium constant K for dissociation of dinitrogen oxide is 0.1481. What are the thermodynamic driving forces making the gases (i) mix and (ii) equilibrate spontaneously?

Answer :

4. Gas Equilibrium (5 credits)

Phosgene ($COCl_2$) is a toxic, colorless gas used in the manufacturing of polyurethanes and polycarbonate plastics. At 527°C, it decomposes into carbon monoxide and chlorine.

a) Formulate the balanced chemical equation for the decomposition of $COCl_2$, including states.

Answer :

b) At 527°C, the equilibrium constant K is 3.08×10^{-4}. Given the thermodynamic data in Table 1, determine K at 50°C.

Compound	Δ H$_f^\circ$ (kJ/mol)
Phosgene	-220.92
Carbon Monoxide	-110.54
Chlorine	0

Table 1: Standard enthalpy of formation data.

Answer (3 significant figures):

5. Essay Question: Intermolecular Interactions (4 credits)

The boiling points of methanol, methanethiol, and methaneselenol are 65°C, 6°C, and 12°C. Explain in a few sentences what types intermolecular interactions are present in each of these cases, and give a rationale for the trend in the observed boiling points. Why does methanethiol have the lowest boiling point of all three?

Answer :

6. Boiling Points and Vapor Pressures (4 credits)

Consider the following compounds: water, decane, sulfuric acid, and methanol.

a) Order the above compounds by decreasing volatility.

Answer :

b) Order the above compounds by decreasing boiling point.

Answer :

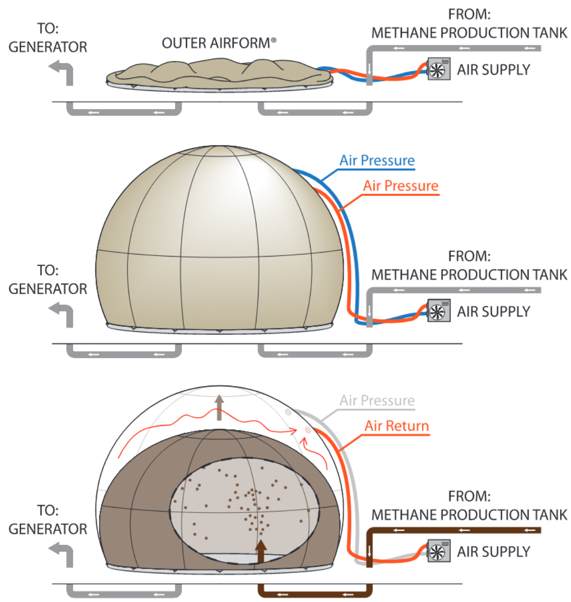
7. Colligative Property of Solutions (4 credits)

An aqueous solution contains 10.5% NaCl by mass. What is the substance amount of water in mol contained in 2.5 L of the vapor above the solution at 55°C? The vapor pressure of pure water at 55°C is 118 torr. Assume ideal behavior.

Answer (3 significant figures):

8. Statistical Thermodynamics (7 credits)

Dairy farms accounted for approximately 10% of greenhouse gas emissions in 2019, according to the US Environmental Protection Agency. Some farms use manure to convert it to methane gas, which may be used, e.g., for electricity generation. Assume ideal gas conditions in the following.



a) Methane gas is stored in an airtight tank, see Figure . Determine the total enthalpy of 10 kg of methane stored at 300 K.

Answer (3 significant figures):

b) Estimate the root mean square velocity of the methane molecules in m/s at 300 K. The molecular mass of methane is 2.665×10^{-26} kg.

Answer (3 significant figures):

c) On a warm day, the tank expands from 15 L to 17.5 L. Estimate the molar heat capacity $C_{p,m}$ in multiples of the ideal gas constant R using the equipartition theorem.

Answer :

d) Compute the change in internal energy for this state change.

Answer (3 significant figures):

9. Boiling Water at High Elevation (8 credits)

The barometric formula is

$$P_h = P_0 e^{-\frac{Mgh}{RT}}$$

where P_h is the pressure at height h, P_0 is the pressure at sea level, M is the molar mass of air (28.97 g/mol), R is the ideal gas constant, and T is the temperature. Report to 3 significant figures.

a) Before hiking to the peak of Mt. Everest, hikers often make a stop at the Everest base camp in Nepal. The altitude is 5,364 m. Approximate the atmospheric pressure at the base camp given that the pressure at ground level and 25°C is 760. torr.

Answer (3 significant figures):

b) At the Everest base camp, what temperature does the water boils at? Assume the enthalpy of vaporization of water ΔH_{vap} is 40.7 kJ/mol.

Answer (3 significant figures):

c) Use the value in part b), how much energy is needed to convert 1 L of ice (density is 0.917 g/mL) at -10° into steam? Assume the specific heats of ice and water are 2.093 J/(g °C) and 4.186 J/(g °C), respectively. The ΔH_{fus} is 6.01 kJ/mol.

Answer (3 significant figures):

10. Essay Question: Properties of Water (4 credits)

a) Water has unique properties that allow life to thrive on Earth. Explain in a few sentences how water plays a key role in regulating the Earth's climate. Include in your asnwer at least one relevant property of water.

Answer :

b) Based on the phase diagram in Figure 2, why is the solid-liquid slope steep and negative? *Hint:* Gibbs–Duhem equation $\sum_i N_i \Delta\mu_i = V\Delta P - S\Delta T$

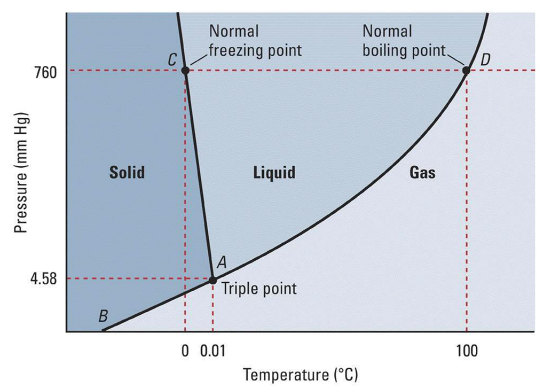


Figure 2: Phase diagram of water

Answer :

11. Extra Credit: Crystal Structures (3 credits)

Classify the following solids as molecular, covalent, ionic, and metallic solids: polonium, ammonium sulfate, silicon dioxide (sand), ice, and graphite.

Answer :

Appendix A: Constants and Unit Conversions

Constant	Symbol	Value
Ideal gas constant	R	8.3145 J/(mol K)
Boltzmann constant	k	1.3806×10^{-23} J/K
Avogadro's constant	N_A	6.022×10^{23} mol^{-1}
Standard temperature (STP)	T_s	273.15 K
Standard pressure (STP)	P_s	101325 Pa = 1 atm
Molar volume of an ideal gas at STP	v_s	22.414 L/mol
Standard thermodynamic pressure	P°	100 kPa

Table 2: Physical constants

Quantity	Conversion
Volume	1 gal = 3.7854 L
Temperature	$\theta_C/^\circ C = (\theta_F/F - 32) \times \frac{5}{9}$
Pressure	1 atm = 101325 Pa = 760 torr
Energy	1 kWh = 3.6×10^6 J

Table 3: Unit conversions

Appendix B: Identities

Free energy change of an isothermal gas expansion:

$$G(P) = G^\circ + nRT \ln \frac{P}{P^\circ}$$

Van't Hoff Equation:

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

Average kinetic energy:

$$E_{\mathrm{kin}} = \frac{1}{2} m v_{\mathrm{rms}}^2$$

Clausius–Clapeyron Equation:

$$P_f = P_i e^{-\frac{\Delta H_{\mathrm{vap}}}{R}\left(\frac{1}{T_f} - \frac{1}{T_i}\right)}$$

Appendix C: Periodic Table of the Elements

Periodic Table of the Elements

Do NOT use the atomic weights given here to answer exam questions!!!

hydrogen 1 **H** 1.0079																		helium 2 **He** 4.0026
lithium 3 **Li** 6.941	beryllium 4 **Be** 9.0122												boron 5 **B** 10.811	carbon 6 **C** 12.011	nitrogen 7 **N** 14.007	oxygen 8 **O** 15.999	fluorine 9 **F** 18.998	neon 10 **Ne** 20.180
sodium 11 **Na** 22.990	magnesium 12 **Mg** 24.305												aluminium 13 **Al** 26.982	silicon 14 **Si** 28.086	phosphorus 15 **P** 30.974	sulfur 16 **S** 32.065	chlorine 17 **Cl** 35.453	argon 18 **Ar** 39.948
potassium 19 **K** 39.098	calcium 20 **Ca** 40.078		scandium 21 **Sc** 44.956	titanium 22 **Ti** 47.867	vanadium 23 **V** 50.942	chromium 24 **Cr** 51.996	manganese 25 **Mn** 54.938	iron 26 **Fe** 55.845	cobalt 27 **Co** 58.933	nickel 28 **Ni** 58.693	copper 29 **Cu** 63.546	zinc 30 **Zn** 65.39	gallium 31 **Ga** 69.723	germanium 32 **Ge** 72.61	arsenic 33 **As** 74.922	selenium 34 **Se** 78.96	bromine 35 **Br** 79.904	krypton 36 **Kr** 83.80
rubidium 37 **Rb** 85.468	strontium 38 **Sr** 87.62		yttrium 39 **Y** 88.906	zirconium 40 **Zr** 91.224	niobium 41 **Nb** 92.906	molybdenum 42 **Mo** 95.94	technetium 43 **Tc** [98]	ruthenium 44 **Ru** 101.07	rhodium 45 **Rh** 102.91	palladium 46 **Pd** 106.42	silver 47 **Ag** 107.87	cadmium 48 **Cd** 112.41	indium 49 **In** 114.82	tin 50 **Sn** 118.71	antimony 51 **Sb** 121.76	tellurium 52 **Te** 127.60	iodine 53 **I** 126.90	xenon 54 **Xe** 131.29
caesium 55 **Cs** 132.91	barium 56 **Ba** 137.33	57-70 *	lutetium 71 **Lu** 174.97	hafnium 72 **Hf** 178.49	tantalum 73 **Ta** 180.95	tungsten 74 **W** 183.84	rhenium 75 **Re** 186.21	osmium 76 **Os** 190.23	iridium 77 **Ir** 192.22	platinum 78 **Pt** 195.08	gold 79 **Au** 196.97	mercury 80 **Hg** 200.59	thallium 81 **Tl** 204.38	lead 82 **Pb** 207.2	bismuth 83 **Bi** 208.98	polonium 84 **Po** [209]	astatine 85 **At** [210]	radon 86 **Rn** [222]
francium 87 **Fr** [223]	radium 88 **Ra** [226]	89-102 **	lawrencium 103 **Lr** [262]	rutherfordium 104 **Rf** [261]	dubnium 105 **Db** [262]	seaborgium 106 **Sg** [266]	bohrium 107 **Bh** [264]	hassium 108 **Hs** [269]	meitnerium 109 **Mt** [268]	ununnilium 110 **Uun** [271]	unununium 111 **Uuu** [272]	ununbium 112 **Uub** [277]		ununquadium 114 **Uuq** [289]				

*Lanthanide series	lanthanum 57 **La** 138.91	cerium 58 **Ce** 140.12	praseodymium 59 **Pr** 140.91	neodymium 60 **Nd** 144.24	promethium 61 **Pm** [145]	samarium 62 **Sm** 150.36	europium 63 **Eu** 151.96	gadolinium 64 **Gd** 157.25	terbium 65 **Tb** 158.93	dysprosium 66 **Dy** 162.50	holmium 67 **Ho** 164.93	erbium 68 **Er** 167.26	thulium 69 **Tm** 168.93	ytterbium 70 **Yb** 173.04
**Actinide series	actinium 89 **Ac** [227]	thorium 90 **Th** 232.04	protactinium 91 **Pa** 231.04	uranium 92 **U** 238.03	neptunium 93 **Np** [237]	plutonium 94 **Pu** [244]	americium 95 **Am** [243]	curium 96 **Cm** [247]	berkelium 97 **Bk** [247]	californium 98 **Cf** [251]	einsteinium 99 **Es** [252]	fermium 100 **Fm** [257]	mendelevium 101 **Md** [258]	nobelium 102 **No** [259]