Name ____________________________ Topics ID # _____________________

Team Name ____________________________________

2023 WUCT: Chemistry of Astronomy

April 1st, 2023
11:00 a.m. – 12:00 p.m.

1 HOUR will be allowed for the exam. The examination contains **7** questions on **21** numbered pages, including the last **SCRATCH PAGE**.

TURN IN THE ENTIRE EXAM (INCLUDING THE SCRATCH PAGE) WHEN YOU ARE FINISHED!

Exam Points Breakdown:

1. (14 pts)
2. (12 pts)
3. (17 pts)
4. (12 pts)
5. (14 pts)
6. (15 pts)
7. (16 pts)
Total Points: (100 pts)

Please fill in the numbers of your 6-digit topics ID:

Topics ID

⑨	⑨	⑨	⑨	⑨	⑨
⑧	⑧	⑧	⑧	⑧	⑧
⑦	⑦	⑦	⑦	⑦	⑦
⑥	⑥	⑥	⑥	⑥	⑥
⑤	⑤	⑤	⑤	⑤	⑤
④	④	④	④	④	④
③	③	③	③	③	③
②	②	②	②	②	②
①	①	①	①	①	①
⓪	⓪	⓪	⓪	⓪	⓪

2023 WUCT: Chemistry of Astronomy

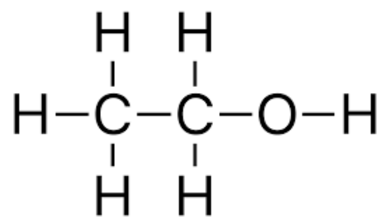
This exam consists of 7 questions and is worth 100 points. You will complete this exam as a team. You will have 1 hour to take the exam. The only allowed resources for this exam are a calculator and the provided equation sheet. You may NOT use any other notes or books. You must show your work and box your final answer to receive credit for a problem. NOTE: If you get the answer to an early part of a question incorrect but later use that answer for a subsequent part of the question, you can still earn full credit for those subsequent parts. Please write your answer in the designated space on the answer sheet. If you need additional space for a problem, you may use the blank scratch page at the end of the exam. Make sure to clearly indicate in the problem's designated space where the rest of your work can be found. Any work anywhere other than the exam or the scratch page will not be graded. Dark pencil or pen is preferred.

Problem #1: ***(14 points)***

Astrochemists use methanol to measure magnetic fields. By measuring the radio signals from methanol molecules, they can better understand the magnetic fields that play a vital role in determining where enormous stars are born.

a. Methanol has the molecular formula CH_3OH. Draw the viable Lewis structure(s) and label any non-zero formal charges. If any valid resonance forms exist, draw them and circle the major contributor. ***(2 points)***

Sagittarius B2 is a massive molecular cloud of gas and dust located almost 390 lightyears away from Earth. It contains methanol, ethanol, and vinyl alcohol. The Lewis structure for ethanol is provided below.



b. Using the provided structure for ethanol, as well as the Lewis structure(s) you drew for methanol in part (a), determine which has the larger vapor pressure based on the strength of their intermolecular forces and molecular sizes. Explain your ranking. Assume both compounds exist in a liquid state at the same temperature. ***(3 points)***

Over the past 20 years, researchers have discovered that interstellar clouds contain methanol. To better understand the organic compound, they have devised an experiment in which a 5.48 mol sample of methanol is placed in a 13.5 L evacuated rigid tank before being heated to 333˚C. Since methanol's boiling point is 64.7˚C, all of the methanol in the tank is vaporized at 333˚C and the methanol decomposes to form carbon monoxide and hydrogen gas.

c. Write the balanced molecular equation for this decomposition process. ***(1 point)***

d. The reaction mixture has 4.58 mol of H_2(g) at 333˚C. Calculate the number of moles of CO(g) in the tank. ***(2 points)***

e. At 333˚C, rank the three gases (CH_3OH, CO, and H_2) based on increasing average molecular speed, then rank them based on increasing kinetic energy. Note: You should have two separate rankings. ***(2 points)***

Now consider the reverse reaction of the one you provided in part (c). This combination reaction was studied at 29˚C and the following results were obtained.

Experiment	$[CO]_0$ (mol/L)	$[H_2]_0$ (mol/L)	Initial Rate (mol/L*s)
1	0.070	0.035	13.0×10^{-6}
2	0.035	0.035	6.5×10^{-6}
3	0.070	0.0175	6.5×10^{-6}
4	0.030	0.035	5.57×10^{-6}
5	0.050	0.030	7.5×10^{-6}

f. Determine the rate law with correct orders for each species. Based on the order of the reaction with respect to each species, what is the overall order? ***(3 points)***

g. Assume the reaction was a fourth order reaction. If the concentration of one of the reactants doubles, the rate increases by a factor of 2. How will the rate of the reaction change if the concentration of the other reactant is halved? Explain. ***(1 point)***

<u>Problem #2</u>: *(12 points)*

The majority of Venus's atmosphere is made up of carbon dioxide gas, $CO_2(g)$. Thick clouds of gaseous sulfuric acid, $H_2SO_4(g)$, trap heat and cause a runaway greenhouse gas effect.

a. Draw the most preferred Lewis structure of H_2SO_4 with minimized formal charges. ***(1 point)***

b. Name the geometry of the central S atom. ***(1 point)***

c. A sample of a cloud in the atmosphere of Venus is collected in an evacuated, heat-resistant 10.0 L container. The total pressure inside the container is 7,220 torr. 85% of that pressure is due to CO_2. The temperature inside the container is measured to be 37 °C. How many moles of H_2SO_4 are in the sample? Assume the gases are behaving ideally. ***(3 points)***

d. If all of the H_2SO_4 gas collected in part (c) was distilled into liquid, what would the mass of this liquid be? ***(2 points)***

One common reaction that occurs in Venus's atmosphere is the synthesis of H_2SO_4 from sulfur dioxide, oxygen, and water.

e. Balance the following equation: ***(2 points)***

________SO_2 + ________O_2 + ________H_2O → ________H_2SO_4

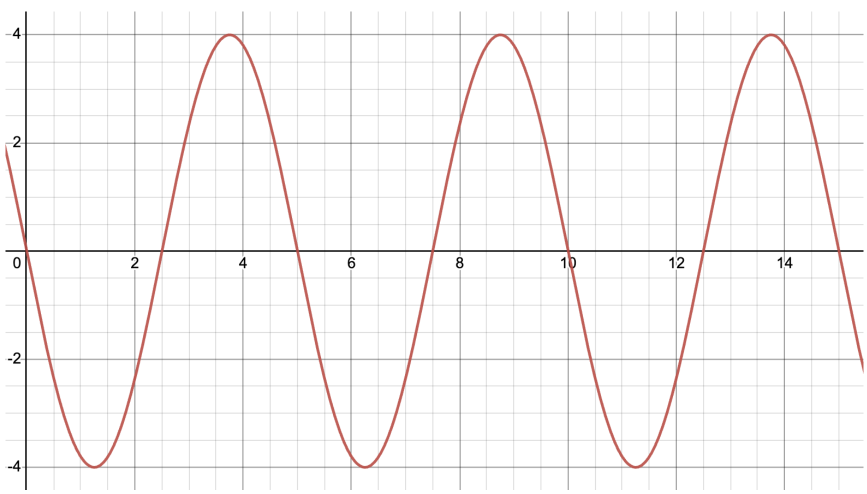
f. Recreating this synthesis in a lab back on Earth, chemists combine 17 mol of SO_2 and 20 mol of O_2 with an excess of water vapor. How many mL of H_2SO_4 are produced if the density of H_2SO_4 is 1.83 g/mL? ***(3 points)***

<u>Problem #3</u>: *(17 points)*

The greatest amount of sunlight is emitted in waves with wavelengths around 500 nm, which is why the sun appears yellow. However, the sun also emits wavelengths of light in many other regions of the electromagnetic spectrum, such as the infrared, ultraviolet, and radio regions.

a. A wave of light with a frequency of $1.038 \times 10^{15}\ Hz$ is emitted from the Sun. What is the wavelength of this wave **in nanometers**? ***(2 points)***

b. The graph below plots the position of a point on a radio wave over time in picoseconds. Answer the following questions.



i. What is the wavelength of this photon (in meters)? ***(3 points)***

ii. What is the energy of this radio wave (in Joules)? ***(2 points)***

c. A UV light wave with a wavelength of 259 nm emitted from the sun zooms through space and strikes a large piece of aluminum metal on Earth. Electrons are ejected with a maximum speed of $4.97 \times 10^5\ m/s$. Answer the following questions.

i. What is the work function of the aluminum metal in **electron volts (eV)**? ***(3 points)***

ii. If the electrons on the piece of aluminum metal absorbed 2.5 eV of energy, what speed would they be ejected with? Explain in 1-2 sentences. ***(2 points)***

d. The amount of energy it takes to remove an electron from an atom or ion is called an ionization energy. Rank the following atoms from lowest first ionization energy to highest. ***(1 point)***

Cl, As, N, S

(lowest) __________ < __________ < __________ < __________ (highest)

e. After having been hit by a beam of UV light from the sun, a barium (Ba) atom's valence electrons are ejected. Name the ion and write out the complete ground state electron configuration for it, listing each orbital and the number of electrons present. ***(2 points)***

f. Another beam of UV light strikes a zirconium (Zr) atom, and electrons are ejected until there are 38 remaining. Name the ion and write out the ground state noble gas electron configuration for it. ***(2 points)***

<u>Problem #4</u>: *(12 points)*

Hydrogen is the most abundant element in stars. The light and heat produced in stars is from a process called Nuclear Fusion, in which two nuclei collide into each other in order to form a heavier new atom with a heavier nucleus.

a. Using the information above, what other element besides hydrogen is abundant in stars? Please explain your answer. ***(2 points)***

b. Please write a possible equation of the process illustrated above and explain your reasoning. (Hint: Use "Energy" somewhere in the equation and use your answer to part (a)) ***(2 points)***

c. It is hypothesized that some redox reactions on interstellar dust grains have the ability to create various polyatomic species. Consider the redox equation below. Find the oxidation and reduction half reaction as well as the fully balanced redox reaction. ***(6 points)***

$NiO_2 + Fe \Rightarrow Ni(OH)_2 + Fe(OH)_2$ in basic solution

Oxidation Half Reaction:

Reduction Half Reaction:

Fully Balanced Equation:

d. Spectroscopy is a technique used by astronomers to measure electromagnetic radiation from celestial objects. A spectrum of colors can be displayed and allow astronomers to predict what kinds of elements are in that celestial object. Suppose you had a wavelength that measured 560 nm. How much energy is released? ***(2 points)***

<u>Problem #5</u>: ***(14 points)***

On Earth, sulfur dioxide (SO_2) is naturally produced by volcanoes. This also happens to be the case on other terrestrial planets, such as Venus, and even Jupiter's moon Io. The story is completely different on gas giants such as WASP-39b, an exoplanet in the WASP-39 system with an equilibrium temperature of approximately 1100 K. The James Webb Space Telescope observed WASP-39b using its NIRSpec instrumentation and found an unexplained peak with a wavelength of 4.05 μm. The researchers working on this project were interested in determining if SO_2 was responsible for this peak and how it could be generated in WASP-39b's atmosphere.

a. In an H_2 rich atmosphere, the primary sulfur species is H_2S.

   i. What is the oxidation state of sulfur in H_2S? ***(2 points)***

   ii. What is the oxidation state of sulfur in SO_2? (***2 points)***

   iii. Can redox chemistry explain the generation of SO_2? Explain in one sentence. ***(2 points)***

b. The researchers studying the WASP-39b atmosphere proposed a free-radical based mechanism to explain their observations.

   i. Define "free-radical." ***(2 points)***

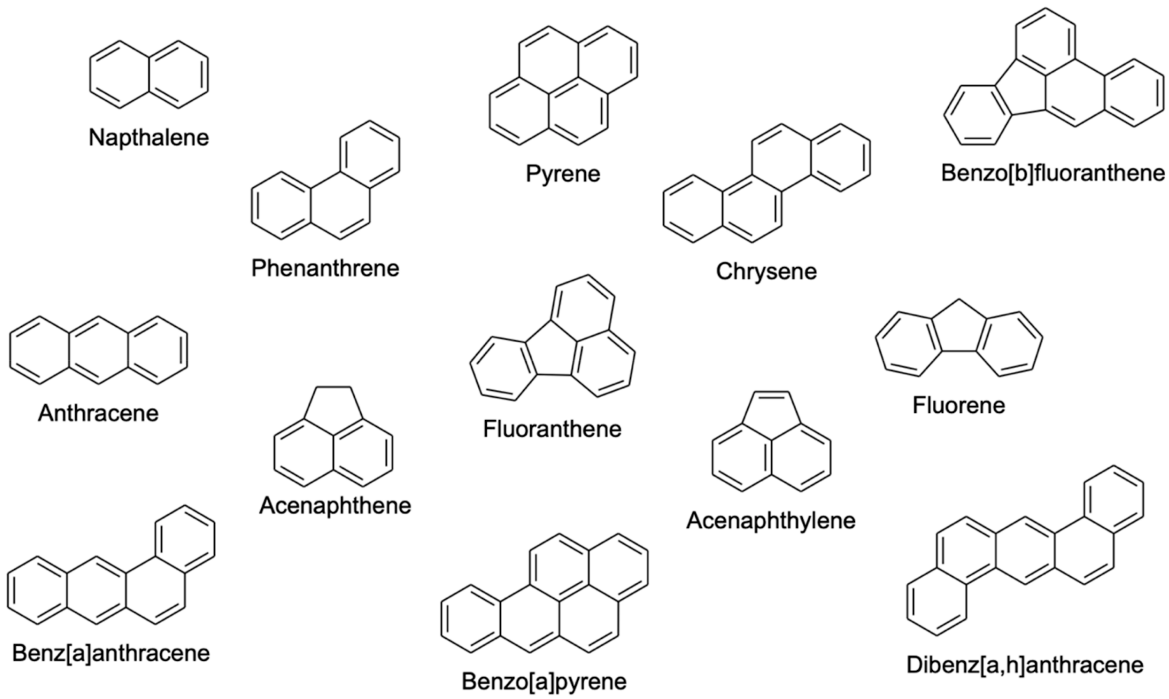
ii. The first step of the researchers' proposed mechanism generates a hydrogen and a hydroxyl radicals through photolysis according to the equation shown below:

$$H_2O \xrightarrow{hv} HO\cdot + H\cdot$$

Given the starting materials of 2 equivalents of H_2O and 1 equivalent of H_2S, propose a series of reactions using free-radical intermediates to yield 1 equivalent of SO_2 and 3 equivalents of H_2. (hint: one of the key intermediates in the process include the $S^{-\cdot}$ radical) ***(6 points)***

Problem #6: ***(15 points)***

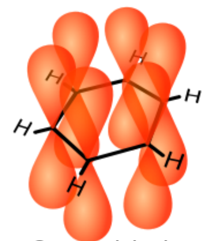
Most of the carbon in space is thought to exist in a form of molecules called polycyclic aromatic hydrocarbons (PAHs). Since the 1980s, evidence has shown that these molecules are abundant in space. However, they have not yet been directly observed. This speculative hypothesis, called the PAH World Hypothesis, proposes that polycyclic aromatic hydrocarbons are abundant in our universe today.



a. Explain why PAHs show low solubility in water. ***(2 points)***

b. Of the molecules that are shown above, which one has the lowest boiling point? ***(2 points)***

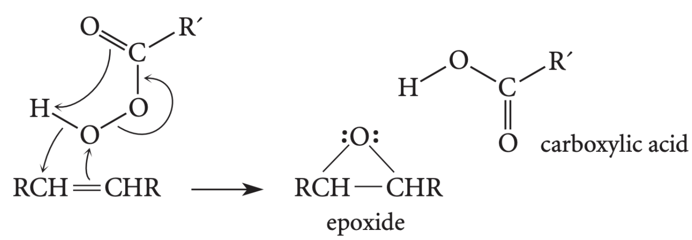
c. Aromatic molecules show π–π stacking (pi-pi stacking) interactions. π–π stacking refers to the attractive, noncovalent interactions (orbital overlap) between the p-orbitals of aromatic rings. The 6 p-orbitals of benzene are shown below. In the π–π stacking interaction for 2 benzene molecules, the 6 p-orbitals of one benzene molecule perfectly stack on top of the 6 p-orbitals of the other benzene molecule. Draw the full π–π stacking interaction between 2 anthracene molecules. ***(4 points)***



6 p-orbitals

d. When PAHs are subject to ionizing radiation like solar UV light, one of the outer hydrogens can get stripped off and get replaced by a hydroxyl (an -OH) group. If naphthalene is exposed to solar UV light, draw what the final molecule would look like. ***(2 points)***

e. One common modification that occurs on PAH molecules is epoxidation, which will make PAHs more reactive. Peroxycarboxylic acids are commonly used in epoxidation reactions. The full mechanism of epoxidation by peroxycarboxylic acids is shown below. Draw out the mechanism of epoxidation on fluorene in the presence of peroxycarboxylic acid. ***(3 points)***



f. Looking at the structure of epoxides, why are epoxides such reactive molecules? ***(2 points)***

Problem #7: ***(16 points)***

During the Big Bang, only the lightest elements were formed. The rest of the elements were formed through nuclear reactions. An example of an element formed in the Big Bang is hydrogen. Hydrogen has some stable isotopes. Deuterium, also called a heavy hydrogen, is an isotope of hydrogen with a nucleus that contains 1 proton and 1 neutron. The amount of deuterium made in Big Bang is about 10^{-5} of the amount of hydrogen produced. However, in recent years, observational results reveal that many interstellar molecules contain many deuterium atoms. These species have an abundance ratio compared to their fully hydrogenated forms. This enhancement in the ratio of D/H is due to a process called fractionation.

a. One of the important reactions involved in fractionation is:

$$H_3^+ + HD \rightleftarrows H_2D^+ + H_2$$

i. Assume that the left-to-right reaction is exothermic with $\Delta H =- 230kJ$ and the reaction happens at a temperature of 10K, calculate the entropy of the surroundings. ***(2 points)***

ii. Assuming that this reaction involves only gaseous molecules, predict the change in positional entropy in this reaction. Does it increase, decrease or stay the same? Justify your answer. ***(2 points)***

iii. At temperatures of cold interstellar clouds of 10K, the reverse reaction is inhibited. Explain why this happens in terms of Le Chatelier's Principle. ***(2 points)***

Deuterium can participate in a nuclear fusion reaction called deuterium-tritium fusion, which is one of the most efficient types of fusion for fusion devices used in power generation. (Tritium is an isotope of hydrogen with a nucleus that contains 1 proton and 2 neutrons).

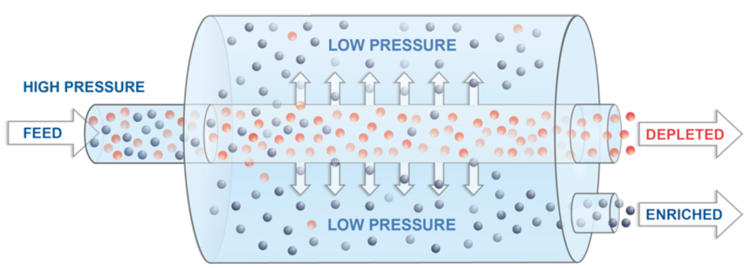
b. Given that in deuterium-tritium fusion, one deuterium atom fuses with one tritium atom to produce a helium atom with 1 neutron and 17.59 MeV of energy, write down the balanced equation for this nuclear reaction. ***(1 point)***

c. Since large quantities of energy are produced in nuclear fusion, scientists are trying to develop a feasible fusion process for energy generation. However, a major obstacle is that high temperatures are needed to initiate nuclear fusion. Explain why high temperature is necessary to initiate this reaction. ***(3 points)***

Another type of nuclear reaction process is nuclear fission, which is more stable than nuclear fusion and is used in all nuclear power plants. The most common substance used in the nuclear fission process is uranium-235. However, most of the natural uranium is uranium-238, which is non-fissionable, and there's only about 0.72% of uranium-235 by mass. In order to conduct nuclear fission, the amount of uranium-235 needs to be increased to about 3%. To enrich uranium-235, a process called gaseous diffusion is used.

d. In the diffusion process, natural uranium reacts with fluorine to form UF_6, and the gaseous diffusion process is based on Graham's law, which is an empirical law that states that the rate of effusion of a gas is inversely proportional to the square root of the mass of its particles ($\frac{Rate\ of\ effusion\ for\ gas\ 1}{Rate\ of\ effusion\ for\ gas\ 2} = \frac{\sqrt{M_2}}{\sqrt{M_1}}$). Given that fluorine only has one natural and common isotope, explain its significance in relation to Graham's law. ***(3 points)***

e. Using the given image below, explain the process of enrichment through the concepts in Graham's law. ***(3 points)***



<u>Scratch Page</u>