

Last Name: \_\_\_\_\_ First Name \_\_\_\_\_ NetID \_\_\_\_\_  
Discussion Section: \_\_\_\_\_ Discussion TA Name: \_\_\_\_\_

*Instructions—*

***Turn off your cell phone and put it away.***

***Keep your calculator on your own desk. Calculators may not be shared.***

***This is a closed book exam. You have ninety (90) minutes to complete it.***

1. Use a #2 pencil; do **not** use a mechanical pencil or a pen. Fill in completely (until there is no white space visible) the circle for each intended input – both on the identification side of your answer sheet and on the side on which you mark your answers. If you decide to change an answer, erase vigorously; the scanner sometimes registers incompletely erased marks as intended answers; this can adversely affect your grade. Light marks or marks extending outside the circle may be read improperly by the scanner.
2. Print your last name in the **YOUR LAST NAME** boxes on your answer sheet and print the first letter of your first name in the **FIRST NAME INI** box. Mark (as described above) the corresponding circle below each of these letters.
3. Print your NetID in the **NETWORK ID** boxes, and then mark the corresponding circle below each of the letters or numerals. Note that there are different circles for the letter “I” and the numeral “1” and for the letter “O” and the numeral “0”. **Do not** mark the hyphen circle at the bottom of any of these columns.
4. **This Exam Booklet is Version A.** Mark the **A** circle in the **TEST FORM** box at the bottom of the front side of your answer sheet.
5. Stop **now** and double-check that you have bubbled-in all the information requested in 2 through 4 above and that your marks meet the criteria in 1 above. Check that you do not have more than one circle marked in any of the columns.
6. Do **not** write in or mark any of the circles in the STUDENT NUMBER or SECTION boxes.
7. On the **SECTION line**, print your **DISCUSSION SECTION**. (You need not fill in the COURSE or INSTRUCTOR lines.)
8. Sign (**DO NOT PRINT**) your name on the **STUDENT SIGNATURE line**.

*Before starting work, check to make sure that your test booklet is complete. You should have 11 **numbered pages** plus two Formula Sheets at the end.*

***Academic Integrity—Giving assistance to or receiving assistance from another student or using unauthorized materials during a University Examination can be grounds for disciplinary action, up to and including expulsion.***

*Exam Grading Policy—*

The exam is worth a total of 108 points, composed of two types of questions.

**MC5:** *multiple-choice-five-answer questions, each worth 6 points.*

**Partial credit will be granted as follows.**

- (a) If you mark only one answer and it is the correct answer, you earn **6** points.
- (b) If you mark *two* answers, one of which is the correct answer, you earn **3** points.
- (c) If you mark *three* answers, one of which is the correct answer, you earn **2** points.
- (d) If you mark no answers, or more than *three*, you earn **0** points.

**MC3:** *multiple-choice-three-answer questions, each worth 3 points.*

**No partial credit.**

- (a) If you mark only one answer and it is the correct answer, you earn **3** points.
- (b) If you mark a wrong answer or no answers, you earn **0** points.

**The next two problems are related to the following situation:**

Consider a gas of  $O_2$  molecules (weight 32 g/mol) which are found to have an average rotational energy,  $\frac{1}{2}I\omega_x^2 + \frac{1}{2}I\omega_y^2$ , of  $4.9 \times 10^{-21}$  J.

1. What is the typical translational speed of these molecules?
  - a. 303 m/s
  - b. 350 m/s
  - c. 429 m/s
  - d. 526 m/s
  - e. 632 m/s
2. Now assume the container also has some Si atoms (also weight 32 g/mol, but monatomic). Compare the speeds of the two species.
  - a.  $v_{Ge} < v_{O_2}$
  - b.  $v_{Ge} > v_{O_2}$
  - c.  $v_{Ge} = v_{O_2}$

**The next two problems are related to the following situation:**

A 1-liter box contains 1 mole of  $N_2$  gas and 3 moles of He gas, all at temperature  $20^\circ C$ .

3. What is the pressure inside the box?
  - a. 6.6 atm
  - b. 96 atm
  - c. 120 atm
4. How much heat is required to raise the temperature of this gas mixture to  $30^\circ C$  (at constant volume)?
  - a. 340 J
  - b. 582 J
  - c. 970 J

**The next two problems are related to the following situation:**

Low temperature physicists need to pump heat away from their samples, to keep the environment from heating the samples up. To model this, consider a copper wire connected to a 100-K silver block at the “sample” end and to the room temperature (293 K) environment at the other end, as shown below. The wire has length 0.5 m, cross sectional area  $0.03 \text{ mm}^2$ , and thermal conductivity  $400 \text{ W/m-K}$ .



5. How much heat per second needs to be removed from the block to keep its temperature constant? (For this problem, ignore the heat capacity of the copper wire).

- a.  $4.6 \times 10^{-3} \text{ W}$
- b.  $2.1 \times 10^{-2} \text{ W}$
- c.  $8.7 \times 10^{-2} \text{ W}$
- d.  $35 \text{ W}$
- e.  $42,000 \text{ W}$

6. Assuming you are **not** using a refrigerator to keep  $T$  constant, compare the time it takes for the silver block to heat from 100 K to 105 K to the time it takes to heat from 105 K to 110 K.

- a.  $t_{100 \rightarrow 105} > t_{105 \rightarrow 110}$
- b.  $t_{100 \rightarrow 105} = t_{105 \rightarrow 110}$
- c.  $t_{100 \rightarrow 105} < t_{105 \rightarrow 110}$

**The next two problems are related:**

7. A 10-g lead bullet is traveling at 1000 m/s and has a temperature of 300° C immediately before it is embedded into a 500-g block of clay at 30° C, where it comes to a complete stop. The heat capacity of the lead bullet = 1.28 J/K, the heat capacity of the clay = 690.5 J/K. Assuming all of the bullet's kinetic energy is turned into thermal energy, what will the temperature of the system be when it reaches equilibrium?

- a. 30.5° C
- b. 37.7° C
- c. 29.7° C
- d. 303° C
- e. 278° C

8. Compare the change in entropy of the bullet ( $\Delta S_{\text{bullet}}$ ) to the change in entropy of the clay ( $\Delta S_{\text{clay}}$ ).

- a.  $|\Delta S_{\text{bullet}}| < |\Delta S_{\text{clay}}|$
- b.  $|\Delta S_{\text{bullet}}| = |\Delta S_{\text{clay}}|$
- c.  $|\Delta S_{\text{bullet}}| > |\Delta S_{\text{clay}}|$

**The next two problems are related:**

9. Consider a system of 6 spins that have values of either +1 or -1. Calculate the probability of finding a macrostate with total spin 0.

- a. 0
- b. 0.26
- c. 0.31
- d. 0.5
- e. 1

10. What is the dimensionless entropy of this macrostate?

- a. 0
- b. 3.00
- c. 3.47
- d. 4.16
- e. 4.79

**The next three problems are related:**

11. There are 10 oscillators (with the same energy level spacings) that share 6 energy quanta. What is the probability that one particular oscillator has just one energy quantum?

- a. 0.06
- b. 0.26
- c. 0.60
- d. 0.68
- e. 0.98

12. What is the most likely energy for one of the oscillators (in units of energy quanta)?

- a. 0
- b. 0.4
- c. 0.6

13. If two more oscillators are added to the system and thermally coupled to the rest of the oscillators, what is the change in dimensionless entropy?

- a. 0.23
- b. 0.45
- c. 0.72
- d. 0.91
- e. 1.11

14. Calculate the ratio of the entropies  $S_{\text{single}}/S_{\text{multiple}}$  obtained for the case of two distinguishable marbles in three single-occupancy bins compared to two distinguishable marbles in three multiple- occupancy bins, respectively:

- a.  $S_{\text{single}}/S_{\text{multiple}} = \ln(6)/\ln(9)$
- b.  $S_{\text{single}}/S_{\text{multiple}} = \ln(2)/\ln(3)$
- c.  $S_{\text{single}}/S_{\text{multiple}} = \ln(8)/\ln(9)$

**The next two questions pertain to the following situation:**

Professor Paul takes his dog Bumper on a walk every day. As this is often the time that Bumper needs to go to the bathroom, Paul carries along small plastic bags in which to pick up her “solid waste material”. After sealing one of the plastic bags, he notices that after about 10 seconds, he can nevertheless start to smell the contents, due to diffusion of the compounds through the thin plastic bag material (at least, we’ll model it that way here).

15. In order to increase the time before the bag starts smelling, Paul decides to use multiply nested bags, thereby increasing the effective thickness through which the molecules have to diffuse. In order to increase the time from 10 seconds to  $> 4$  minutes, what is the minimum number of bags should be nested together?

- a. 3
- b. 4
- c. 5
- d. 8
- e. 24

16. Paul notices that the problem is not so bad in the winter. What is the ratio of diffusion times when the temperature is  $-20^{\circ}\text{C}$  to when it is  $20^{\circ}\text{C}$  (assuming the mean free path in the plastic does not depend on temperature)?

- a.  $t(-20^{\circ}\text{C})/t(20^{\circ}\text{C}) = 1.08$
- b.  $t(-20^{\circ}\text{C})/t(20^{\circ}\text{C}) = 1.16$
- c.  $t(-20^{\circ}\text{C})/t(20^{\circ}\text{C}) = 1.48$

**The next four questions are related.**

Consider an atom with the following energy level structure: the ground (1s) and first excited (2s) states are singly degenerate, while the next level (2p) is triply degenerate ( $2p_x$ ,  $2p_y$ , and  $2p_z$ ) [here we ignore the additional degeneracies from electron spin].

$$\begin{array}{ll}
 E_{2p} = -2.0 \text{ eV} & \text{———} \quad \text{———} \quad \text{———} \quad 2p_x, 2p_y, 2p_z \\
 E_{2s} = -2.6 \text{ eV} & \text{———} \quad 2s \\
 \\ 
 E_1 = -3.6 \text{ eV} & \text{———} \quad 1s
 \end{array}$$

17. At  $500^\circ\text{C}$ , what is the probability to find an atom in the highest level?

- a.  $2.2 \times 10^{-16}$
- b.  $3.7 \times 10^{-11}$
- c.  $1.1 \times 10^{-10}$

18. As the temperature becomes very large, what happens to  $P(1_s)$ ?

- a.  $P(1_s) \rightarrow 0$
- b.  $P(1_s) \rightarrow 1/5$
- c.  $P(1_s) \rightarrow 1/3$
- d.  $P(1_s) \rightarrow 2/3$
- e.  $P(1_s) \rightarrow 1$

19. What is the entropy of  $N$  such atoms in the limit as  $T \rightarrow \infty$ ?

- a.  $S = 0$
- b.  $S = Nk \ln 5$
- c. Cannot tell from the information given

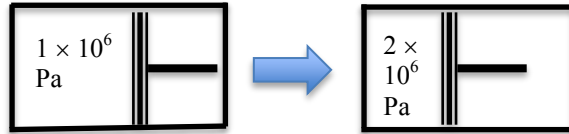
20. What happens to the contribution to the heat capacity of the atoms from these internal states, as  $T \rightarrow 0$ ?

- a.  $C \rightarrow 0$
- b.  $C \rightarrow Nk \ln 3$
- c.  $C \rightarrow Nk \ln 5$



The next three problems are related to the following situation:

A box contains  $10^{-3} \text{ m}^3$  of Ar gas at a pressure of  $1 \times 10^6 \text{ Pa}$ . The gas is compressed so that its final pressure is  $2 \times 10^6 \text{ Pa}$ . The box is isolated from its environment so there is no heat flow in or out.



21. How much work was done on the gas to compress it?

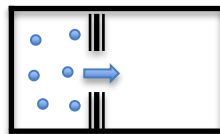
- a. 30 J
- b. 112 J
- c. 127 J
- d. 390 J
- e. 480 J

22. Compare the work done on the gas in the situation above ( $Q = 0$ ) to the cases where the gas is compressed at constant pressure ( $\Delta p = 0$ ) or at constant temperature ( $\Delta T = 0$ ), assuming the gas is initially at the same  $p$ ,  $V$ , and  $T$ . [Hint:  $PV$  diagrams are helpful here].

- a.  $W_{\Delta p=0} > W_{\Delta T=0} > W_{Q=0}$
- b.  $W_{Q=0} > W_{\Delta T=0} > W_{\Delta p=0}$
- c.  $W_{\Delta T=0} > W_{Q=0} > W_{\Delta p=0}$
- d.  $W_{\Delta p=0} > W_{Q=0} > W_{\Delta T=0}$
- e.  $W_{Q=0} > W_{\Delta p=0} > W_{\Delta T=0}$

23. After the gas is compressed, it is expanded again by opening a hole in the piston, as depicted below. The box is still thermally isolated from its environment. After it expands in this way, the temperature of the gas

- a. increases.
- b. decreases.
- c. stays the same.



24. The ratio of the number density  $n$  (e.g., molecules per liter) of He and  $H_2$  is 10.4 at sea level, i.e.,  $n(He)/n(H_2) = 10.4$ . At what approximate altitude (above sea level) would the number densities be the same (assuming the system can be well described by a Boltzmann distribution)? (Assume the temperature is a constant 270 K for all altitudes. Recall that  $m_{H_2} = 2$  g/mol,  $m_{He} = 4$  g/mol.)

- a. 1.5 km
- b. 90 km
- c. 140 km
- d. 270 km
- e. there is no altitude where these will have the same concentration

**Check to make sure you bubbled in all your answers.  
Did you bubble in your name, exam version and network-ID?**