Name: ________________________________

Student ID: ____________________________  TA: ____________________________

Contents: 9 pages
A. Multiple choice (7 points)
B. Stoichiometry (9 points)
C. Electron diffraction (8 points)
D. Particle-in-a-box (6 points)
E. Atomic orbitals (6 points)
F. Ionic bonding (6 points)
G. Covalent bonding (10 points)

Total Points: 50 points + 2 bonus

Instructions: Closed book exam. Basic scientific calculators are OK. Set brains in high gear and go!
It is usually a good idea to do the questions you find easy first.

Some possibly useful facts and figures:

\[ R = 8.3145 \text{ J mol}^{-1} \text{ K}^{-1} \]

\[ h = 6.6261 \times 10^{-34} \text{ J s} \]

\[ c = 2.9979 \times 10^8 \text{ m s}^{-1} \]

\[ m_e = 9.1094 \times 10^{-31} \text{ kg} \]

\[ N_0 = 6.0221 \times 10^{23} \text{ mol}^{-1} \]

\[ \text{molar volume at STP} = 22.4 \text{ L} \]

\[ \hbar = h / 2\pi \]

\[ 1 \text{ eV} = 1.60 \times 10^{-19} \text{ J} \]

\[ m_n = 1.6726 \times 10^{-27} \text{ kg} \]

Some possibly relevant equations:

Planck relation: \[ E = \hbar \nu \]

de Broglie relation: \[ p = \frac{\hbar}{\lambda} \]

wave equation: \[ c = \frac{n}{\lambda} \]

uncertainty principle \[ \Delta \varphi \Delta x \geq \hbar / 2 \]

particle-in-a-box \[ E_n = \frac{n^2 \pi^2 \hbar^2}{2ma^2} \]

hydrogen atom \[ E_n = -\frac{Z^2}{n^2} R_y \]

linear momentum \[ p = mv \]

kinetic energy \[ T = \frac{1}{2}mv^2 \]

photoelectric effect \[ E_{\text{kin}} (e^-) = h\nu - \Phi = h\nu - h\nu_0 \]
Multiple choice (7 points): there may be one or more correct solutions, so circle all that apply

1. Which of the following pairs of molecules have the same empirical formula?
   (a) acetylene (C₂H₂), benzene (C₆H₆) ✓
   (b) nitrogen dioxide (NO₂), dinitrogen tetroxide (N₂O₄) ✓
   (c) ethane (C₂H₆), butane (C₄H₁₀)
   (d) diphenyl ether (C₁₂H₁₀O), phenol (C₆H₅OH)

2. Which of the following set of quantum numbers are not allowed in the hydrogen atom?
   (a) n=3, l=2, m_l=2 ✓
   (b) n=0, l=0, m_l=0
   (c) n=4, l=3, m_l=4
   (d) n=2, l=-1, m_l=1

3. An electron’s wave-particle duality is captured by
   (a) the Schrodinger equation, \( \hat{H}\psi_n(x) = E_n\psi_n(x) \)
   (b) Heisenberg uncertainty, \( (\Delta p)(\Delta x) \geq h/4\pi \)
   (c) the wave equation, \( \psi = \lambda v \)
   (d) the De Broglie relation, \( p = h/\lambda \)

4. In a photoelectric effect experiment, green light is observed to lead to electron emission from a metal surface. Which other colors should lead to electron emission?
   (a) red
   (b) purple ✓
   (c) blue ✓
   (d) none of the above

5. The Bohr model is valid for which atoms?
   (a) H_2
   (b) Li^{2+} ✓
   (c) Be^{2+}
   (d) He^+

6. An atomic orbital of the hydrogen atom
   (a) has (n-1) total nodes ✓
   (b) determines the energy of the electron ✓
   (c) has l angular nodes ✓
   (d) when squared gives the probability density

7. Some plant fertilizer compounds are (NH₄)₂SO₄, Ca₃(PO₄)₂, K₂O, P₂O₅, and KCl. Which pairs contains molecules that both have a mixture of ionic and covalent bonds?
   (a) (NH₄)₂SO₄ and KCl ✓
   (b) K₂O and P₂O₅
   (c) (NH₄)₂SO₄ and Ca₃(PO₄)₂ ✓
   (d) P₂O₅ and KCl
B. (9 points) Stoichiometry and DDT
DDT is an insecticide that has been proven to be harmful to fish, birds and humans. It is produced by the following reaction
\[ \text{C}_6\text{H}_5\text{Cl} \text{ (chlorobenzene) } + \text{C}_2\text{HOCl}_3 \text{ (chloral)} \rightarrow \text{C}_{14}\text{H}_9\text{Cl}_5 \text{ (DDT) } + \text{H}_2\text{O}. \]

(a) (2 points) Write a balanced equation for this reaction.

\[ \text{ } \]

(b) (2 points) A sample of 1142 g of chlorobenzene is available. How many moles are in this sample? Provide the correct number of significant figures for full credit.

\[ \text{ } \]

(c) (2 points) The chlorobenzene sample from (a) is reacted with 6.000 moles of chloral. Which reagent is limiting and which reagent is in excess?

\[ \text{ } \]

(d) (3 points) What mass of excess reactant is left over if the reaction goes to completion? Both show your work, and record your final answer in the lower right.

\[ \text{ } \]
C. (8 points) Electron diffraction and wave-particle duality. A beam of electrons can exhibit diffraction from an ordered metal surface under some conditions, something which not be expected to happen according to classical physics.

(a) (2 points) What is the magnitude of the momentum for an electron beam with kinetic energy of 49 eV? Give units for full credit.

(b) (2 points) Suppose an electron beam with momentum $3.0 \times 10^{-24}$ kg m s$^{-1}$ causes diffraction on a metal surface. What de Broglie wavelength do the electrons have? Give units for full credit.

(c) (2 points) Would a beam of neutrons (mass $m_n$) require different energy to exhibit diffraction? Explain why or why not.

(d) (2 points) Evaluate the kinetic energy (give units) of the neutrons that would give diffraction.
D. (6 points) **Wavefunctions and nodes of the particle in a box.** An electron is trapped in a confining potential (like the particle in a box) which restricts its position in one dimension to a length of $3.14 \text{ Å}$.

(a) (2 points) The electron is described by a wavefunction that has the form $\sin(3x)$ where $x$ is the electron position (in Å). Make a sketch of how this wavefunction depends on $x$ from 0 to 3.14 Å.

(b) (1 point) How many nodes do you observe in your wavefunction, and what quantum number does this correspond to?

<table>
<thead>
<tr>
<th>Number of nodes?</th>
<th>Quantum number?</th>
</tr>
</thead>
<tbody>
<tr>
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<td></td>
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</table>

(c) (1.5 points) Would you expect that another particle in a box wavefunction of the form $\sin(4x)$ would have a lower or higher energy than your wavefunction in (a). Give a reason.

<table>
<thead>
<tr>
<th>Lower or higher?</th>
<th>Reason?</th>
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(d) (1.5 points) If the box size were halved to 1.57 Å, which of $\sin(3x)$ and $\sin(4x)$ would remain an allowed wavefunction? Give a brief reason.

<table>
<thead>
<tr>
<th>Which is allowed?</th>
<th>Reason?</th>
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</table>
E. (6 points) Atomic orbitals and their energy levels.

(a) (2 points) Write the ground state electron configurations of the following atoms and ions.

<table>
<thead>
<tr>
<th>Li:</th>
<th>F:</th>
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<tbody>
<tr>
<td>Ne:</td>
<td>Cr:</td>
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</table>

(b) (2 points) Electron attachment is the process of adding an electron to an atom or a molecule. Does this process release heat or not for the F atom? Give a reason for your answer.

(c) (2 points) (2 points) Does electron attachment release heat or not for the C atom? Give a reason for your answer.
F. (6 points) Ionic bonding

(a) (1.5 points) Give the expected charge of the ions of each of the following atoms.

Cl  | Al  | S

(b) (1 point) Predict the empirical formula of the ionic compound formed between aluminum and sulfur.

(c) (2 points) Suggest two factors that are important in comparing the lattice energy of LiF relative to the lattice energy of MgO (recall that the lattice energy is the difference between the ionic solid and the isolated gas phase ions).

1.  

2.  

(d) (1.5 points) Explain why you expect the lattice energy of LiF to be either smaller or bigger in magnitude than the lattice energy of MgO, based on the factors you identified above.
G. (10 points) Covalent bonding and Lewis structures.

(a) (4 points) Draw Lewis structures for the following species, showing lone pairs, unpaired electrons, resonance structures and formal charges, as necessary.

\[
\begin{array}{c|c}
\text{H}_2\text{O} & \text{C}_2\text{H}_4 \\
\text{CH}_3\text{O} & \text{C}_6\text{H}_6 \\
\end{array}
\]

(b) (2 points) The \(\text{CO}_3^{2-}\) ion is often used in water softeners, and has 3 O atoms coordinated to the central C atom. Draw Lewis structures for this ion including all relevant resonance forms and showing any lone pairs and formal charges.

(c) (1 point) What is the bond order of the CO bond in the \(\text{CO}_3^{2-}\) ion?

(d) (2 points) The \(\text{SO}_4^{2-}\) ion has 4 O atoms coordinated to the central S atom. Draw Lewis structures for this ion including all relevant resonance forms and showing any lone pairs and formal charges.

(e) (1 point) Does each O atom satisfy the octet rule in your Lewis structures? If not, how many electrons do O have a share in? Then repeat for the S atom.

\[
\begin{array}{c|c}
\text{O:} & \text{S:} \\
\end{array}
\]