(12 pts) 1. The rate of decay of $^{238}\text{U}$ is directly proportional to the amount of $^{238}\text{U}$ present. The half-life of $^{238}\text{U} = 4.47$ billion years $= 1.41 \times 10^{17}$ seconds. Calculate the number of disintegrations per second in 2.38 grams of $^{238}\text{U}$ (atomic mass = 238 g/mol).

\[
\begin{align*}
\ln 0.5 &= -k \times 1.41 \times 10^{17} \\
0.01 \text{ mol} \cdot 0.5 &= \frac{1}{2} k 1.41 \times 10^{17} \\
k &= \frac{-\ln 0.5}{1.41 \times 10^{17}} = 4.92 \times 10^{-18} \text{ dis. s}^{-1} \text{ per atom} \\
\frac{dN}{dt} &= -kN = (4.92 \times 10^{-18}) \times 0.01 \times 6 \times 10^{23} \\
&= 29,520 \text{ dis./sec}
\end{align*}
\]

(11 pts) 2. Calculate the Arrhenius activation energy for a reaction whose rate constant increases by a factor of 10 when the temperature is raised from 333.33 K to 400 K.

\[
\ln \frac{K_2}{K_1} = -\frac{E_a}{R} \left( \frac{1}{T_2} - \frac{1}{T_1} \right)
\]

\[
E_a = -R \ln \frac{K_2}{K_1} = -8.3145 \ln 10 \left( \frac{1}{T_2 - T_1} \right) = -8.3145 \ln 10 \left( \frac{1}{0.0005} \right) = 38,290 \text{ J/mol}
\]

\[
38.29 \text{ kJ/mol}
\]
(11 pts) 3. Calculate the ratio of excited state molecules to ground state molecules at equilibrium at 300 K if the energy level difference is given by the following photon wavenumbers. The Boltzmann constant is 0.697 cm⁻¹ K⁻¹.

(a) 1 cm⁻¹
\[ \frac{N_e}{N_g} = e^{-\frac{1}{209}} = 0.995 \]

(b) 300 cm⁻¹
\[ n = e^{-\frac{300}{209}} = 0.238 \]

(c) 1500 cm⁻¹
\[ n' = e^{-\frac{1500}{209}} = 0.00076 \]

(11 pts) 4. Consider the following mechanism of the reaction whose stoichiometry is given by:

\[ \text{H}_2 + \text{I}_2 \rightarrow 2\text{HI} \]

1) \[ \text{I}_2 \leftrightarrow 2\text{I} \] forward rate constant = \( k_1 \); back rate constant = \( k_1 \)
2) \[ \text{H}_2 + 2\text{I} \rightarrow 2\text{HI} \] (forward rate constant = \( k_2 \))

(a) What is the initial rate law predicted by this mechanism if step 1 is rate determining?

\[ \text{rate} = k_1 [\text{I}_2] \]

(b) What is the initial rate law predicted by this mechanism if step 2 is rate determining?

\[ \text{rate} = k_2 [\text{H}_2][\text{I}]^2 \]

but \[ k_1 [\text{I}]^2 = k_1 [\text{I}_2] \]

\[ [\text{I}]^2 = \frac{k_1 [\text{I}_2]}{k_1 - k_2} \]

(11 pts) 5. The reduced mass for a homonuclear diatomic molecule = \( \frac{1}{2} \) the mass of one of the atoms. If the vibrational frequency of an \( \text{H}_2 \) molecule = 4400 cm⁻¹, what will be the vibrational frequency for \( ^3\text{H}-^3\text{H} \) (diatomic tritium).

\[ \frac{\text{v}^3\text{H}-^3\text{H}}{\text{v} \text{H}-\text{H}} = \sqrt{\frac{1}{3}} = (4400) (0.5773) = 2540 \text{ cm}^{-1} \]
(11 pts) 6. For each type of electromagnetic radiation listed below, write a convenient wavelength, or frequency, or wave number (cm$^{-1}$), and indicate the most energetic kind of change a photon of that radiation can cause in a molecule. If there is more than one choice of effect, give both.

- **gamma rays**
  - Wavelength: $< 0.1 \text{ Å}
  - Ionize, Photochem.

- **x-rays**
  - Wavelength: $> 1 \text{ Å}
  - Ionize, Photochem.

- **UV**
  - Wavelength: 200 - 400 nm
  - Excite electrons, Photochem.

- **visible light**
  - Wavelength: 400 - 700 nm
  - **Excite molecular rotation**, **electron spin**

- **microwaves**
  - Wavelength: 1 cm$^{-1}$
  - Excite molecular rotation, electron spin

- **infra red**
  - Wavelength: > 600 cm$^{-1}$
  - Excite vibrations

- **radio**
  - Wavelength: > 600 MHz
  - Excite nuclear spin

(11 pts) 7. Calculate the electrostatic energy in kJ per mole for the 4 charges at the corners of a square 1 Angstrom on each side.

\[
V_1 = \frac{1389 \text{ kJ}}{\text{mol}} \left(1 + \frac{1}{\sqrt{2}} - 1 - \frac{1}{\sqrt{2}}\right)
\]

\[
= \frac{2 \times (1389)}{\sqrt{2}} \approx 1964 \text{ kJ/mol}
\]
(11 pts) 8. Write 5 quantum concepts and the corresponding mathematical equations. Define each of the symbols in the equations.

- Quantization of Energy: \( \Delta E = \hbar \nu \)
- Particle nature of light: \( \mathbf{p} = \frac{\hbar}{\lambda} \)
- Wave nature of particles: \( \lambda = \frac{\hbar}{\mathbf{p}} \)
- Quantization of angular momentum: \( L^2 = \mathbf{L} \cdot \mathbf{L} = \sum_{i=1}^{3} l_i^2 \quad \text{or} \quad L^2 = \hbar^2 \frac{(2\pi)^2}{\lambda^2} \quad m = -l \pm 1 \)
- Uncertainty principle: \( \Delta x \Delta p_x \geq \frac{\hbar}{4\pi} \)

- \( h = \text{Planck constant} \)
- \( \nu = \text{frequency} \)
- \( \mathbf{p} = \text{momentum} \)
- \( \lambda = \text{wavelength} \)
- \( L^2 = \text{total angular momentum squared} \)

(11 pts) 9. If the shape depicted below is filled with water, draw curves that indicate the intensity of absorbed radio frequency energy during an MRI of this object when the magnetic field gradient is in the x or y and z directions. (Field strength increases with increasing x, or y, or z.)

- Field gradient in x or y direction
- Field gradient in z direction