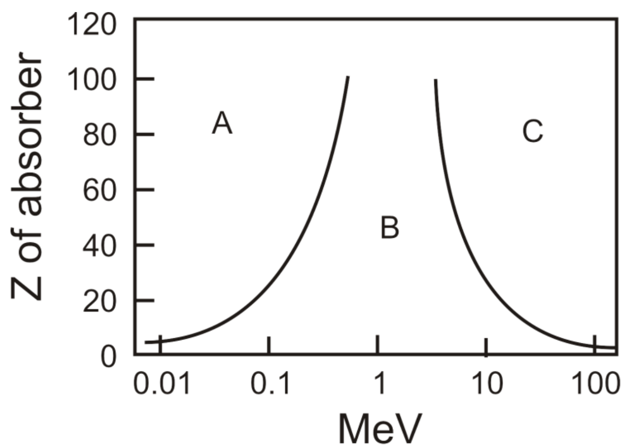
Nuclear Chemistry
Cumulative Examination
Wednesday, 17 March 2010

The examination focuses on the interaction of radiation with matter. Write your answers to the following questions in the order listed. Make sure that your answers are organized and self-explanatory.

1. (12 points) Consider the interactions of gamma rays with matter. For each region, A, B, and C, on the figure below, identify which of the following photon interaction processes dominate: photoelectric effect, Compton scattering, or pair production.



   a. What is the dominant energy loss mechanism for a 1 MeV photon in Ge.

2. (12 points) A beam of radiation passes through a shield and is detected 1 meter away at 0 degrees with respect to the incoming beam. What is the energy of the detected radiation in each of the following situations?
   a. A 1 MeV gamma ray beam impinging on a 1-mm thick Pb shield. The mass attenuation coefficient is 0.07 cm^2/g for a 1-MeV gamma-ray in Pb.
   b. A 1 MeV neutron beam impinging on a 1-mm thick polyethylene shield, where the 1-MeV neutron scattering cross section on H is 4.2 barns.
   c. A 1 MeV electron beam impinging on a 1-mm thick Al shield. The de/dx for 1-MeV electron in Al is 1.28 MeV/cm

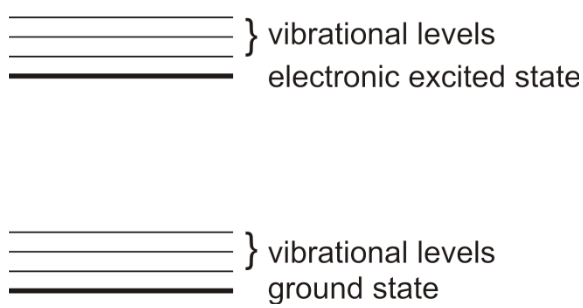
3. (12 points) Sketch the gamma-ray spectrum expected for the following three scenarios: Clearly label, and provide approximate energies, for all spectral features.
   a. A 1-MeV gamma-ray interacting with a Ge detector that is small enough that, at most, one interaction is recorded per incident photon.
   b. A 2-MeV gamma-ray interacting with a Ge detector that is small enough that, at most, one interaction is recorded per incident photon
   c. A 2-MeV gamma-ray interacting with a Ge detector that is large enough to capture all interactions.

4. (10 points) Heavy charged particles are useful for radiation therapy. This is due to the high linear energy transfer (LET) that occurs as the charged particle traverses matter. Explain the term LET by sketching the stopping power of a heavy charged particle as a function of penetration distance in the stopping material.

5. (9 points) For a 1-MeV electron, rank the following materials in terms of the energy necessary to create an electron/hole pair in increasing order.
   a. Ge
   b. Si
   c. gas proportional counter

6. (9 points) List the detector materials in question 5 in order of increasing energy resolution and describe how the energy necessary to create an electron/hole pair affects the energy resolution of a detector.

7. (12 points) Shown below is a schematic representation of two electronic states and various associated vibration levels in an organic scintillator. Reproduce this picture in your book:



   a. Sketch the excitation and fluorescence that occurs when a heavy charged particle interacts with the scintillator.
   b. Is this scintillator transparent to its own emissions?

8. (12 points) Thermal neutrons can be detected in a ^{3}He gas proportional counter. The neutrons are capture by the ^{3}He, which then breaks apart according to the following reaction:

$$^{3}\text{He} + \text{n} \rightarrow {}^{3}\text{H} + \text{p} + 0.764\ \text{MeV}$$

Sketch the expected spectrum (counts as a function of energy) provided by this ^{3}He detector, assuming that the detector is not large compared to the range of the triton and proton. Label the features of the spectrum with their approximate energies.

9. (12 points) Describe how a 2-MeV neutron is detected in an organic scintillator (make sure to mention the particle that is directly responsible for depositing energy in the scintillator)?

Equation Sheet

$$\Delta E = E_{initial} - E_{final} = R_\infty hcZ^2(\frac{1}{n_{initial}^2} - \frac{1}{n_{final}^2})$$

$$m^{nucl}c^2 = M^{atomic}c^2 - [Zm_oc^2 + B_e(Z)$$

$$B_{tot}(A,Z) = [ZM(\,^1H) + (A-Z)M(n) - M(A,Z)]c^2$$

$$S_n = [M(A-1,Z) + M(n) - M(A,Z)]c^2$$

$$B_{tot}(A,Z) = a_v - a_sA^{2/3} - a_c\frac{Z^2}{A^{1/3}} - a_a\frac{(A-2Z)^2}{A} \pm \delta$$

$$N_2(t) = \frac{\lambda_1}{\lambda_2 - \lambda_1}N_1^0\left(e^{-\lambda_1 t} - e^{-\lambda_2 t}\right) + N_2^0e^{-\lambda_2 t}$$

$$A_2(t) = \frac{\lambda_1\lambda_2}{\lambda_2 - \lambda_1}N_1^0\left(e^{-\lambda_1 t} - e^{-\lambda_2 t}\right) + A_2^0e^{-\lambda_2 t}$$

$$B_{sp}(E,l) = \frac{1}{4\pi}[\frac{3}{(l+3)}]^2(r_0)^{2l}A^{2l/3}e^2fm^{2l}$$

$$B_{sp}(M,l) = \frac{10}{\pi}[\frac{3}{(l+3)}]^2(r_0)^{(2l-2)/2}\mu_n^2fm^{(2l-2)}$$

$$N_1 = N_1^0e^{-\lambda t}$$

$$\gamma = (1-\beta^2)^{-1/2}$$

$$A = A_oe^{-\lambda t}$$

$$\tau = \frac{1}{\lambda}$$

$$\lambda = \frac{\ln 2}{t_{1/2}}$$

$$\lambda = \lambda_1 + \lambda_2 + \ldots = \sum_{i=1}^{N}\lambda_i$$

$$\frac{I}{I_0} = e^{-\mu x}$$

$$\lambda = \frac{h}{p}$$

$$N = \phi n\sigma\Delta xt$$

$$\Delta E = \frac{dE}{dx}\Delta x \qquad -\frac{dE}{dx} \propto \frac{Aq^2}{E} \qquad N = \frac{\phi n\sigma\Delta x}{\lambda}(1 - e^{-\lambda t})$$

$$\beta = \frac{4}{3}\sqrt{\frac{\pi}{5}}\frac{b-a}{R_{average}} \qquad \lambda - \lambda' = \frac{h}{m_ec}\ (1 - \cos\Theta) \qquad E_\gamma^{\min} = \frac{m_ec^2}{2}(\frac{1}{1+\frac{m_ec^2}{2E_\gamma}})$$

$$E_1 = \left(\frac{m_2}{m_1+m_2}\right)E \qquad \alpha = \frac{\lambda_{IC}}{\lambda_\gamma} \qquad F_c = \frac{kq_1q_2}{r_{12}^2}$$

$$R = r_oA^{1/3} \qquad T_{cm} = T_{lab}(\frac{m_p}{m_p+m_t}) \qquad E_{rot} = \frac{J(J+1)\hbar}{2\mathfrak{I}}$$

$$x = y(\frac{S_1}{S_2} - 1) \qquad q = \frac{r}{(S_q/S_r) - 1}$$

Constants:

Atomic mass unit (u) – 931.494 MeV

Electron mass (me) – 0.510999 MeV

Proton mass (mp) – 938.272 MeV

Neutron mass (mn) – 939.566 MeV

Plank constant (h) – 6.58212 x 10^{-22} MeV s

Rydberg constant (R_∞hc) – 13.605698 eV

Speed of light (c) – 2.99792458 x 10^8 m/s

Elementary charge (e) – 1.60217733 x 10^{-19} C