1. (10 min.) Fission chambers and $^{10}$BF$_3$ gas-filled detectors are used in reactor start-up and in certain dosimetric applications.

   a) (70%) Describe the mechanisms by which these proportional counters detect neutrons. Include in your discussion general design information and considerations of the influence of “background radiations” that might be present when applied specifically to start-up of nuclear reactors.

   b) (30%) What advantages do $^{10}$BF$_3$ gas-filled detectors have over detectors in which the boron is plated on the detector electrodes?

2. (20 min) A circular dish of diameter $D$ contains a layer of material with a uniform distribution of a single isotope that emits beta radiation. The depth of this layer is $W$. Assume that $W$ is larger than $R$, the maximum range of the beta particles, and that the material emits $B$ betas/cm$^2$-s. Near the center of the dish, at what rate per unit area (betas/cm$^2$-s) will beta particles exit from the top surface of the material? Assume that all betas travel in straight lines and have the maximum range, $R$. Also assume that the diameter of the dish is much greater than $2R$.

3. (20 min.) A nucleus of $^{6}\text{Be}$ is at rest but is excited by $E_{ex} = 10$ MeV. It decays by $\beta^+$ emission directly to the ground state of the recoil nucleus. For the case that the neutrino kinetic energy is zero, derive the relevant equation to find the kinetic energy of the recoil nucleus and then calculate the kinetic energy of the recoil nucleus. You may neglect the rest-mass energy of the neutrino. A table of nuclear masses is given below.

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>NUCLEAR Mass (amu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^6\text{B}$</td>
<td>6.016005</td>
</tr>
<tr>
<td>$^6\text{Be}$</td>
<td>6.017531</td>
</tr>
<tr>
<td>$^6\text{Li}$</td>
<td>6.013477</td>
</tr>
</tbody>
</table>

Equations of possible value: $N = \rho N_0 / A$, $E^2 = p^2c^2 + m_0^2c^4$, $\phi = \nu v$, $\int ud\nu = \nu v - \int v d\nu$. 
4. (15 min.) Write the coupled set of time-dependent, ordinary differential equations describing the nuclide concentrations for the following set of radioactive decays:

\[ X_1 \xrightarrow{\lambda_1} Y_3 + \beta^+ + \nu \]
\[ X_1 \xrightarrow{\lambda_1} 2Y_1 \text{(stable)} + p \]
\[ X_2 \xrightarrow{\lambda_2} Y_2 + \alpha \]
\[ Y_2 \xrightarrow{\lambda_3} Y_1 \text{(stable)} + \beta^- + \bar{\nu} \]
\[ Y_3 \xrightarrow{\lambda_4} 2Y_1 \text{(stable)} + n \]

5. (10 min.) When high energy protons (above 100 MeV) irradiate tissue, there is a significant probability of nuclear collisions of the proton with carbon or oxygen. These interactions can result in target nucleus fragmentation, producing several neutrons, protons, other light ions and even a few alpha particles. Describe the relevant characteristics (energy, range, stopping power) of the fragmentation products relative to those characteristics of the primary proton.

6. (25 min.) (a.) (60%) You have been assigned to accurately measure the thermal neutron fluence rate in a test position near the NSC reactor. Preliminary measurements indicate that \( \Phi_0 \) is \( 10^9 \) neutrons/cm\(^2\)-s. You choose to use a 0.500 gram Au-Al alloy foil (0.200% Au, balance is Al) and plan to count the foil beginning 12 hours after irradiation using a HPGe detector system with a 35 \( \mu \)s deadtime for the 411 keV photon emitted by Au-198. Recall that the deadtime is the time following a count that the detector system is blocked on “dead” for a subsequent count. Your boss tells you to set the activity of the foil so that the percent deadtime of the system at the beginning of the count is 5%. Using a NIST traceable foil, you determine that the peak efficiency of the HPGe detector for 411 keV photons is 5.20% for the same counting geometry. How long should the foil be irradiated in the reactor?

(b) (20%) Sometime much later, your results are called into question. You retrieve your foil, but now there are only about 196 cpm (counts per minute) in the 411 keV peak. How long must you count to get 0.1% statistical error?

(c) (20%) At an even later time, the count rate is 20 cpm. How long should you count now to meet the 0.1% criterion?

You may use the Chart of the Nuclides.
7. (20 min.) The Department of Food Science at Texas A&M University wants to build an irradiation facility on campus for research and testing of food products. They have asked you to assist them with their shielding calculations, although the design tentatively has been set. The current design assumes that the irradiation source will be $^{60}$Co with an initial activity of 15 MCi (i.e., 15 million curies). The source will be moved from its shipping container to its location inside a heavily shielded concrete room. The source will be located in the center of a cubical concrete room, which has inside dimensions of 5 m x 5 m x 5 m and the walls are 1 m thick. For this arrangement:

a. (30%) Since the source will be removed from its container and moved manually into the room, the Radiation Safety Officer wants to know the exposure rate of the unshielded source. The handling rod for the source is 4 meters long. Calculate the exposure rate at a distance of 4 meters from the unshielded source.

b. (10%) What is the maximum working time for a single individual (i.e., an occupationally-exposed individual) involved in this operation, without exceeding federal regulations on radiation exposure?

c. (30%) Calculate the maximum fluence rate (in photons cm$^{-2}$ s$^{-1}$) on the exterior surface of the shield wall (i.e., at a distance of 3.5 m from the source).

d. (20%) What are the exposure rate and the absorbed dose rate in tissue at this exterior point?

e. (10%) Is the shield wall sufficiently thick to comply with federal exposure regulations? Explain your answer.

Ignore air scatter and scatter from the walls other than the wall between the reference point and the source. The table below and the attached graph may be of use to you in solving this problem. State all assumptions and show all your work.

Useful data: \[ \Gamma (^{60}\text{Co}) = 13.2 \text{ R cm}^2 \text{ h}^{-1} \text{ mCi}^{-1} \]

The $\Gamma$-constant can be interpreted as the exposure rate in R/hour-mCi at 1 cm.
### Table of Linear Attenuation Coefficients and Fluence Buildup Factors for Concrete

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>$u$ (1/cm)</th>
<th>$B_{ux = 7}$</th>
<th>$B_{ux = 10}$</th>
<th>$B_{ux = 15}$</th>
<th>$B_{ux = 20}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.204</td>
<td>16.6</td>
<td>29.0</td>
<td>58.1</td>
<td>98.3</td>
</tr>
<tr>
<td>1.0</td>
<td>0.149</td>
<td>11.7</td>
<td>18.7</td>
<td>33.1</td>
<td>50.6</td>
</tr>
<tr>
<td>1.17</td>
<td>0.140</td>
<td>11.0</td>
<td>17.5</td>
<td>30.6</td>
<td>46.4</td>
</tr>
<tr>
<td>1.25</td>
<td>0.135</td>
<td>10.7</td>
<td>16.9</td>
<td>29.4</td>
<td>44.4</td>
</tr>
<tr>
<td>1.33</td>
<td>0.130</td>
<td>10.4</td>
<td>16.3</td>
<td>28.2</td>
<td>42.4</td>
</tr>
<tr>
<td>1.5</td>
<td>0.121</td>
<td>9.7</td>
<td>15.0</td>
<td>25.7</td>
<td>38.2</td>
</tr>
</tbody>
</table>
Fluence rate, photons/cm²·sec to give 1 R/hr

Energy fluence rate, MeV/cm²·sec to give 1 R/hr

Specific gamma ray constant (R/hr/Ci) or (R/h/Ci at 1 m)
Figure 2-18 Energy dependence of the various gamma-ray interaction processes in sodium iodide. (From The Atomic Nucleus by R. D. Evans. Copyright 1955 by the McGraw-Hill Book Company. Used with permission.)