Nuclear Chemistry Cumulative Examination
Wednesday, 25 January 2o12

This examination is concerned with the general properties of radiation detectors and related equipment as discussed in Chem-985 and the textbook Radiation Detection and Measurement by Knoll.

The exam has a total of 90 points.

1. (20 points, 5 points each) Give a concise and accurate answer to each of the following short questions about gas-filled nuclear radiation detectors.

   (a) Explain why gas-filled proportional chambers tend to be constructed with a very thin central wire (perhaps 40μm in diameter) and often have a cylindrical geometry.
   This is a simple geometry that produces a very strong electric field at the wire proportional to 1/r.

   (b) Which fill gas would you expect to give a larger gain in a gas proportional counter, pure helium or a mixture of helium and a small amount of argon, all other things being equal? Explain your answer.
   The mixed gas due to the added mechanism of Penning Ionization. Excited atomic states of He have sufficient energy to ionize neutral Argon atoms that would not lead to ionization in pure helium gas.

   (c) A Geiger counter is closely related to a gas-filled proportional counter but is generally operated with the Ar/Methane gas mixture commonly called P-10 and not with a He/Ar mixture. Why is methane needed in a Geiger counter and not Argon?
   Geiger counters operate in the extreme range of multiplication that a single electron will cause a discharge. The molecular species can absorb delayed de-excitation photons (and thermalize that energy into vibrational motion) that would otherwise cause a retriggering of the discharge.

   (d) The so-called ion chambers used at the NSCL are often really proportional chambers. Explain why the filling gas (the active ingredient) in these devices has to be flowed through the chamber (at a low rate) in order to ensure reproducible operation during the course of a three-day long experiment.
   In a word: Radiolysis. The molecular component of the gas (i.e., methane in P-10) gets destroyed over time by the ionization process and needs to be refreshed.

2. (25 points, 5 points each) Give a concise and accurate answer to each of the following short questions about photomultiplier tubes (PMT) that are used extensively in nuclear

radiation detectors.

(a) What is the definition of the quantum efficiency, η, of a PMT and give a typical vaule of η for a modern PMT operating in the visible region.
η **is simply the ratio of photoelectrons to the number of photons,** $\eta \approx 0.25$

(b) The dynodes of a PMT are described by a coefficient δ. Give a definition of this coefficient and a typical value for the dynodes in a modern PMT.
δ **is the gain of the dynode, i.e., the ratio of the number of emitted secondary electrons to the number of incident electrons,** $\delta \approx 5$

(c) What is the most important parameter of the **window** of a PMT that must be matched to the properties of a given scintillator to ensure maximum efficiency of the whole detector?
The optical transmission of the window depends on photon wavelength and must be matched to the emission spectrum of the scintillator.

(d) All PMT's need to be connected to a "base" to operate. What is the difference between a so-called "active base" and a "passive base" for a photomultiplier tube?
A passive PMT base consists of a simple resistive voltage divider to supply biases to the cathode and dynodes. A passive base generally includes some capacitors across the last dynodes to help stabilize the applied voltages during a pulse. An active PMT base will include transistors across the last few dynodes that "actively" supply current to each dynode during the pulse.

(e) The Department of Homeland Security has made a big push to replace their "Portal Monitors" used to screen cargo containers and trucks that rely on plastic scintillators connected to PMT's with some other scintillation material in order to perform **spectroscopic identification** of radioactivities. Explain why the present portal monitors are not good for spectroscopy and indicate the important properties of another scintillator that would make a better portal monitor.
Plastic scintillators are polystyrene which is essentially $(CH_2)_n$**, so the major interaction process for photons is Compton Scattering and very little Photoelectric Effect. Thus, the full energy peak in a spectrum for a given photon energy will be very small and "spectroscopy" would be very difficult. A better material would have a high probability of Photoelectric effect for the photons of interest, this would generally be a material with a high atomic number. It would also be useful for absorption if the material had a high density.**

3. (25 points, 5 points each) Give a concise and accurate answer to each of the following short questions related to radiation detectors that use germanium diodes.

(a) The preferred material for gamma-ray detectors used in nuclear reaction studies is n-type germanium. Describe the most likely damage mechanism to the germanium crystals used in nuclear reaction studies, the way to repair this damage, and why vacuum is applied to the detector during the repair process.

Most likely damage process is (n,n') scattering of the germanium atoms, causing atomic delocation and lattice damage. The delocalized atoms can be (effectively) driven back and the lattice repaired by annealing or heating the crystal for a period of time. The detector holder has to be pumped to remove off-gases from other materials inside the detector housing, such as cables, that might coat the crystal after cooling.

(b) The central contact n-type germanium detectors in segmented devices is connected to high voltage while the other contacts are at ground potential. What charge carriers are collected on the central contact and what is the expected polarity of the output signal? Is this signal AC or DC coupled?

n-type has electrons as the majority carriers, they can be collected at a positive potential applied to the central contact and thus their motion will induce a negative signal on the positive HV. This signal needs to be AC-coupled to "remove" pulse from the HV line.

(c) Describe the geometry of a true-coaxial germanium detector and an end-cap germanium detector and clearly indicate the most significant differences between the two geometries.

A true-coaxial detector is cylindrical with a hold drilled through the entire crystal along the central axis. This geometry provides a very uniform electric field and uniform pulse shape with the obvious loss of efficiency at the center. An end-cap geometry is similar in construction except the hole does not go all the way through the crystal. This device has a higher efficiency for low energy photons that are incident on the closed end but the electric field is very nonuniform which leads for a variety of pulse shapes depending on the position of the photon interaction in the crystal.

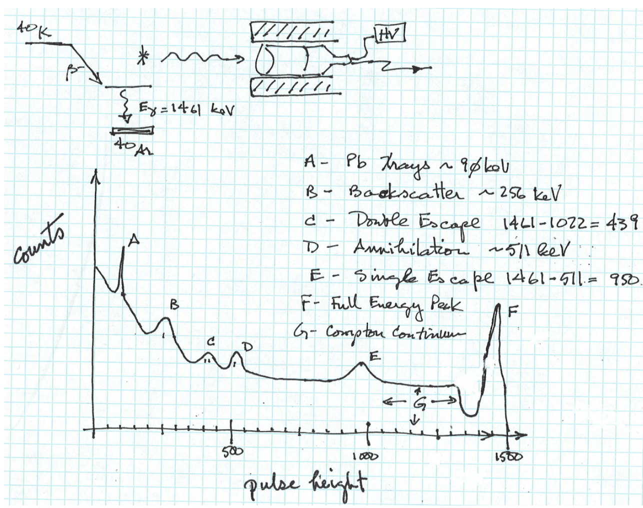
(d) "Wilkinson ADC's" presently provide the highest resolution for signal processing in nuclear spectroscopy. Describe the basic operation of a "Wilkinson" ADC.

The charge from a single pulse is collected on a (standard) capacitor and then the amount of time necessary to discharge the capacitor by a constant current source is measured by counting the ticks from a fixed frequency clock. The voltage capacitor is said to be ramped down to zero and so these devices are sometimes called Ramp-ADC's.

(e) Give separate reasons for using: (a) the shortest possible connection between a radiation detector and its preamp, and (b) for using a twisted-pair connection between the preamp and the next stage of the signal processing system?

a) shortest cable between the detector and preamp will add the lowest (stray) capacitance to the detector capacitance and give the lowest degradation of the signal. b) twisted pair connection, i.e., differential signal, from the preamp is best fro suppressing induced noise, particularly from ground loops.

4. (10 points) Make an accurate sketch of the features that would be present in a pulse-height spectrum obtained from a small inorganic scintillation crystal in a close-fitting lead shield that is thick enough to absorb external background radiation. The device is used to measure the potassium content of various materials via the decay of naturally occurring ^{40}K. This nuclide decays by β^- emission to an excited state in the daughter, the daughter promptly decays by the emission of a 1461 keV photon. Indicate all of the features you expect to be present in the spectrum.



5. (10 points) A gamma-ray detector in use at the NSCL has a photopeak efficiency of 75%. What is the expected counting rate for the 0.662 MeV peak from a 10μCi ^{137}Cs point source at a distance of 50 cm from one of these detectors?
Note that detector area is needed but not given!

$$Rate = 10\mu Ci * 3.7x10^4/s * 0.75 * (Area\ in\ cm^2)/(4\pi * 50^2)$$

$$Rate = 8.83 * (Area\ in\ cm^2)/s$$