Nuclear Chemistry Cumulative Examination
Wednesday, 19 March 2o14

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

The exam has a total of 100 points.

1. (25 points, 5 each) Provide **concise** and accurate answers to the following five questions about vacuum equipment.

   (a) Give a general description of the operation of a Piranni vacuum gauge (i.e., what is measured and how is that sensitive to pressure).
   A Prianni vacuum gauge measures the cooling of a heated wire by thermal transpiration of the residual gas, AKA convection transfer of heat by the gas. The transfer of heat is approximately linear with gas pressure in the region of 0.01 Torr to 10 Torr and thus limits the utility of these gauges.

   (b) Describe the purpose of the filament in a standard (Bayard-Alpert) hot-cathode vacuum gauge.
   A hot-cathode gauge measures the ion current of gaseous ions created by electron bombardment of the residual gas. The (hot) filament is the source of the electrons that ionize the gas.

   (c) What is the most likely (highest pressure) gas and what is its source in a sealed metal beam pipe (no leaks) immediately after the air is removed and the pumping system has just reached its base pressure?
   Water that was absorbed on the metal surfaces when the pipe was exposed to the atmosphere.

   (d) How does the conductance of a round pipe scale with the radius of that pipe in the laminar flow region?
   The conductance increases with the fourth power of the radius, $C \propto r^4$.

   (e) What is the effective speed of a high vacuum pump, S=250 L/s for air, that is connected to a vacuum chamber with a straight pipe with a molecular-flow conductance of 150 L/s for air?

$$1/S_{eff} = 1/C + 1/S = 1/150 + 1/250$$
$$1/S_{eff} = 1/50 * (1/3 + 1/5) = 0.02 * (0.333 + 0.20) \approx 0.011$$
$$S_{eff} \approx 1/0.011 = 90L/s$$

2. (15 points, 5 points each) Give a concise and accurate answer to each of the following short questions about neutron detectors that are used extensively in nuclear science.

   (a) The Dept. of Homeland Security has cornered the market on ^{3}He that is the "active ingredient" in gas-filled neutron detectors. Give a concise explanation of the mechanism for neutron detection with ^{3}He gas.
   The ^{3}He is used as the filling gas in a cylindrical metal tube with a central anode creating a gas-proportional counter. Thermal and slow neutrons are captured by the ^{3}He in the gas phase and undergo a nuclear reaction that releases energy in the form of nuclear recoils.
   $^3He +^1 n \rightarrow^3 H +^1 H + energy$. **The ionization of the gas by the recoils is multiplied and observed as an electrical pulse on the anode.**

   (b) The high cost and low availability of ^{3}He has driven the exploration of plastic scintillators for neutron detectors. Give a concise explanation of the mechanism of neutron detection with plastic scintillators.
   A plastic scintillator is a solid piece of organic plastic, mostly carbon and hydrogen atoms, (often polystyrene) that contains a small amount of an organic molecule dissolved in the solid (co-polymerized) that emits visible light after it is excited (a *scintillator* or *fluor*). The incident neutron strikes a hydrogen atom in the matrix of the polymer and knocks the hydrogen (a proton) out creating a fast moving charged particle. The neutron and proton have almost the same mass and so neutron scattering can transfer a significant fraction of energy to the proton. The moving proton creates ionization in the plastic, some of which is transferred to the *fluor* which then creates visible light that is observed by photomultiplier tube(s).

   (c) A recent manuscript reported using a "total absorbing" detector to measure the neutron flux in a particular experiment. Explain why there is no such thing as a "totally absorbing detector" for neutrons.
   Perhaps semantical but the flux of neutrons in a beam or otherwise undergoes exponential attenuation in any/all materials. Thus, the flux can be made arbitrarily small but strictly speaking not zero.

3. (20 points) A gamma-ray detector in use at the NSCL has a photopeak efficiency of 50% and a cross-sectional area of 10 cm^2. What is the expected counting rate for the 0.662 MeV peak from a 1μCi ^{137}Cs point source (one photon per decay) at a distance of 50 cm from one of these detectors?
   Rate = Activity * Branching Ratio * Geometrical Efficiency * Photopeak Efficiency

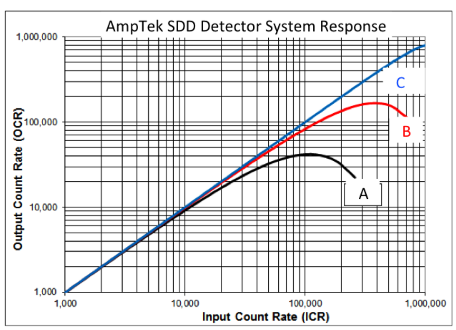
$$Rate = 1\mu Ci * 3.7x10^4 decay/s/\mu Ci * 1photon/decay * 10cm^2/(4\pi 50^2 cm^2) * 0.5$$

$$Rate = 3.7x10^5/(8\pi * 250)/second = 59/s$$

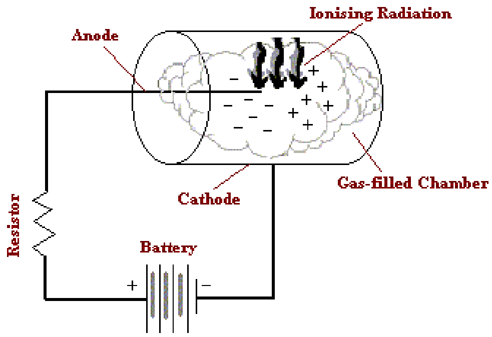
4. (20 points) The following figure shows the response of a commercial x-ray spectrometer system as a function of incident x-ray rate with three different "user options." The options are labeled A, B and C for our purposes.

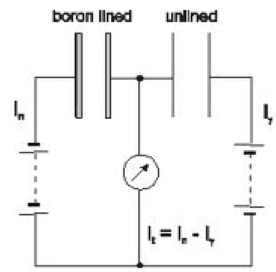
   (a) (10 point) Based on the information for Option-A in the figure, is this system paralyzable or non-paralyzable based on the information in the figure? Explain your answer.
   The figure indicates that the response of the device is double-valued as a function of incident rate, thus, the device is "paralyzable". As the name indicates, the response of the device goes to zero at very high rates. This is a worrisome behavior for radiation detectors.

   (b) (10 points) Based on the Interval Distribution for the time distribution of random events, describe the most likely time difference between two random decays of a radioactive source.
   The Interval Distribution is an exponential distribution in time, t, with the highest probability at t=0. Thus, the most likely time difference between two random events is zero. Note: many people don't understand this, even more don't believe it when told.



5. (20 points) Consider the two figures shown below that were found on the web for radiation detectors. (a) Explain why the figure on the left is too simple and will never be able to detect (typical strength) radiation sources. (b) On the other hand, how can the device on the right provide a reliable measurement of neutrons even in the presence of strong gamma-ray sources?





(a) The simple detector circuit on the left indicates that the current created by the primary ionization can be collected on the biased central anode wire and then readout as a current across the resistor in the circuit. The current from the primary ionization is extremely small in all realistic cases and will be overwhelmed by leakage current created by the bias circuit.

(b) The double chamber system on the right creates a so-called *compensated* **circuit. Any leakage through the bias circuit will occur in both chambers and the meter in the center can be set to zero (nulled-out). A signal from the ionization created by a neutron reaction with the boron on the walls of of the lined chamber can be detected since it will be in addition to the (zeroed out) leakage current.**