PHYS 275 – Experiment 3
Statistics of Random Decay

Experiment Summary

- Today we will study the distribution of the number of radioactive decays in a fixed time interval
  - We will study statistical fluctuations, and use data-analysis techniques to characterize them
- Experimental apparatus
  - A Geiger-Muller counter
  - A Co-60 radioactive source
    - It is *not* hot, but follow ALARA principles and keep it as far from you and your colleagues at all times
      - ALARA = [keep dose] as low as reasonable achievable

What should we learn today?

- Key difference between Exp-2 and Exp-3: we do not know the outcome probabilities!
  - We will try to measure them, and our measurement will suffer from statistical fluctuations
- Dice rolling
  - We can get, with equal probability, a roll of 1 to 6
  - The distribution of rolls is BINOMIAL
    - $B(m, N) = \binom{N}{m} P(n)^m (1 - P(n))^{N-m} = \frac{N! P(n)^m (1-P(n))^{N-m}}{m!(N-m)!}$
- Radioactive decays
  - Random process characterized by lifetime τ
  - The distribution of decays in a time interval Δt follows POISSON distribution
    - $P(n, \mu) = \frac{\mu^n}{n!} e^{-\mu}$, where μ is the average number of decays

Radioactivity History

- Modern physics begins with the discovery of natural radioactivity by Becquerel in 1895
  - Quite by chance: he was studying phosphorescence, and originally thought that phosphorescent materials (such as uranium salts) would emit X-rays when illuminated by bright sunlight. He left his apparatus in a drawer during a cloudy day…
- Subsequent investigations by the Curies, Rutherford, and others quickly revealed that nuclear decays produce three distinct kinds of ionizing radiation: *alpha*, *beta*, and *gamma*
  - Radioactivity refers to the particles which are emitted from nuclei as a result of nuclear instability
- Ionizing radiation emitted by the radioactive materials can pose a hazard to human health. For this reason, special precautions must be observed when radioactive are used.
  - The possession and use of radioactive materials in the US is governed by strict regulatory controls.

Units

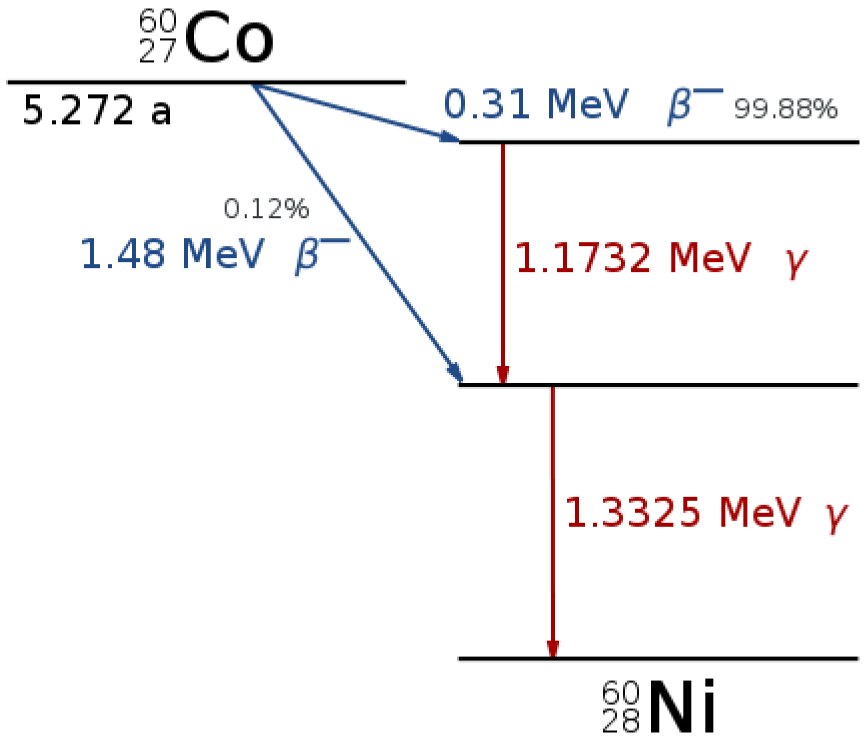
- Curie (Ci)
  - The quantity that express the degree of radioactivity or radiation-producing potential of a given amount of radioactive material is called *activity*
  - The special unit for activity is the Curie (Ci), originally defined as the amount of any radioactive materials which disintegrates at the same rate as one gram of pure Radium (Ra)
- Gray (Gy)
  - The *absorbed dose* is the quantity that expresses the amount of energy which ionizing radiation imparts to a given mass of matter
  - The SI unit for absorbed dose is the Gray (Gy), which is defined as a dose of one joule per kilogram
- Roentgen Equivalent Man (rem)
  - Although the biological effects of radiation are dependent upon the *absorbed dose*, some types of particles produce greater effects than others for the same amount of energy imparted. In order to account for these variations when describing *human health risk* from radiation exposure, the quantity called *dose equivalent* is used
  - The special unit for dose equivalent is the rem

More on Units

- US background/year: ~ 360 mrem
  - 1/3 from cosmic ray
  - 1/3 from radioactivity components from rocks
  - 1/3 from X- rays, etc.
- Workers limit:
  - US ~5 rem/year
  - UK ~1.5 rem/year
  - old SU ~50 rem/year
  - CERN ~ 2 rem/year (public: 0.1 rem/year)
  - Fermilab ~ 1.5 rem/year (public: 0.1 rem/year
- Half-lethal dose in 30 days: ~ 250-300 rem
  - Whole body
- Radioactivity source used in this experiment:
  - Brand-new Co-60 source ~10^{-2} mrem/hour

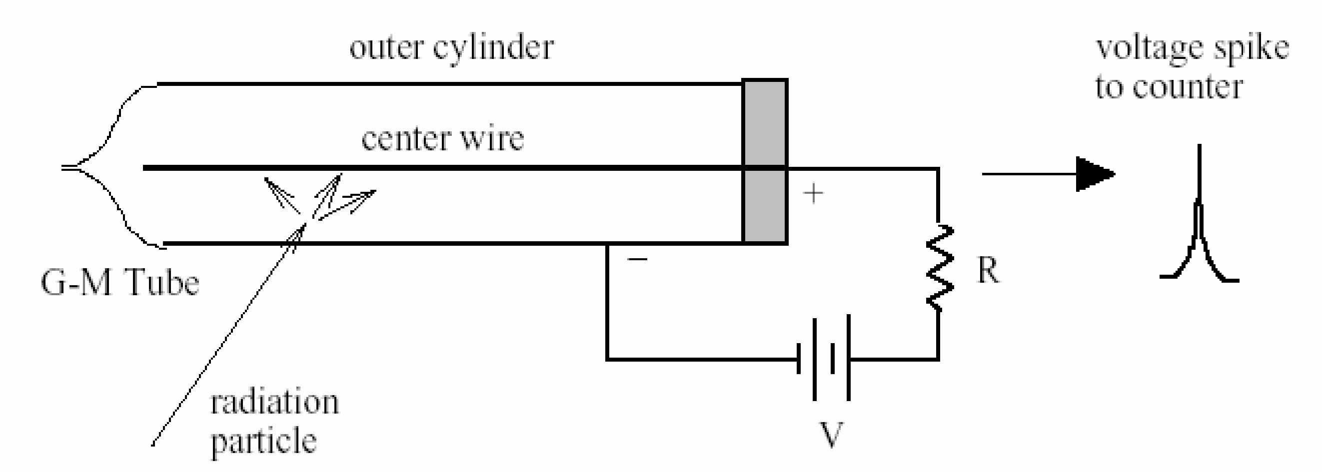
Our Source

- Co-60
  - Half-life: 5.2yr
  - Activity: 1 μCi = $3.7 \cdot 10^4$ Bq
    - Ci = Curie; Bq = Becquerel
    - 1 Bq = 1 disintegration per second



Lifetime of intermediate state: $8 \cdot 10^{-13}$s
Geiger-Mueller counter cannot discriminate the two photons

The G-M Counter



- The rate of emission of radiation is measured using a Geiger-Mueller (G-M) tube in conjunction with an electronic counter
- The G-M tube is simply a gas filled tube with a straight central wire which is connected to a high positive voltage compared to the counter cylinder
  - A *beta* particle or a *gamma* photon enters the tube, some of the atoms of gas within become ionized producing electrons and positive ions
  - These charges are accelerated by the voltage toward opposite electrodes causing further ionization so that when the electrodes are reached, a large current flows out of the tube
  - The current quickly drops to zero so that a single voltage “spike” occurs across the resistor and is registered by the electronic counter
  - For each successive radiation particle, the same process occurs and produces a voltage spike.

Theory of Counting

- Radioactive decay is a random process characterized by a mean lifetime τ
  - This means that if I have a large number of radioactive nuclei (N), in the time interval Δt I expect $n = N\Delta t/\tau$ nuclei to decay
- If I keep counting decays in an interval Δt I do not always count exactly n, of course
  - However, if I build the distribution of my counts, I should find a Poisson distribution with average n and standard deviation $\sigma = \sqrt{n}$
- Example: $N = 10^6$ and $\Delta t/\tau = 10^{-4}$
  - Then, $n = N\Delta t/\tau = 100$ and $\sigma = \sqrt{n} = 10$
  - Therefore, I expect to count 100 ± 10 decays
    - I.e., in 2/3 of measurements I will count between 90 and 110 decays, in the remaining 1/3 of measurements I will count fewer than 90 or more than 110 decays

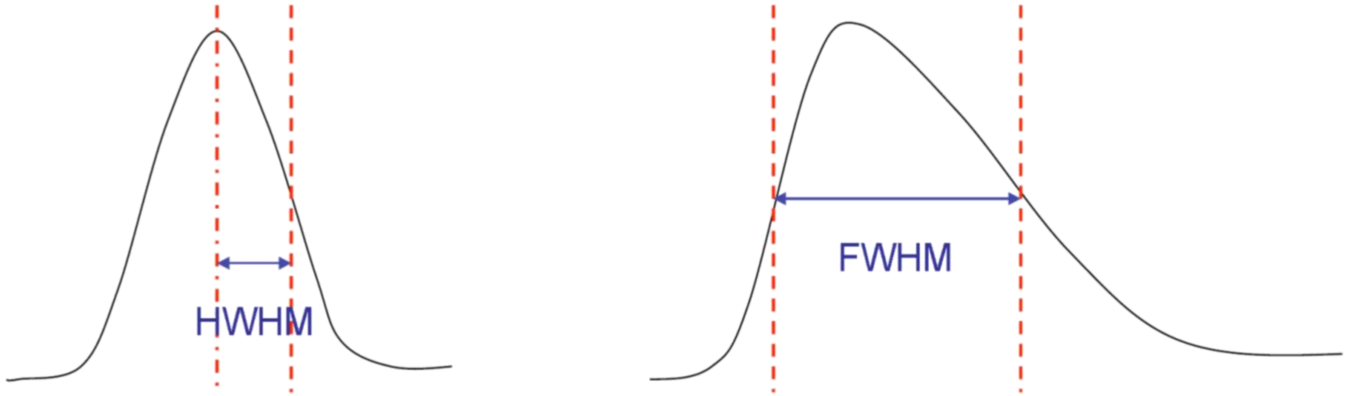
Today's Experiment

- We will estimate the number of decays in a fixed time interval
  - Note: we will only count gamma rays that hit our G-M tube: this could actually be a quite low fraction of the total number of disintegrations per second!
- LoggerPro will do the grunt work for us, and log the number of counts per time interval a few hundred of times
  - We will obtain a set of n_i measurements, each of which has a statistical uncertainty $\sigma_{n_i} = \sqrt{n_i}$
- What is the best estimate for the average count and its standard deviation, if I made m measurements n_i?
  - $\langle n \rangle = {\sum_{i=1}^{m} n_i}/{m}$
  - $\sigma_{\langle n \rangle} = {\sigma}/{\sqrt{m}} = \sqrt{{\langle n \rangle}/{m}}$

can use standard deviation of distribution $\sigma = \sqrt{\langle (n - \langle n \rangle)^2 \rangle}$ or (assuming it is Poisson) use $\sqrt{\langle n \rangle}$

Some Suggestions

- Question D3
  - Sometimes your distributions will be skewed (asymmetric): estimate the half-width at half-max (HWHM) by taking ½ of the full-width at half-max (FWHM)



- Question E3
  - Careful with the χ^2: how many degrees of freedom do you have? Are you comparing with your fit or theory (e.g., what is written on source)? Are you using experimental parameters when evaluating your χ^2?

Last Caveat and Reminders

- Caveat
  - Wire connections in some of your setups might not be reliable, and that can cause artifacts in data collection. If you notice some abnormal data points (or your histogram does not follow a Poisson line shape), please let us know immediately
- Important reminders
  - Submit your Excel spreadsheet on ELMS and turn in your check sheet <u>before</u> leaving the lab
  - Complete the final version of your report by 1pm next week
  - Finish the homework set in Expert-TA by 2pm next week
  - <u>Save your data on the local disk frequently!</u>

Solid Angle

- Solid angle is defined as the angle seen from the center of a sphere that includes a given area A on the surface of that sphere, divided by the square of the sphere radius
  - $\Omega = {}^{A}/_{r^2}$
  - Any shape on the surface of that sphere that holds the same area will define a solid angle of the same size.
- Any area on a sphere which is equal in area to the square of its radius, when observed from its center, subtends precisely one steradian
  - The full area of a sphere corresponds to 4π steradians