• Gamma-Ray Spectroscopy requires good detection efficiency and good energy resolution and both requirements are reasonably well met by thallium-activated sodium iodide, NaI(Tl), which is widely used
  - Detection of a $\gamma$ requires a relatively high probability of interaction in which its energy is transferred to an electron that subsequently excites the detecting medium; a high probability of interaction requires a reasonable dense medium (usually a solid or liquid)

• Response of Detectors
  - Electrons can escape from small detectors and not deposit all the energy-leads to escape peak
  - Back scattered $\gamma$ from Compton scattering in material surrounding detector (scattering angles greater than about $120^\circ$ gives $\gamma$'s of similar energy)
  - X-ray escape peaks due to emission of say K-shell x-ray that escapes
Physics 433 - Lecture 4

- Sodium Iodide NaI(Tl) has very good light output and is widely used for gamma ray spectroscopy
  - About 25eV/photon, which means about four times more photons than we get from plastic scintillator
  - Hydroscopic and must be encapsulated
  - Decay time is about 230 ns
    - Not very good for fast timing applications
  - Has also some very long lived phosphorescence states
    - Mean decay time of 0.15 s
    - Amounts to about 9% of light yield
    - Can present problems in high counting rate applications

- Other Alkali Halide Scintillators
  - CsI(Tl) and CsI(Na) are used in space applications because gamma-ray absorption coefficient per unit size is larger than NaI(Tl)
Detecting gamma rays

- Gamma rays (g) are photons, the quanta of electromagnetic radiation, that have energies of KeV or greater
- In this course the gamma rays we will use come from the decay of radioactive nuclei that emit gamma rays as they undergo transitions from a higher to a lower energy state
- Gamma rays have no charge consequently do not directly excite scintillating atoms or molecules - need charged particles such as electrons
  - Fortunately gamma rays interact with matter to produce charged particles which then excite the scintillating material that in turn emit light which can be focused onto a photomultiplier tube
  - Measuring the energy of gamma rays therefore requires transferring their energy to charger particles
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• Basic interactions of gamma rays with matter
  - Photoelectric absorption
    • In this case the photon interacts with an atom, completely disappears, and a photoelectron is ejected from one of the atom's shells
    • The ejected photoelectron has energy $E_e = h\nu - E_b$, where $E_b$ is the binding energy of the photoelectron in whatever atomic state it was leaving the atom in an ionized state
      - The atom captures a free electron and/or undergoes a rearrangement of electrons from other atomic states
      - In general one or more x-rays are emitted in this process
    • The photoelectric effect is the predominant energy interaction mechanism for gamma rays of energies less than a few MeV
    • The photoelectron has essentially the entire energy of the gamma ray, the scintillation light emitted because of the interactions electron provides a good estimate of the energy of the of the gamma ray - it results in the “photopeak” that is observed from scintillating detectors
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- **Compton scattering**
  - Compton scattering is the elastic collision of a gamma ray with an electron in the absorbing material.
  - The incoming electron is scattered through an angle $\theta$ with respect to its original direction.
  - A fraction of the photon's energy is transferred to the electron which recoils with an energy ranging from 0 to a large fraction of the initial gamma ray energy.
  - From conservation of energy and momentum we obtain
    \[ h\nu' = h\nu[1 + h\nu(1 - \cos\theta)/m_0c^2] \]
    where $h\nu'$ ($h\nu$) is energy of scattered (recoil) gamma ray and $m_0c^2$ is the rest-mass energy of the electron.
  - This results in a maximum energy that can be transferred to the scattered electron and scattered gamma ray never has 0 energy.
  - The observed energy in, say, a NaI scintillating detector will have a distribution with an edge – the Compton edge!
• The energy response of a scintillating detector such with a NaI to gamma-rays emitted from a low energy source (less than a few MeV) will in general be a spectrum resulting from scintillation induced by Compton electrons and photoelectrons.

Typical pulse height spectrum of radiation emitted by a $^{137}$Cs source detected by a NaI(Tl)
Pair production

- For $\gamma$ energies greater than twice the mass of the electron (1.02 MeV) pair production is possible
  - Here the $\gamma$-ray interacts with the coulomb field of the nucleus, disappears and an electron-positron pair recoil with the energy of the initial photon less the rest-mass energy required to create the $e^+e^-$ pair
  - Pair production is the dominant energy loss mode for very high energy electrons; for energies below 10 MeV it is negligible

- Measurements of $\gamma$-ray energies at very high energies depend entirely of pair production and subsequent Bremsstrahlung radiation to create more $\gamma$-rays, which in turn create more $e^+e^-$ pairs etc. leading to a shower of electrons
• Radiation sources used in the Phys 433 lab
  - $\gamma$-sources used in many of Phys 433 labs are $^{22}\text{Na}$, $^{60}\text{Co}$, $^{137}\text{Cs}$ and in at least one lab $^{55}\text{Fe}$
  - It is very important when using these sources that you respect the safety rules
    • The sources are stored in a safe and must be returned there at the end of the day.
    • While our sources are very low level and quite safe to handle it is prudent and established practice to not handle them any more than necessary and to avoid pointing the source end directly towards you or your colleagues.
    • On my web site you will find some tables that list the particles emitted and their energies for many sources including those you will use this quarter.
This week laboratory explores energy measurements with a scintillation counter
- The light output of a scintillating material is approximately proportional to the energy deposited by the particle we are detecting
- If in addition the response of the phototube is proportional to the light input we can easily use a scintillation counter to make energy measurements

The first part of the lab you will use a light pulser (source of short duration light pulses) to measure the response of the phototube or verify that it is approximately linear

In the second part you will study the response of plastic and NaI scintillation counters for which you will need to use a Multi-channel Analyzer (MCA)
Multichannel Analyzers

- Measures differential pulse height spectrum
  - We define \( N \) to be the total number of channels
  - \( \frac{dN}{dH} \) is the differential number of pulses in an increment \( dH \) of pulse height
  - We are interested in \( \Delta N/\Delta H \), the pulses in an increment \( \Delta H \), which is the channel width

- The pulse height spectrum is a plot of \( \Delta N/\Delta H \) vs. \( H \)

- Total number of channels to use depends on the resolution desired required and the total number of counts (pulses) to be registered
  - If there are peaks in the distribution, for example photopeaks, then one should have at least 5 channels for the range of pulse heights (PH) corresponding to the Full Width Half Maximum (FWHM) of the peak
Resolution of Multichannel Analyzers is then given by
\[ R = \frac{\Delta H}{H} = \text{FWHM}/H, \quad H=\text{position of peak} \]

Thus for 1% resolution, \( H_{\text{peak}} = 5/0.01 = 500 \) and we would need more than 500 channels.

If the channel number is very large then the individual channel width, \( \Delta H \), is very small
- For \( N \) very large each channel will then have many counts and we begin to approximate a continuous distribution
- BUT, if \( N/(\text{total # of channels}) \) is small the channel-to-channel fluctuations will become large and details are lost
  - For any given channel with \( n \)-counts the standard deviation \( \sigma = n^{1/2} \), so 100 counts will have a \( \sigma = 10 \) or a relative uncertainty of 10%
  - The conclusion is that the total number of channels and consequently channel width are determined by the resolution desired and the total data sample that can collected in a reasonable amount of time
• Poisson Distribution $P_{\mu}(x) = e^{-\mu} \frac{\mu^x}{x!}$ applies for the important case where the average number of successes is much smaller than the number of trials; $\mu$ is the mean and $x$ the number of events observed in an interval.

- It is used in a large number of applications where the measurement is a number of counts per some interval such as time when we measure the decay of unstable nuclei or particles or could be the number of people riding the bus each day as observed for 60 days.

  • In such experiments we measure $n_i$ events occurring in a time interval $\Delta t$, where the total number of decays $N>>n_i$.

• The variance of the Poisson distribution, $\sigma^2$ is given by

$$\sum_{x=0}^{\infty} (x - \mu)^2 \left( \frac{\mu^x}{x!} \right) e^{-\mu} = \mu$$

• The standard deviation is therefore $\sigma = \sqrt{\mu}$.
For the Poisson distribution the mean and the variance are equal
\[ \sigma^2 = \mu \]

As the mean, \( \mu \), increases the Poisson distribution becomes more Gaussian like and for very large \( \mu \) can be approximated by a Gaussian as shown in these figures, where

\[ \Psi(k) = \mu^k e^{-\mu}/k! \]

Thus for large values of \( \mu \) it is customary to approximate the Poisson distribution by a Gaussian.
Physics 433 – Lecture 4

• Poisson Distribution plays an important role in many different fields because it applies anytime we have a situation where the probability of an occurrence or event is much smaller than the total sample of all events.
  - In Phys433 we will be mainly interested in applying it to the distribution of the number of events or occurrences observed in a given interval of, for example, energy ($\Delta E$) or time ($\Delta t$).
  - The number of events observed in an events in an interval $\Delta E$ is Poisson distributed.
    • If we observe $N$ events in $\Delta E$ the best estimate of the mean number of events is $N$ and its uncertainty according to Poisson distribution is $\pm \sqrt{N}$
    • Note that 100 events results in 10% uncertainty and 1000 events 3% uncertainty.