Name: _____ Partner(s): _____

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ELECTROMAGNETIC INTERACTIONS IN MATTER

By now use should be familiar with the various classifications of light within the electromagnetic spectrum. These range from low-energy radio waves through high-energy gamma rays. The purpose of this laboratory session is to demonstrate various electromagnetic interactions in matter. In particular, you will familiarize yourself with the instrumentation used to analyze the high-energy emission spectra of unstable isotopes. Additionally, you will analyze the structure of emission spectra of various radioactive isotopes to determine the physical processes that are taking place.

Gamma Spectrum Analysis (Background)

Recall that atoms emit light (photons) when higher-shell electrons drop down into a lower level. The energy of the emitted photons depends of the initial and final states of the transition. For example, in a hydrogen atom transition from higher states into the first excited state ($n = 2$) give rise to visible light photons. Transition to the ground state ($n = 1$) give rise to ultraviolet photons. In heavier atoms (such as molybdenum or copper), transitions from higher shells to the 1s state (a.k.a. the *K*-shell) give rise to x-rays.

Gamma rays are generated in a similar way except that the transitions involved are not from electrons dropping down into lower energy levels, but rather nucleons in in the nucleus rearranging themselves into lower energy states. Because many of these nuclear transitions are a easily million times more energetic than electrons transitions, the resulting photons well above 100 keV.

The gamma ray spectroscopy arrangement can be explained as follows: a gamma source is placed near a sodium iodide crystal doped with thallium. The NaI crystal has a high density and thus provides a high probability that a gamma (γ) ray entering the crystal will be absorbed. The crystal contains thallium (Tl) impurities (~1%) that form localized energy levels just below the energy required to boost an electron from the valence band to the conduction band of the crystal. An electron knocked into the conduction band typically returns to the valence band in a time of $\sim 10^{-8}$ s with the emission of a photon whose energy is equal to the band gap energy. The Tl impurities trap the electrons and keep them from returning to the valence band for up ~1 ms as shown in Fig. 1.

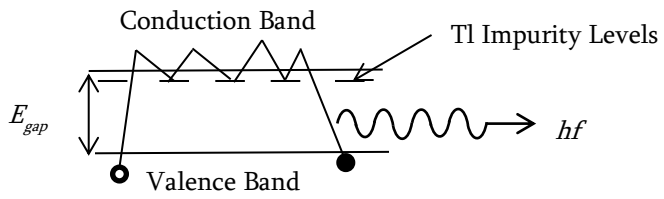

Fig 1: An electron in the valence band is boosted into the conduction band. The thallium impurities create trapping levels that delay the electron's return to the valance band. When the electron returns to the valence band a photon whose energy equals that of the band gap energy is emitted.

Upon returning to the ground state in the valence band, a photon is emitted. Since the band gap energy is on the order of a couple of eV, the emitted photon is that of visible light. These photons pass through the (transparent) NaI crystal into a *photomultiplier tube* where they strike a photocathode. The photocathode will emit electrons (recall the photoelectric effect) whose number is proportional to the number of photons striking it. Since the number of photons striking the photocathode is proportional to the energy of gamma ray, the number of photoejected electrons will be proportional the energy of the gamma ray.

The photoejected electrons are then accelerated by a positive voltage toward the first of series of about ten *dynodes*. Each dynode has a positive potential difference with respect to the previous one. As an electron accelerates toward the first dynode, it gains enough kinetic energy to knock additional electrons from that dynode. These electrons are then accelerated toward the next dynode, which knock out still more electrons, as so on. The process continues until the cascade of electrons reaches the anode where they produce measureable current pulses. The current then goes to a linear amplifier and finally to a *multichannel analyzer* where a discriminator will bin the resulting voltage pulses into specific channels. This use of the multichannel analyzer is referred to as *pulse height analysis*. Peaks in various channels correspond to γ-rays of particular energies being detected.

I. Detector Resolution

Detector resolution is a measure of the detector's ability to distinguish γ-rays of similar energies. A rough determination of the resolution of the detector can be found using:

$$R(\%) = \frac{FWHM\,(\Delta\text{Channels})}{\text{Centroid Channel \#}} \times 100\%\,,$$

where FWHM is called the "Full Width at Half Maximum," and is found to reasonable accuracy by finding the two channels on each side of the peak that have the number of counts closest to ½ of the maximum number of counts in the peak. The "Centroid Channel #" is the channel that corresponds to the location of the maximum count number for that peak.

In this part, you will acquire and analyze the gamma spectra of various radioactive isotopes. You will examine the spectra of ^{137}Cs, ^{60}Co, ^{54}Mn, and ^{22}Na while you determine the energy dependence of the detector resolution.

Your group will need to following equipment for this part:

- 1 multi-channel analyzer with scintillation counter and stand
- Computer with gamma analysis software
- Various μCi sources and appropriate shielding

Procedure

1. Place one of the sources on the tray and insert the tray in the sample holder so that it is as close as possible to the photomultiplier tube.
2. Click start button and collect a spectrum until there are about 2000 counts in a peak near the center of the screen. (Note that the y-axis is scaled logarithmically.) Then click the stop button.
3. Check with your instructor that you have a quality spectrum. Upon instructor approval, print the gamma spectrum for further analysis.
4. Determine which peak(s) correspond to photoemission peak (See chart under "Total absorption photoemission peak" on the next page.) Determine the resolution of the detector for that energy by recording the centroid channel and the FWHM for the total absorption photoemission peak.
5. Determine the left and right-side half maxima for the tallest ^{22}Na peak and complete the first row of Table 1 below.
6. Drag the cursor along the data to identify the channels (and energies) associated with each peak. Record these in tables provided at the end of this packet.
7. Remove the source, return to its case, and repeat these steps for the other sources.

Checkpoint: Consult with your instructor before proceeding. **Instructor's OK:** _____

II. Typical Gamma Ray Processes

The information on the following pages is to provide you with the information necessary to identify the various processes taking place in a typical gamma spectrum. As you will see, there are several peaks and valleys that are observed for the various sources. However, not all of the features observed are due to radioactive decay directly. Many of these features are the result of secondary processes such as electron photoejection and Compton scattering. Your task will be to identify as many of these additional processes as you can.

Question: Note centroid channel and energy of the tallest peak on the ^{22}Na spectrum. Using the information under the "Process Descriptions" below, identify the cause of this peak.

Table 1:

Isotope ^{A}X	**Energy** (keV)	**Centroid Channel**	**Left-side half-max channel**	**Right-side half-max channel**	**FWHM**
^{22}Na					
^{137}Cs	662				
^{54}Mn	835				
^{60}Co	1173				
^{22}Na	1275				
60Co	1332				

Question: How will you determine the energy of the 180° backscatter peaks (E_{bs})? Show a sample calculation for the tallest peak of the ^{22}Na spectrum.

Checkpoint: Consult with your instructor before proceeding. **Instructor's OK:** _____

8. Determine the 180° backscatter ed photon energies for the remaining five photoemission peaks shown in Table 2. Complete Table 2.

Table 2:

Isotope ^{A}X	**γ-Energy** (keV)	λ (pm)	$\Delta\lambda$ (pm)	λ_{bs} (pm)	E_{bs} (kev)
^{22}Na					
^{137}Cs	662				
^{54}Mn	835				
^{60}Co	1173				
^{22}Na	1275				
60Co	1332				

Process Descriptions

Total absorption photoemission peak:

When a radioactive source decays, the daughter nucleus is often in an energetically excited state. When the nucleus de-excites, electromagnetic energy corresponding the energy difference between the nuclear energy levels is radiated. (Because these are nuclear transitions, the energy of this radiation is much higher than those involving electron transitions.) The nuclear radiation emitted tends to be in the γ-ray regime of the electromagnetic spectrum. Different γ-emitters have different characteristic energies for their photoemission peaks. Below is a table of the of the photoemission energies of various sources.

Isotope ^{A}X	**Photoemission Energy** (keV)
^{137}Cs	662
^{54}Mn	835
^{22}Na	1275
^{60}Co	1173 and 1332

Internal conversion peak:

The ^{137}Cs nucleus decays by β^--emission into an excited state of ^{137}Ba. The ^{137}Ba nucleus de-excites and can either emit a 662 keV photon or give up its energy to a core (usually a *K*-shell) electron. When a higher shell electron (usually from the *L*-shell) drops down to fill the vacancy, a characteristic 33 keV x-ray is emitted. When these photons enter the detector, a strong signal at 33 keV is observed.

Pb x-ray peak:

Often, the scintillation counter is surrounded by a thick lead (Pb) barrier to shield the detector from stray background radiation. The γ-rays emitted from the source can have a photoelectric interaction with the lead shield that ejects a core (*K*-shell) electron. When an electron from the *L*-shell drops to fill the *K*-shell vacancy, a 75 keV photon is emitted. Many of these photons enter the detector where they are recorded.

Since this peak is due to photoelectric interactions with the lead shield surrounding the detector, it will generally appear for any radioactive source that emits photons greater than 75 keV.

Compton backscatter peak:

This peak is the result of source γ-rays that undergo 180° Compton interactions with the surroundings opposite the detector and then enter the detector. Recall that the wavelength shift in the Compton effect is given by

$$\lambda' - \lambda = \frac{h}{m_e c}(1 - \cos\theta),$$

where λ' is the wavelength of the Compton shifted photon, λ is the wavelength of the incident photon, h is Planck's constant, m_e is the electron mass, c is the speed of light, and θ is the angle at which the scattered photon travels with respect to the incident photon. For Compton backscattering, $\theta = 180°$.

Compton edge:

A typical γ-ray spectrum will show a sudden drop-off in counts at energies just below a peak. The energy where this "edge" occurs just before the drop-off corresponds to the energy of the recoiling electrons after a Compton backscattering. This energy plus the energy of the 180° backscattered photon equals the photon energy of the original γ-ray.

The "dip" seen at energies just above the Compton edge is referred to as the *Compton valley*. This valley is due to photons that interact with the detector via the Compton effect, then scatter out of the detector never to be detected.

Annihilation peak:

These peaks are found in β^+-emitters. The positron ejected from the decaying nucleus quickly meets an electron where the electron and positron annihilate each other and produce two equal photons whose energies equal the rest mass energies of the annihilating pair. Both the electron and the positron have rest mass energies of 511 keV. Typically, one of these photons enters the detector and the other moves in the opposite direction and is not detected. (A peak at 511 keV is the signature of a β^+-emitter.)

Sum peaks:

In some instances, two principle γ-rays entering the detector are detected at the same time. When this occurs, the detector cannot distinguish between two separate γ-rays or a single γ-ray having the energy equal to the sum of the two individual γ-rays. As a result there will often be a small peak at that sum energy. This is not a true γ-ray energy emitted from the source, but rather an anomaly that occurs within the detector.

Use the information above to identify the feature in the spectra of the radioisotopes.

Cesium-137

Feature	Measured Energy (keV)	Theoretical Energy (keV)	% Error

Manganese-54

Feature	Measured Energy (keV)	Theoretical Energy (keV)	% Error

Sodium-22

Feature	Measured Energy (keV)	Theoretical Energy (keV)	% Error

Cobalt-60

Feature	Measured Energy (keV)	Theoretical Energy (keV)	% Error

Checkout: Consult with you instructor before exiting the lab. **Instructor's OK: _____**