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GAMMA-RAY CRYSTAL SPECTROMETER EXPERIMENT

References

1. Fermi. E., Nuclear Physics; reprint- Compton scattering, photoelectric effect, Moseley's Law.
2. W.R. Leo, Techniques for Nuclear and Particle Physics Experiments, Springer-Verlag 1994. Chapter 1 for a discussion of β decay, gamma emission, annihilation radiation, internal conversion, etc.
3. Knoll, G. F., Radiation Detection and Measurement (1989) Chapter 8 II; Chapter 9 I,II Photomultipliers; Chapter 10 I-IV - Detector properties. Chapter 18 first few pages- Multichannel analyzer.
4. Handbook of Chemistry and Physics.
5. Lederer C. and Shirley V., Table of Isotopes.

Principles of Operation

When an energetic gamma ray is totally absorbed in the NaI crystal, all of its energy can be transferred to electrons in the crystal as a result of Compton scattering and the photoelectric effect. The electrons then make many ionizing collisions in the crystal, losing an average energy of 30 eV for each ion pair they make, until they lose all of their energy and stop in a short distance. A small but fixed fraction of the total energy lost in the crystal is then radiated as visible light (scintillation). A total of approximately 8700 visible photons are radiated for each MeV of energy loss.

The transparent NaI crystal is optically coupled to the face of a photomultiplier tube. In order to collect as much light as possible, the crystal is surrounded by a highly efficient diffuse reflector of visible light. The inner surface of the photomultiplier face is coated with a photoemissive material; this is called the photocathode. The quantum efficiency of the photocathode is defined as the probability of emitting an electron per incident photon. The photoelectrons are then accelerated and focussed by electrostatic fields on a series of dynodes; electron multiplication takes place successively at each dynode, by the emission of several secondary electrons for each incident electron. The result of this cascade is a pulse of current at the anode.

Energy Resolution

The energy resolution of the NaI detector, (i.e. the variation in output current pulses for gamma rays of energy E) is determined primarily by the statistical fluctuation in N_{PE}, the number of photoelectrons emitted by the photocathode. With Gaussian or Poisson statistics the standard deviation is $\sigma(N_{PE}) = \sqrt{N_{PE}}$. Since N_{PE} is proportional to E, the relative statistical uncertainty in E is

$$\frac{\Delta E}{E} = \frac{\sigma(N_{PE})}{N_{PE}} = \frac{\sqrt{N_{PE}}}{N_{PE}} = \frac{A}{\sqrt{E}}$$

where A is a constant of the detector. Variation of quantum efficiency over the area of the photocathode, variation of light collection over the volume of the NaI crystal, and other small factors give a constant contribution C, to $\Delta E/E$, not depending on E. Since the two contributions are independent, they add in quadrature, and the total $\Delta E/E$ is given by

$$\left(\frac{\Delta E}{E}\right)^2 = \left(\frac{A}{\sqrt{E}}\right)^2 + C^2$$

Note that the energy resolution is usually expressed as the full width at half maximum (FWHM), and that for a Gaussian distribution FWHM=2.4 σ.

Procedure for GCS Experiment

1. Use the oscilloscope to view the output pulses from a few γ-ray sources. Note the features of the spectra, and measure pulse heights of the full-energy peaks, and the upper Compton edges.

2. Use the pulse height analyzer to measure the centers of the full-energy peaks for γ-rays from each of the collection of sources. The channel with largest number of counts is not necessarily the center because of statistical fluctuations. Estimate by eye the channel at the center of the peaks and compare to average of channel numbers of the half-maximum points. Do this several times for one peak to determine error.

Note the Compton edge and backscattered peaks and compare the energies with that calculated from Compton scattering kinematics.

Print out each spectrum and note the channel numbers of the features directly on the plot.

3. Measure the energy resolution of the NaI detector (FWHM) for several γ-ray energies, covering as large a range as possible, (at least 30 keV to 1 MeV). The data will be used to determine the constants A and C as well as N_{PE} per MeV and the quantum efficiency of the photocathode. The Ba x-ray from the Cs 137 source (due to internal conversion) is a good low energy point.

For an isolated peak, the FWHM is easy to determine. When a peak is close to another peak, the half width (HWHM) on the other side can be used. Use only the most clear cut cases for the analysis.

4. Measure the fluorescent x-rays (produced by Co-57 x-rays) from a series of known targets. Note the Kα and Kβ x-ray peaks, where possible, and the peak due to the escape of the iodine K x-ray where present. Choose samples well spaced in Z. X-rays with energy below 20 Kev will be very difficult to see using the NaI detector. Use the 122 Kev gamma ray directly from the Co-57 source and the 30 Kev Ba x-ray from the Cs-137 source for the initial calibration. Change the calibration so that the 122 Kev peak appears in the upper half of the display range.

Targets, some of which are powders, are sealed in small plastic envelopes. Do not remove them from the envelopes.

5. Measure the fluorescent x-rays from the "unknown" target, in order to identify the unknown.

Analysis

1. Use the energies of four or five prominent gamma rays to determine a linear energy calibration. E_γ= gC +o where C is the channel number, g is the gain in [Mev/channel] and o is small offset.

Use the calibration to determine the energy of all other gamma rays and spectrum features.

Make a plot of E_γ versus channel number including all gamma rays and spectrum features. On the same graph, draw the fitted calibration.

A separate calibration is needed for the oscilloscope, for the PHA gamma ray source data, and for the x-ray fluorescence data.

2. Compare the energies of the Compton edge and backscattered peak with those calculated from Compton scattering kinematics.

3. For a few cases draw the energy level diagram of the nuclei and note the transitions corresponding to gamma rays which you have observed.

4. Use the data to determine the constants A and C as well as N_{PE} per MeV and the quantum efficiency of the photocathode (Refer to section on Energy resolution above). A plot of $(\Delta E/E)^2$ versus $1/E$ can be used.

5. The energy of the Kα x-rays grows approximately as $(Z-1)^2$ (Moseley's Law). Compare your data graphically to this expression.