Compton Scattering

M McCartney PHY334

Concepts

Compton scattering, differential scattering cross-section, source activity, shielding and dosimetry (RAD/REM), background correction, signal/noise with Poisson statistics, scattering geometry (apertures, solid angle, flux, scattering volume, convolution, etc).

Background Reading

Melissinos 2nd edition: pp. 333-357 (scintillation detectors), 367-385 (scattering, Compton effect and Klein-Nishina formula), appendix re "radiation dose, flux and safety". Also review text material from PHY310; Google, as appropriate.

Equipment and Skills

Photomultiplier tube (PMT), scintillation detector, multi-channel analyzer (MCA), Geiger counter, radioactive sources.

Precautions

Handle the radioactive sources carefully. They can be dangerous if not handled properly. Radiation dosimetry is a complex subject. For now, just recognize that total counts, counts/area and counts/(area, time) are all important. Dose can be very high even for small objects if they are close to (or in contact with!) parts of your body. So, keep your distance and wash your hands (and/or use gloves) after handling any source, to avoid contact of source material with your eyes, mouth, skin, lungs, etc. The sources we use are relatively low intensity, but they all deserve respect. The lead shielding may also be hazardous since it is a neurotoxin. It should be handled similarly – with gloves and/or washing.

Energy shift due to Compton scattering

A simple analysis of kinematics (energy and momentum conservation) for a photon scattered from a free electron predict a frequency shift of the photon given by

$$\lambda' - \lambda = \lambda_c \left(1 - \cos\theta\right), \qquad \text{Eq 1}$$

where $\lambda_c = h/mc \sim 0.024$ Ang is the Compton wavelength. The corresponding energy shift is given by

$$\frac{E'}{E} = \frac{1}{1 + \left(E / mc^2\right)\left(1 - \cos\theta\right)}. \qquad \text{Eq 2}$$

Scattering cross section: total and differential

In a typical scattering experiment, a target is uniformly illuminated by a parallel incident beam and produces a scattered flux that varies with angle. We define a total cross-section as

$$\sigma = \frac{\left(\frac{\#scatt}{\sec}\right)}{N\left(\frac{\#inc}{\sec * A}\right)}, \qquad \text{Eq 3}$$

where # is the number of counts received by the detector (for all angles!) and N is the number of illuminated target particles (electrons in the metal target). The units for total cross-section are area/atom. The differential cross-section is a more useful quantity, both for experiment and theory when only a protion of the scattered γ-rays are detected, and is defined as

$$d\sigma(\theta,\varphi)/d\Omega = \frac{\left(\frac{\#scatt}{\sec d\Omega}\right)}{N\left(\frac{\#inc}{\sec A}\right)}, \qquad \text{Eq 4}$$

where dΩ is the solid angle of the detector, viewed from the target. The differential cross-section usually varies with θ (in-plane angle), being strongly peaked or divergent at θ =0, but usually does not vary much with Φ (out-plane angle). The detector solid angle is given by $\Omega = A_{det}/r^2$, where A_{det} is the physical aperture of the detector viewed from the target and r^2 the distance from target to aperture.

If all target atoms receive the same illumination as they do using the small cylindrical target, the denominator is simple, just NI_0. More commonly, one has a variable illumination. In this case, we need an average value given by

$$< NI_0 >= \iint I(x,y)N(x,y)dxdy \qquad \text{Eq 5}$$

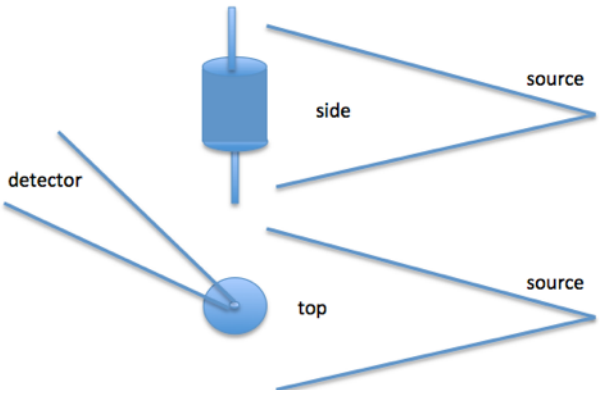
Here, I(x,y) is the beam profile and N(x,y) represents the *projected* areal density of target atoms. This integral may be very complicated and require numerical integration.

Part I: Detector set-up; MCA binning; scattering geometry

In this section, you will set up the photomultiplier tube (PMT) detector. This operates as follows: a gamma ray passing through a plastic scintillator material creates a cascade of visible photons that are measured by a PMT that provides suitable (enormous) amplification. *Each gamma ray produces a single pulse whose height is proportional to the energy of the incident gamma ray.* The proportionality depends (exponentially!) on the PMT gain, so you need to choose a suitable gain and leave it fixed for the entire run. The pulses are sent through a "multichannel analyzer" (MCA) that provides a histogram of pulse heights and displays them on a computer. Condensed directions for running the MCA are posted in the lab. Additional details may be found in the on-line manual or the hardcopy manual. The same software is also available on other lab computers for off-line analysis.

1. Run "HWSuper" to connect instrument to the software:
   Click "Serial Port"
   Click "PGT/ANS Com"
   Click top left Quantum Com, choose 19200 Baud is chosen, click "Update"
   Should say "communications verified". Close HWSuper.
   Start QtmMCA software

2. Be sure to save all scans in both native and *.txt format, so you can do analysis off-line.
3. The instructor will insert the ^{137}Cs calibration source into the detector. This source emits γ-rays at 0.6617 MeV with a half-life of 30 years.
4. Power up the detector electronics: MCA (rear rocker switch), scope, NIM crate and HV enable (red rocker). Bring the HV up to 1000V (do not exceed 1200V – you will fry the PMT) watching for pulses on the scope. Note the approximate height (Volts) and width (usec) of the pulses. Consider questions Q1 and Q2 below (end of section). When you are finished for the day, power down the electronics in the reverse order.
5. Load the MCA software and start a spectrum acquire, using the condensed instruction sheet posted in the lab. After a moment, a spectrum should be discernible. It is useful to use autoscale and log scale for visibility. Leaving the spectrum running, increase the HV to 1200V and note the effect.
6. **Scattering geometry**: (You may wish to do this item after you get the counting started, to be "multitasking" during data acquisition, which can be slow). Measure the physical scattering geometry for your experiment. That is, the location and size of source, detector and target and appropriate apertures. You will need this to determine absolute scattering cross-section later. Make a decent sketch of the geometry, both in your notebook and later in your report. Basically, you need to determine how many Al atoms are illuminated by the incident beam and the solid angle for the detector aperture, viewed from the target.



Top and side views of scattering geometry of cylindrical target

Part II: Geiger counter, incident beam profile, source activity, shielding and dosage (RAD/REM)

1. The instructor will insert the ^{137}Cs source into the collimator. This source emits γ-rays at 0.6617 MeV with a half-life of 30 years. Briefly (10 min) explore the spatial pattern of radiation using the Geiger counter. For example, check front vs. side of the collimated

source; inside/outside the lead corral; nearby the locked cabinet, etc. Be sure to turn off the battery when you are finished.

2. ***Set the HV at an appropriate value and leave it fixed for the entire run***.
3. Measure the incident beam profile directly with the PMT. This information is necessary to make absolute cross section calculations, below. Move the source forward on the small rail, such that the source "hot end" (midline on tape) is directly over the pivot point. Put the ½" aperture (1" lead brick) in place in front of the PMT. Record the rate (cps) vs angle, on both sides of maximum, going out to where the beam drops to ~10% of max. You may need to add a Pb attenuator block just in front of the detector aperture to avoid "dead time". Calibrate the attenuation factor, using an angle that avoids saturation (dead time). It is useful to save the full MCA spectrum for the direct beam (at 0 deg), but for the rest, you only need the count rate. This is best done using the ROI feature of the software (shift-drag through region of interest).
4. From the count rate at the beam maximum (center), find the absolute activity, in Curies, for the bare source (no collimator and no attenuator).

Part III: Compton scattering data

5. Move the source back to the scattering position in the large wooden cradle. Place the target (full aluminum post) in the pivot hole. Remove the ½" aperture to expose the full aperture, with no attenuator. Note the typical tradeoff: the count-rate will be much larger, but the angular resolution will be worse. You should complete the measurements below during a single laboratory period, to maintain consistent calibration.
6. Record full MCA spectra for angles from 20 to 90 deg in 10 deg steps. Count at each angle long enough to resolve the spectrum with decent statistics (ie longer for weaker peaks). Also record a background spectrum for each angle by removing the Al target and counting again for the same time. Note that, ironically, background subtraction adds "noise", since the total N is reduced. Be sure to save each run in both raw and *.asc format. You should glance at the "difference spectrum" (signal minus background) to see that a peak is visible in the noise. This is best done offline, with Excel or GA.
7. Optional: use smaller apertures for the incident beam and detector to record small-angle data, and merge this with the data above.
8. Optional: find an accurate scattering volume by numerical convolution (Matlab).

Analysis

9. Determine the peak position and amplitude in the difference spectra (signal – background) for each angle. This might be done by direct integration of the ROI, or better with fits in GA. For your report, show in the appendix the difference curve with peak fit for all scattering angles. Then make a *linearized* fit of this data (energy shift vs angle) using the Compton relation (Eq 2) and from this determine mc^2 for the electron. See Melissinos for details.
10. Determine the differential scattering cross section. Apply the "efficiency" and "Peak Total Ratio" corrections from figure below and described in Melissinos Fig 9.6 with the measured "photopeak" for both incident and scattered beams. Note that we have a 3" NaI crystal. Compare your measurements to the Thomson and Klein-Nishina formulas.

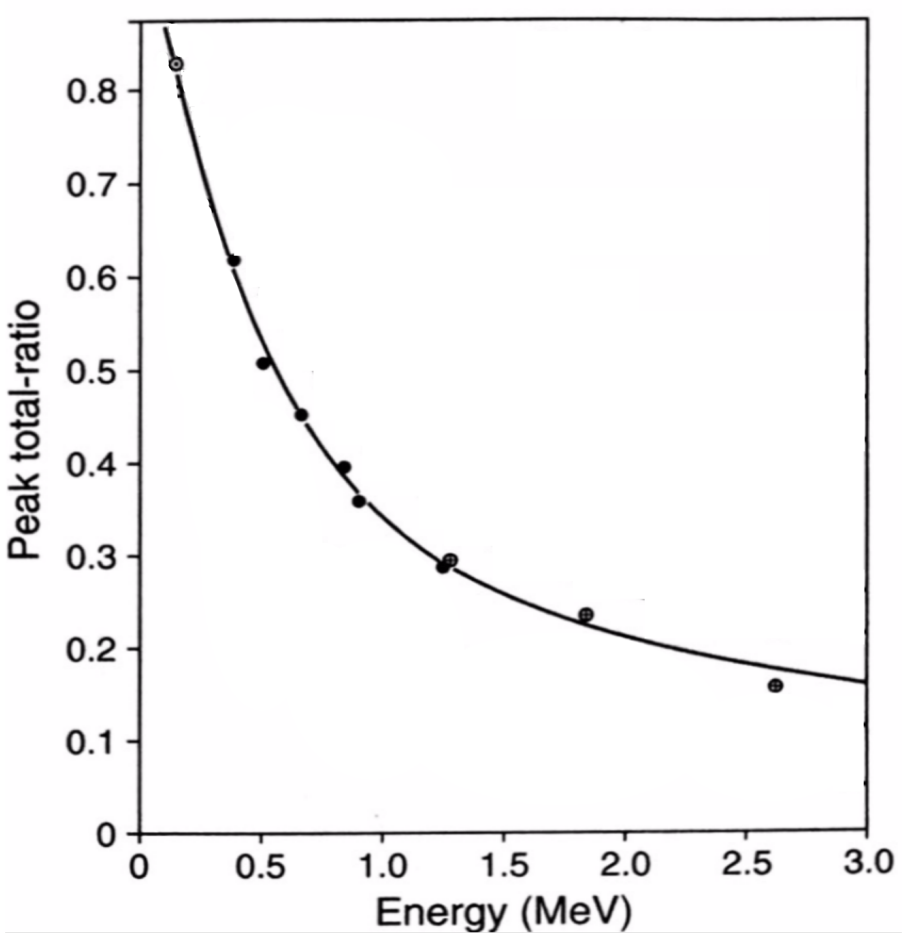


Figure extracted and edited from:
Melissinos, A.C., Napolitano, J. (2003) Experiments in Modern Physics San Diego, CA: Academic Press.

Questions and write-up:

1. Make a block diagram for the electronics used in this experiment.
2. Explain the operating principle for a scintillation detector (50-100 words).
3. Why do some pulses appear at random horizontal locations on the oscilloscope trace?
4. What is the angular resolution of your Compton data, i.e. how precisely can you measure the angle that you are rotating the source?
5. Estimate the dose (in REM) received by the TA during insertion of the source into the collimator. Compare this with a typical dental X-ray.
6. Estimate the "whole-body" dose that you would receive (REM) if exposed to the *unshielded* source (no collimator) at a distance of 3 meters for 3 hrs. How does this compare with federal standards for "allowed radiation exposure"?

Appendix I: Radiation dose, flux and safety

The topic of radiation safety is of vital importance to us all, both in lab and in daily life. Here we summarize the salient features of measuring radiation exposure. For details, see Melissinos and references therein, particularly the website http://pdg.lbl.gov/1998/radiorppbook.pdf. Also, you can find a handy "dose calculator" at http://www.radprocalculator.com/Gamma.aspx. Caution: do not just plug numbers in the calculator – you need to explain your method and values.

Radiation dose D is measured in Greys or Rads, where 1 Gy = 100 rad = 6.24×10^{12} MeV/kg of deposited energy. Note the dimensions of energy/mass. We are concerned here with the biological impact of a dose, given in Sieverts, where 1Sv = 100 REM (Roentgen Equivalent for Man) = 1 Gy * w_g, where w_g is a weighting factor derived from medical risk statistics. The dose received by an object of mass density ρ in a flux of F particles/(cm^2-sec) is given by D = F * dE/dx * 1/ρ. Note that the "stopping power" of the particle, dE/dx, depends on the particle and the target. Putting this all together, we arrive at a "dose conversion factor" (Biological Dose/Flux) for various forms of radiation, as shown in Fig. 26.4.

26.4. Dose conversion factors

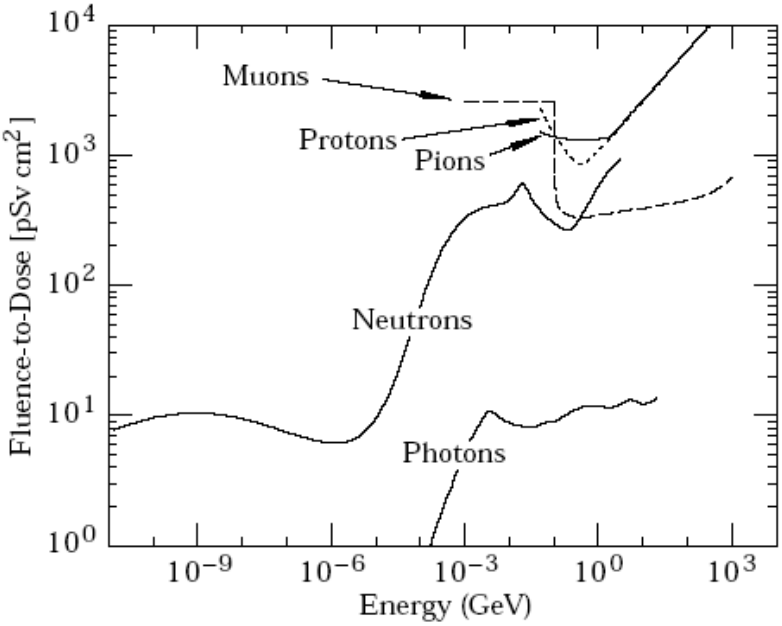


Figure 26.4: Fluence to dose equivalent conversion factors for various particles.

Ref: http://pdg.lbl.gov/1998/radiorppbook.pdf