AN34 Experiment 10

Compton Scattering

EQUIPMENT NEEDED FROM ORTEC

- 113 Preamplifier (2 ea.)
- TRUMP-PCI-2K MCA System including suitable PC operating Windows 98/2000/XP (other ORTEC MCAs may be used)
- 266 Photomultiplier Tube Base (2 ea.)
- 4001A/4002D NIM Bin and Power Supply
- 556 High Voltage Power Supply (2 ea.)
- 480 Pulser
- 855 Dual Spectroscopy Amplifier
- 551 Timing Single-Channel Analyzer
- 427A Delay Amplifier
- 905-3 NaI(Tl) Detector/Photomultiplier Assembly
- C-36-12 Cable (2 ea.)
- C-24-12 Cable (7 ea.)
- C-24-1 Cable (4 ea.)
- C-29 BNC Tee Connector (2 ea.)

OTHER EQUIPMENT NEEDED

- 10 mCi sealed ^{137}Cs source
- Sealed Solid Disk Gamma-Ray Sources ~1 µCi, ^{137}Cs, ^{60}Co, ^{22}Na, ^{65}Zn, ^{54}Mn (substitute alternate sources with similar energies)
- Oscilloscope
- Fast Plastic Scintillator, 1/2 x 4-in. mounted to photomultiplier tube
- Complete Compton Scattering Apparatus
- Aluminum Scattering Rod, 0.5-in diameter x 4-in. long

Purpose

In this experiment, the techniques for studying the effects of Compton scattering will be studied. The scattering will be caused by gamma rays from the ^{137}Cs source striking an aluminum rod and an organic scintillator.

Introduction

The collision of a gamma ray with a free electron is explained by the Compton interaction. The kinematic equations describing this interaction are exactly the same as the equations for two billiard balls colliding with each other, except that the balls are of different size. Fig. 10.1 shows the interaction.

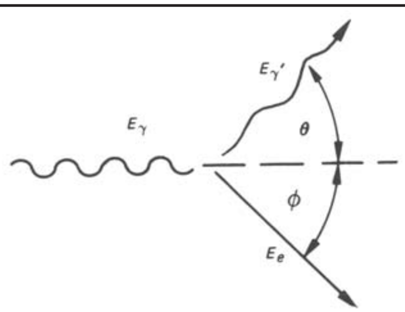

Fig. 10.1. Scattering Caused by Compton Interaction.

In Fig. 10.1 a gamma of energy, $E\gamma$, scatters from an electron with an energy $E\gamma'$. (For convenience, all energies are expressed in MeV). The energy that the electron gains in the collision is E_e. In Fig. 10.1, θ and ϕ are the scattering angles for γ' and the electron respectively. The laws of conservation of energy and momentum for the interaction are as follows:

Conservation of energy,

$$E\gamma = E\gamma' + E_e \, . \tag{1}$$

Conservation of momentum,

$$\text{x direction } \frac{hf}{c} = \frac{hf'}{c} (\cos\theta) + mv\,(\cos\phi). \tag{2}$$

Conservation of momentum,

$$\text{y direction } 0 = \frac{hf'}{c} (\sin\theta) - mv\,(\sin\phi). \tag{3}$$

In the above equations, $E\gamma = hf$, $E\gamma' = hf'$, $E_e = mc^2 - m_0c^2$, $m = m_0/(1 - v^2/c^2)^{-1/2}$ when m_0 = rest mass of the electron, and v = the velocity of the recoil electron.

Solving Eqs. (1), (2), and (3) for $E\gamma'$ results in the following:

$$E\gamma' = \frac{E\gamma}{1 + \frac{E\gamma}{m_0c^2}(1 - \cos\theta)} \tag{4}$$

Note that Eq. (4) is easy to use if all energies are expressed in MeV. From Experiments 3 and 7, m_0c^2 is equal to 0.511 MeV. In this experiment, $E\gamma$ is the energy of the source (0.662 MeV for ^{137}Cs), and θ is the measured laboratory angle.

Fig. 10.2 shows the geometry used for the experiments outlined for Compton scattering. Experiments 10.1 and 10.2 are simple scattering experiments using an aluminum scattering sample. In Experiments 10.3 and 10.4 the aluminum sample is replaced with an organic scintillator coupled to a phototube, and a coincidence is required between the pulse in the organic scintillator and a pulse in the NaI(Tl) crystal.

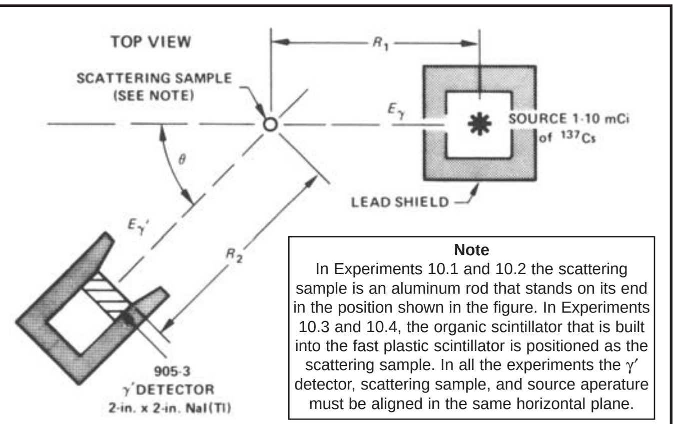

Fig. 10.2. Arrangement of Sources, Sample, and Detector for Experiment 10 Using a Compton Scattering Aapparatus.

EXPERIMENT 10.1
Simple Compton Scattering (Energy Determination)

Procedure

1. Using Eγ = 0.662 MeV for ^{137}Cs in Eq. (4), calculate the values for Eγ′ and enter them in Table 10.1 for the angles to be used in the experiment.

Table 10.1

θ (deg)	Eγ′ (Calculated)	Eγ′ (Measured)
20		
40		
60		
80		
100		
120		
140		
160		

2. Set up the electronics as shown in Fig. 10.3. Calibrate the MCA so that the ^{137}Cs line is in approximately channel 800. This procedure was outlined in Experiment 3.

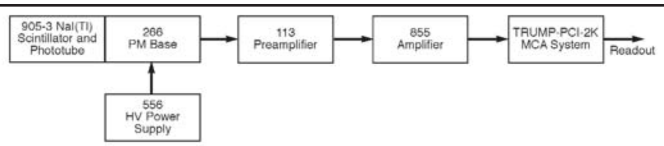

Fig. 10.3. Instrument Interconnections for Experiments 10.1 and 10.2

3. Plot the energy vs. channel number for your calibration. This calibration will be used to determine the Eγ′ (measured) values in Table 10.1.

4. Set θ = 20° (Fig. 10.2) and accumulate for a period of time long enough to determine the position of the photopeak. (Note: If you also plan to do Experiment 10.2, the sum under each photopeak should be at least 1000 counts). From your calibration curve, fill in Eγ′ (measured) in Table10.1. Continue for the other values in the table. Fig. 10.4 shows spectra at 20° and 120°.

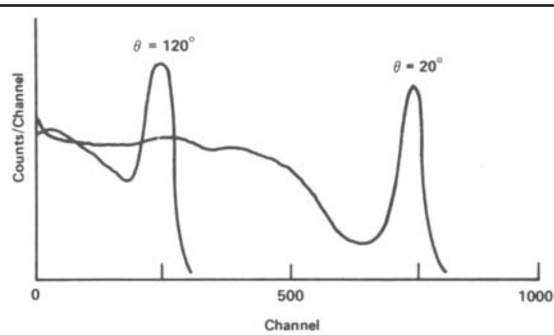

Fig. 10.4. Overlapped Spectra Obtained at Two Scattering Angles.

EXERCISES

a. Plot Eγ′ (calculated) vs. θ on linear graph paper. Put the experimental points with the estimated error on the curve. Do your experimental values agree with the theory?

b. For ^{137}Cs, Eγ′ = 0.662 MeV, and since m_0c^2 = 0.511, Eq. (4) becomes:

$$E\gamma' = \frac{E\gamma}{1 + 1.956E\gamma}\,(1 - \cos\theta) \qquad (5)$$

This can be written:

$$\frac{1}{E\gamma'} = 1.51 + 1.956\,(1 - \cos\theta) \qquad (6)$$

Therefore a plot of 1/Eγ′ vs. (1 – cosθ) should be a straight line with intercept 1.51 and a slope equal to 1.956. Table 10.2 shows θ, 1/Eγ′, and (1 – cosθ) for ^{137}Cs.

Table 10.2

Angle (θ)	1/Eγ′ (MeV^{-1})	1 – cosθ
0	1.51	0
10	1.54	0.015
20	1.63	0.060
30	1.77	0.133
40	1.97	0.234
50	2.20	0.357
60	2.49	0.500
70	2.79	0.658
80	3.12	0.826
90	3.46	1.00
100	3.80	1.17
110	4.13	1.34
120	4.44	1.50
130	4.72	1.64

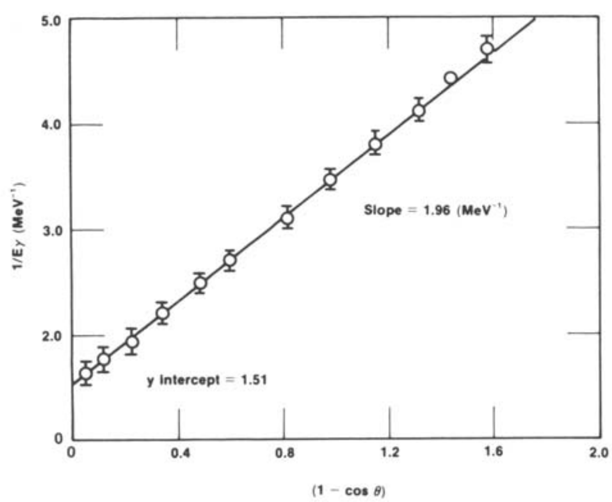

Fig. 10.5. 1/Eγ′ vs. (1 – cosθ) for ^{137}Cs.

Make a plot of $1/E\gamma'$ vs. $(1 - \cos\theta)$ and put your experimental points from Table 10.1 on the graph. Fig. 10.5 shows a typical graph of this function and the experimental data points.

EXPERIMENT 10.2
Simple Compton Scattering
(Cross-Section Determination)

The differential cross-section for Compton scattering, first proposed by Klein and Nishina, is discussed in ref. 1. The expression has the following form:

$$\left(\frac{d\sigma}{d\Omega}\right)_{theory} = \frac{r_0^2}{2}\left\{\frac{1+\cos^2\theta}{[(1+\alpha(1-\cos\theta)]^2}\right\} \times \left\{1+\frac{\alpha^2(1-\cos\theta)^2}{[1+\cos^2\theta]\,[1+\alpha(1-\cos\theta)]}\right\},\ \left(\frac{cm^2}{sr}\right) \qquad (7)$$

where

$r_0 = 2.82 \times 10^{-13}$ cm (classical electron radius),

$$\alpha = \frac{E\gamma}{m_0c^2} = \frac{0.662\ \text{MeV}}{0.511\ \text{MeV}} = 1.29 \text{ for } {}^{137}\text{Cs}$$

$d\Omega$ = the measured solid angle in steradians.

In this experiment we will verify Eq.(7) from the experimental measurements.

Procedure

The procedure here is the same as that for Experiment 10.1, except that for each run the sum under the photopeak should be at least 1000 counts.

1. Solve Eq. (7) for the values of θ used in Table 10.1. (A computer is quite valuable at this point, although not absolutely necessary).

EXERCISE

a. Plot $(d\sigma/d\Omega)_{theory}$ vs. θ on linear graph paper.

2. Find the measured differential cross-section by solving the following expression:

$$\left(\frac{d\sigma}{d\Omega}\right)_{measured} = \frac{\Sigma\gamma'}{N\Delta\Omega I} \qquad (8)$$

where

$\Sigma\gamma'$ = sum under the photopeak divided by the intrinsic peak efficiency (see Experiment 3),

N = number of electrons in the scattering sample

$$= \frac{\text{(volume) (density) (atomic no.) (Avogadro's no.)}}{\text{Atomic weight}}$$

$\Delta\Omega$ = solid angle in steradians of detector

$$= \frac{\text{area of detector (cm}^2\text{)}}{[R_2\ \text{(cm)}]^2}$$

I = the number of incident γ's per cm^2 per second at the scattering sample. This number can be calculated if the activity of the source is known.

EXERCISE

b. Solve Eq. (8) for the measured values. Put the measured values with their estimated errors on the theoretical curve for the Klein-Nishina formula.

EXPERIMENT 10.3
Compton Scattering
(Coincidence Method)

Procedure

1. Set up the electronics as shown in Fig. 10.6. The fast plastic scintillator is an organic scintillation detector that will be used as the scatterer, and should be placed in a sample position as shown in Fig. 10.2. It will also provide a coincident enable signal to the MCA to permit energy analysis of the simultaneous scattered signal from the 905-3 NaI(Tl) detector.

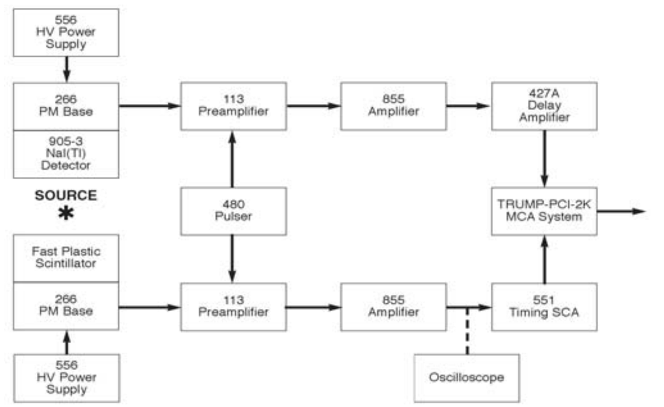

Fig. 10.6. Instrument Interconnections for Experiment 10.3.

2. For the 905-3 circuit, adjust its 556 high voltage and then adjust the gain on its section of the 855 Amplifier so that the ^{137}Cs photopeak is near the top of the MCA range. Set the MCA Gate switch at OFF during this adjustment.

3. For the fast plastic scintillator circuit, adjust its 556 high voltage and adjust the gain on its section of the 855 Amplifier so that the Compton edge of the ^{137}Cs is ~6 V in amplitude at the 855 output, measured with an oscilloscope.

4. Set the 551 Timing SCA Lower-Level dial at 50/1000 or as low as possible without counting noise. Set the Window or Upper-Level dial at 10 V. Adjust the delay to 0.1 µs.

5. Turn on the 480 Pulser and adjust its attenuated output so that the amplitude at the 855 output in the fast plastic scintillator circuit is ~5 V.

6. Set the MCA Gate switch at Coinc (coincidence mode). The analyzer should now store the pulser output pulses. Turn off the 480. The experimental arrangement is now ideal for measuring $E\gamma'$ vs. θ, because the coincidence requirement from the fast plastic scintillator eliminates virtually all the undesired background.

EXERCISE

Repeat all the measurements made in Experiment 10.1 with this coincidence technique. Plot the experimental and theoretical values as in Experiment 10.1.

EXPERIMENT 10.4
Compton Scattering
(Electron Recoil Energy)

Procedure

1. Set up the electronics as shown in Fig. 10.7. The equipment is the same as was used for Experiment 10.3. The fast plastic scintillator is used as the scatterer, set in the sample position on the comptom suppression scattering apparatus, and also provides the source used for energy measurements. The 905-3 will be used to provide the coincident enable signal to the MCA to permit energy analysis of the recoil electrons from the fast plastic scintillator.

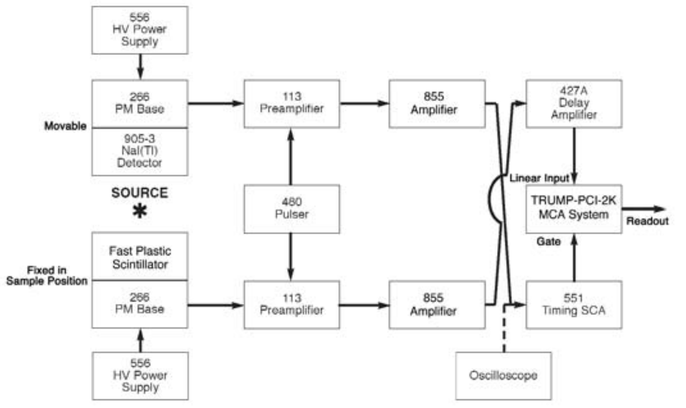

Fig. 10.7. Instrument Interconnections for Experiment 10.4.

2. Adjust the gain of the 855 Amplifier section in the 905-3 circuit so that its output for the 0.662 MeV line of the ^{137}Cs source is ~6 V, measured with an oscilloscope. Set the 551 Timing SCA controls as in Experiment 10.3.

Table 10.3		
θ (deg)	**E_e (Calculated)**	**E_e (Measured)**
0		
20		
40		
60		
80		
100		
120		
140		
160		

3. For the fast plastic scintillator circuit, adjust the gain of the 855 Amplifer so that the Compton edge from the 0.662 MeV line of the ^{137}Cs source is stored in the upper channels of the analyzer.

4. Use Eqs. (1) and (4) to calculate the values for E_e in Table 10.3 and fill in this column of the table.

5. Set the 480 Pulser for the value of E_e at 0°. Adjust the Calibrate dial and the Attenuator switches to place the pulser pulses in approximately the same MCA channel as the Compton edge. The pulser is now approximately calibrated.

6. Store pulses from the pulser for simulated energy levels of 0.100 MeV, 0.200 MeV, 0.300 MeV, 0.400 MeV, and 0.500 MeV. Read the data from the MCA and plot the calibration curve. Turn off the pulser.

7. Set the 905-3 detector at 20° and store a coincidence spectrum for the fast plastic scintillator output for a period of time long enough to determine the position of the recoil electron energy. Record the value in Table 10.3.

8. Repeat the measurements for the other angles in Table 10.3. Fig. 8 shows a typical pair of spectra taken at θ = 160° and 40°.

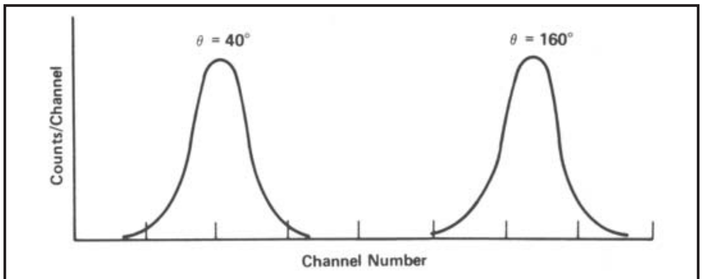

Fig. 10.8. Typical Recoil Electron Spectra Taken at Two Different Angles.

EXERCISE

Plot E_e vs. θ from Table 10.3. From the calibration curve and the data taken in steps 6 and 7, put the experimental points on the curve with the estimated error. How do your values agree?

References

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