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Determination of rest mass energy of the electron by a Compton scattering experiment

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Abstract

We report here a simple Compton scattering experiment which may be carried out in graduate and undergraduate laboratories to determine the rest mass energy of the electron. In the present experiment, we have measured the energies of the Compton scattered gamma rays with a NaI(Tl) gamma ray spectrometer coupled to a 1 K multichannel analyzer at five scattering angles of $\theta = 30^\circ$, 50°, 60°, 70° and 80° using a ^{137}Cs radioactive gamma source and a suitable aluminum absorber. The rest mass energy of the electron is determined as the reciprocal of the slope of the plot of parameter S versus $(1 - \cos\theta)$. The obtained value is found to agree with the standard value.

1. Introduction

Nature manifests itself in the form of matter and radiation. Matter is composed of several types of particles. Every particle is characterized by its own unique finite, real, non-zero rest mass and hence rest energy. Thus, the rest energy can be considered as a signature of the particle.

Compton scattering is the incoherent scattering of incident photons by quasi-free electrons. The photons get scattered as if from a free electron since the binding effects are negligible at energies much greater than the binding energies of the atomic electrons. As the energy of incident photons increases, the scattering cross-section decreases and varies linearly with the atomic number Z.

Compton scattering is an important phenomenon which demonstrates the particle nature of gamma radiation. In the gamma energy region above 200 keV, Compton scattering by

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atomic electrons is the most dominant mode of interaction, particularly for elements of atomic number below 20.

Using a gamma ray spectrometer, Badiger and Thontadarya [1] have demonstrated important aspects of Compton scattering, that the Compton shift in wavelength in any particular direction is independent of the energy of the incident photon and the Compton shift in energy is dependent on the incident photon energy. Sanjeevaiah and Venkataramaiah [2] have measured the variation of Compton shift in wavelength with the angle of scattering. Singhal and Burns [3] have measured the Compton scattering cross-section at various angles and verified the Klein–Nishina formula which predicts the Compton scattering cross-section. Hosur and Badiger [4] have determined the rest mass energy of the electron using the backscattered peak of the NaI(Tl) energy spectra with some gamma ray sources. In the literature, other descriptions of the Compton scattering experiment have also been reported [5, 6].

In this study, an effort has been made to determine the rest mass energy of the atomic electron by making use of Compton scattering as a tool.

2. Theory

In Compton scattering, the gamma photon interacts with free or bound electrons of the target and gets scattered with less energy. As the incident photons are scattered at different angles (from 0 to 180°), the Compton scattered electrons have a distribution of energy from zero to a maximum energy.

In his explanation of the Compton scattering experiment, Arthur Compton [7] treated the x-ray photons as particles and applied conservation of energy and conservation of momentum to the collision of a photon with an electron which is stationary. In his hypothesis, it was suggested that during the Compton effect, individual photons collide with single electrons that are free (or loosely bound) and stationary (at rest) in the atoms of the target. The ‘free’ electron hypothesis limits the theory to those cases in which the atomic binding energy of the struck electron is small compared to the energy of the incident photon. Almost all practical cases of Compton scattering fall within this region [8]. Although the ‘stationary’ electron hypothesis is a special case, the more general case of scattering by a moving electron may be obtained by a Lorentz transformation [8]. The colliding photons transfer their energy and momentum to such electrons. Each of these electrons in turn scatters the photon colliding with it, in some definite direction. This definite angle between the directions of the incident photon and scattered photon is called the scattering angle. In Compton scattering, the energy of the scattered photon is always lower than that of the corresponding incident photon. This difference between the energies of the incident photon and the scattered photon is utilized to recoil the struck electron. With this idea, he arrived at the Compton scattering formula

$$h\upsilon_f = \frac{h\upsilon_i}{(1+\alpha(1-\cos\theta))}, \quad \text{where} \quad \alpha = \frac{h\upsilon_i}{m_0c^2}. \tag{1}$$

Here, θ is the scattering angle. $h\upsilon_i$ and $h\upsilon_f$ are the incident photon energy and scattered photon energy, respectively. The quantity m_0c^2 is the rest energy of the electron.

2.1. Calculation of the rest energy of an electron using the Compton scattering formula

Let $E_\theta = h\upsilon_f$ and $E_i = h\upsilon_i$ be the energy of the photon scattered at an angle θ and the energy of the incident photon, respectively. Then using (1), we can write

$$\frac{(E_i - E_\theta)}{E_i E_\theta} = S(\theta) = \frac{(1-\cos\theta)}{m_0c^2}. \tag{2}$$

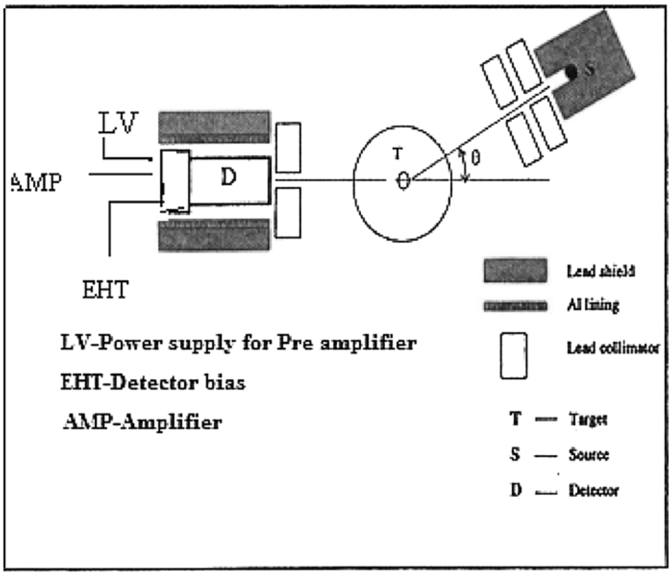

Figure 1. Schematic diagram of the experimental setup.

Table 1. Photo peak channel number for various gamma emitters.

Source	Energy in keV	Peak channel number obtained
^{133}Ba	363	364
^{22}Na	511	515
^{137}Cs	661.6	669
^{54}Mn	840	856

Thus, if E_i is obtained experimentally at the channel number n_i and E_θ is obtained at various values of n_θ for a given incident energy E_i, then (2) is modified to the form

$$\frac{(n_i - n_\theta)}{n_i n_\theta} = S(\theta) = \frac{(1 - \cos\theta)}{m_0 c^2}. \tag{3}$$

Equation (3) here is of the form $A = BX$ with $A = S(\theta)$ and $X = (1 - \cos\theta)$. Hence, if the parameter $S(\theta)$ is experimentally determined for different values of θ and plotted versus $(1 - \cos\theta)$, the resulting plot should be a straight line with a slope, $B = (1/m_0c^2)$. The reciprocal of this slope is an estimate of the rest mass energy of the electron. This idea is made use of in this study to determine the rest energy of the electron.

3. Experimental details

In the experiment, the scattered spectra were recorded at five different angles of $\theta = 30^\circ$, 50°, 60°, 70° and 80°. For this purpose, gamma rays emitted by a 300 mCi ^{137}Cs source procured in the form of a radiographic capsule from M/S Amersham, UK, were used.

A NaI(Tl) scintillation head SH644 supplied by M/S Electronics Corporation of India, Hyderabad, was employed to detect the scattered photons. This scintillation head was

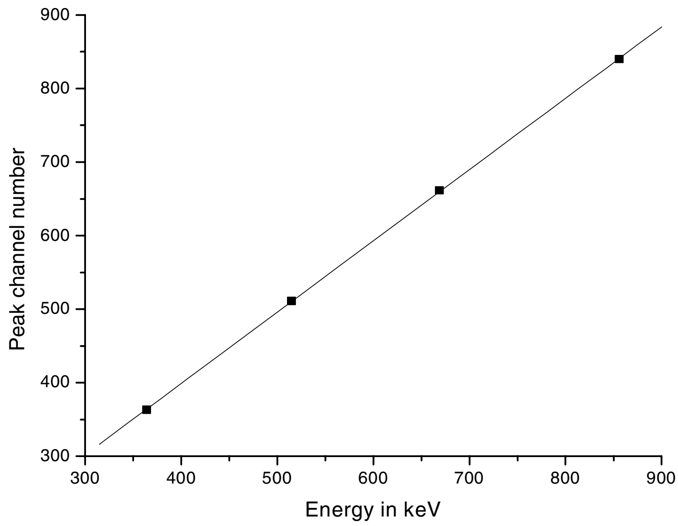

Figure 2. Plot of peak channel number versus energy in keV.

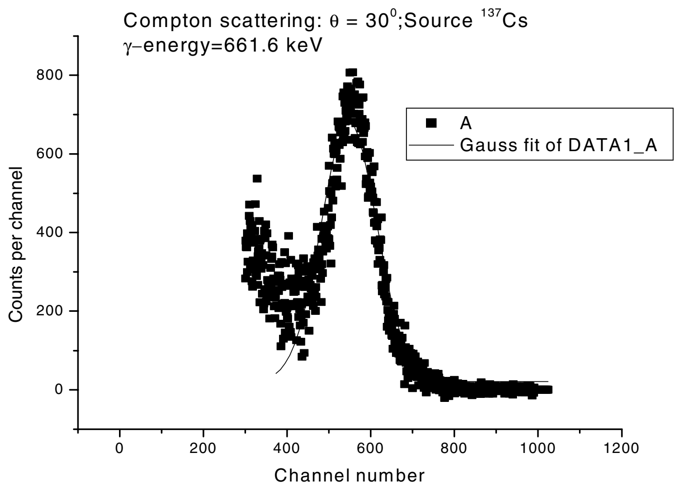

Figure 3. Background subtracted spectrum at 30°.

comprised of a flat (2″ × 2″) NaI(Tl) crystal which was optically coupled to a DuMont 6292 photomultiplier tube (with a flat top) along with a preamplifier. The preamplifier signal was then suitably amplified by a linear amplifier and the spectrum was recorded in a personal-computer-based 1 K multichannel analyzer. A voltage of +1000 V was selected as the operating voltage (EHT). The low voltage supply (LV = +24, +12, 0, +12 and −12 V) required for the preamplifier was drawn via a five-pin socket provided for the purpose, in the instrumentation bin and power supply which was used to house and operate the high voltage unit as well as the amplifier unit which were supplied as standard NIM modular units by M/S Nucleonix, Hyderabad.

The whole experiment was carried out in an air-conditioned room wherein the mains voltage was stabilized in order to minimize the channel drift.

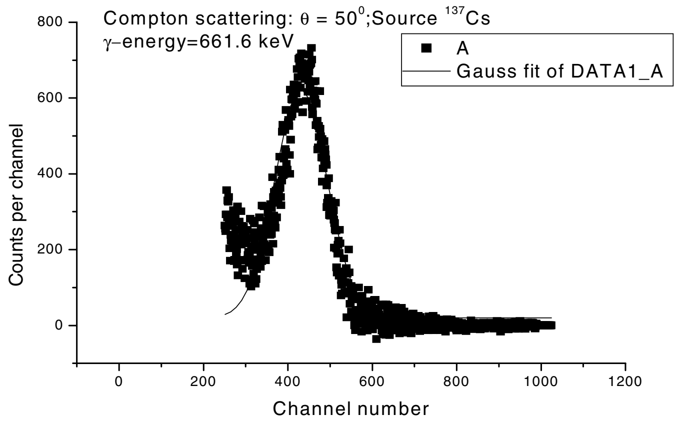

Figure 4. Background subtracted spectrum at 50°.

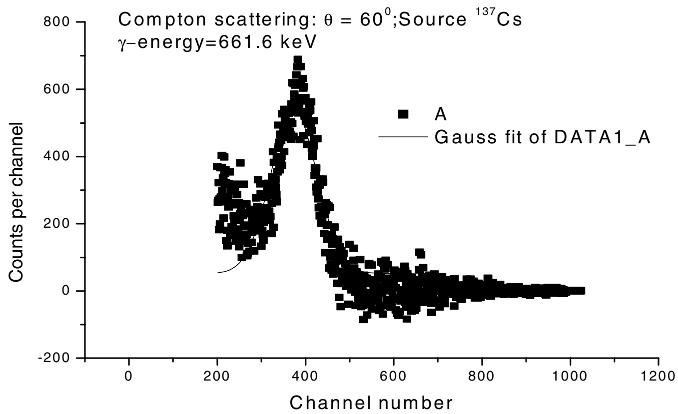

Figure 5. Background subtracted spectrum at 60°.

3.1. Procedure

Throughout the experiment, the detector received the scattered gamma rays at five scattering angles of 30°, 50°, 60°, 70° and 80° (set to one angle at a time) on a goniometer assembly which is schematically shown in figure 1.

3.2. Linearity check

The linearity between the photo peak channel number and photon energy was studied for the direct spectrum (at 0° and without any target in line) using the calibration sources listed in table 1. The peak channel number recorded by the multichannel analyzer in the energy spectra of these sources is also shown along with the emitted gamma ray energies.

Using the values of table 1, a plot of peak channel number was prepared as a function of the energy in keV. The resulting plot is shown in figure 2. It is a straight line implying that the spectrometer was linear in the region of interest.

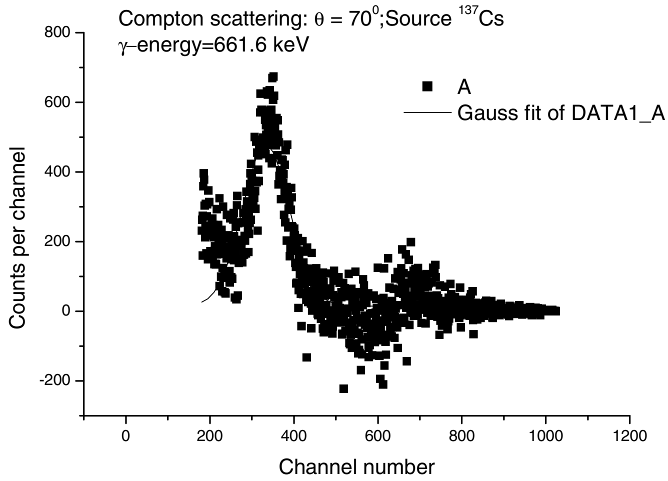

Figure 6. Background subtracted spectrum at 70°.

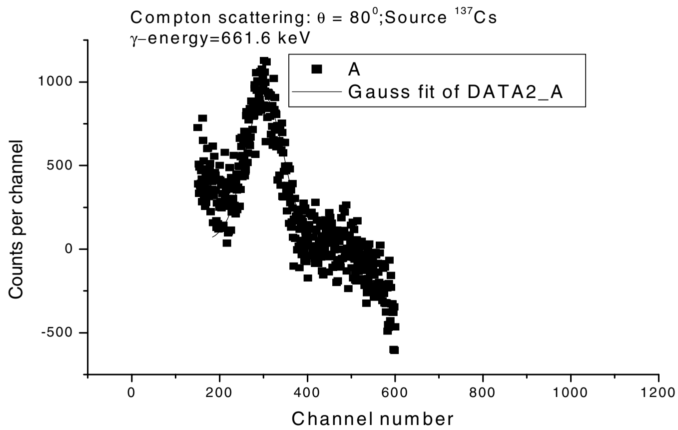

Figure 7. Background subtracted spectrum at 80°.

3.3. Scattering experiment

In the experiment, (figure 1) a collimated beam of photons from the source S was made to fall on an Al target T of thickness 16.2 g cm^{-2} on the target holder. The detector D received the scattered gamma rays. The gamma ray beam was properly shielded by lead throughout its journey from source to the detector and care was taken to minimize the background radiation.

The scattered spectra were recorded at five different angles of $\theta = 30^\circ$, 50°, 60°, 70° and 80° with and without the Al target. Background subtracted spectra were obtained at each of the five angles after subtracting corresponding spectra recorded with the Al target (scattered) and without the Al target (background) from each other. The resulting background subtracted spectra so obtained at all five scattering angles are shown in figures 3–7.

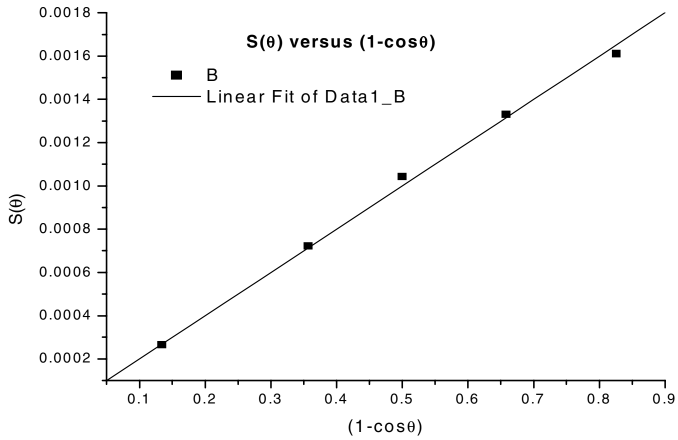

Figure 8. Plot of $S(\theta)$ versus $(1 - \cos\theta)$.

Table 2. Energy of the scattered gamma ray along with the corresponding peak channel number. Incident γ-ray energy $E_i = 661.6$ keV; $n_i = 669$; radioactive source used: ^{137}Cs.

Scattering angle, θ, in degrees	Energy of the scattered photon, E_θ, in keV	Scattered peak channel number, n_θ
30	564	568
50	450	451
60	400	394
70	356	354
80	319	322

4. Results and discussion

4.1. Calculation of rest energy

A suitable Gaussian was fit to the spectra shown in figures 3–7 and the position of the centroid was located. This was taken to be the peak channel number, n_θ, of the scattered spectra at the five angles. These values are listed in table 2 along with the scattered peak energies calculated as per equation (3).

Using the values of n_i and n_θ shown in table 2, the values of $S(\theta)$ were calculated. These values are shown in table 3 along with the $(1 - \cos\theta)$ values. The values of $S(\theta)$ were plotted versus $(1 - \cos\theta)$. The resulting plot is shown in figure 8. A straight line of the form $S(\theta) = B(1 - \cos\theta)$ (cf equation (3)) was fit to this plot. The best fit value of the slope B was 0.001 96. The standard deviation was 3.1×10^{-5}. The R factor was 0.998 51 pointing to a very reliable fit. Since, the slope $B = 1/m_0c^2$, the value of the rest energy of the electron was calculated as

$$1/B = m_0c^2 = 1/0.001\ 96 = 510 \text{ keV}.$$

Table 3. Values of $S(\theta)$ and $1 - \cos\theta$.

Angle of scattering, θ, in degrees	$1 - \cos\theta$	Parameter $S(\theta) \times 10^4$
30	0.134	2.66
50	0.357	7.23
60	0.500	10.43
70	0.658	13.30
80	0.826	16.11

5. Conclusions

Thus, by using Compton scattering as a tool, the value of the rest mass energy of the electron has been determined as 510 keV. This is in close conformity with the standard value of 511 keV. In this experiment, the student can learn

(a) how a scattering experiment may be set up,
(b) about energy calibration and linearity of the gamma ray spectrometer,
(c) that when the incident photon energy exceeds the rest energy of the electron, the free and stationary electron hypothesis of Compton is justified.

Since the Compton shift in energy is independent of the scatterer, the experiment can be repeated with any other available low Z elemental or composite target to verify this aspect.

Hence, we feel that this is a simple laboratory experiment which can be carried out as a part of undergraduate/graduate coursework in radiation physics/chemistry which familiarizes the student with the multichannel analyzer and gamma ray spectrometry.

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