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Determination of rest mass energy of the electron—an undergraduate laboratory experiment

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Abstract
We present a simple Compton scattering experiment to determine the rest mass energy of the electron which is unique for graduate and undergraduate laboratories. In the present experiment, we have measured the energies of the backscattered gamma photons with an NaI(Tl) gamma ray spectrometer coupled to a 1 K multichannel analyser. In order to enhance the backscattered gamma photons, a thick aluminium target is placed over the radioactive gamma source. The rest mass energy of the electron is determined by using ^{203}Hg, ^{137}Cs, ^{54}Mn and ^{60}Co radioactive gamma sources. The measured values are found to agree with the standard value.

1. Introduction

Many laboratory experiments based on the interaction of gamma radiation with matter have been published in the literature [1, 2, 8–11]. Gamma photons interact with matter through photoelectric absorption, Compton scattering and pair production processes. Compton scattering is an important phenomenon which demonstrates the particle nature of gamma radiation. 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 continuum distribution of energy from zero to a maximum energy; the maximum energy of an electron is known as the Compton edge. The minimum energy of the scattered photon occurs in a head-on collision; the minimum photon energy is for the backscattered photon.

Using the gamma ray spectrometer, Badiger and Thontadarya [1] have demonstrated the 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. Bertsch and Nolen [2] have shown that the intensity of the backscattered gamma photon can be enhanced by using a low Z absorber; they have demonstrated that the intensity of the backscattered photons is more pronounced using an aluminium target rather than lead. Sanjeevaiah and Venkataramaiah [10] have measured the variation of Compton shift in wavelength with the angle of scattering. Singhal and Burns [11] have measured the Compton scattering cross-section at various angles and verified the Klein–Nishina formula which predicts the Compton scattering cross-section.

It is interesting to note that the absorption of monoenergetic gamma photons in the thick NaI(Tl) detector leads only to a photopeak; the photopeak is due to the complete absorption of monoenergetic gamma photons entering within the detector. However, for the intermediate thickness of a NaI(Tl) detector, complete absorption of monoenergetic gamma photons leads to a photopeak; the absorption of only recoiled Compton electrons in the detector leads to the Compton continuum; and the absorption of only backscattered photons in the detector through the photoelectric absorption process leads to the backscattered peak. It is important to note that if a head-on collision takes place at the interface between the detector and a glass envelope of a photomultiplier, the forward moving electron escapes from the detector without depositing its energy in the detector and absorption of backscattered photons leads to the backscattered peak. If a head-on collision occurs on the edge or surface of the detector, the backscattered gamma photon may escape from the detector without depositing its energy, and the forward moving electron may deposit its energy to produce the Compton edge. If the head-on collision takes place in the middle of the detector, both the backscattered photon and the Compton electrons together produce photopeak at the incident photon energy.

In the present experiment, we have shown that the rest mass energy of the electron can be determined accurately by measuring the backscattered photon energies with a NaI(Tl) detector spectrometer. The intensity of the backscattered photon is enhanced by keeping the aluminium target over the radioactive gamma source.

2. Theory

When a photon of energy E_γ is scattered by an electron through Compton scattering at an angle θ, the energy of the scattered photon E'_γ is given by

$$E'_\gamma = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_\mathrm{o}c^2}(1 - \cos\theta)}, \tag{1}$$

where $m_\mathrm{o}c^2$ is the rest mass energy of an electron.

The Compton shift in wavelength [3] at any particular angle θ is given by

$$\lambda' - \lambda = \frac{h}{m_\mathrm{o}c}(1 - \cos\theta)\,. \tag{2}$$

The Compton shift in energy [3] of the photon is given by

$$\frac{1}{E'_\gamma} - \frac{1}{E_\gamma} = \frac{1}{m_\mathrm{o}c^2}(1 - \cos\theta)\,. \tag{3}$$

The Compton shift in energy [3] for a head-on collision ($\theta = 180^\circ$) is given by

$$\frac{1}{E_\mathrm{b}} - \frac{1}{E_\gamma} = \frac{2}{m_\mathrm{o}c^2} \tag{4}$$

where E_b is the energy of the backscattered photon.

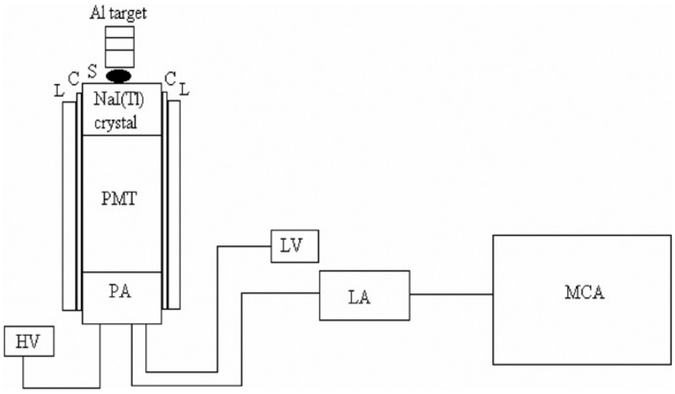

Figure 1. Experimental arrangement: Al target, aluminium target (7.2 cm); S, radioactive gamma source; C, copper foil (∼0.5 cm); L, lead block (∼3 cm); PMT, photomultiplier tube; PA, preamplifier; HV, high voltage unit; LV, low voltage unit; LA, linear amplifier; MCA, multichannel analyser.

The energy of the backscattered photon ($\theta = 180^\circ$) is given by

$$E_\mathrm{b} = \frac{E_\gamma}{1 + 2\frac{E_\gamma}{m_\mathrm{o}c^2}}. \tag{5}$$

Therefore, the rest mass energy of the electron in terms of E_γ and E_b can be written as

$$m_\mathrm{o}c^2 = 2\left[\frac{E_\gamma \times E_\mathrm{b}}{E_\gamma - E_\mathrm{b}}\right]. \tag{6}$$

Hence, by measuring the backscattered photon energy E_b for the known incident photon energy E_γ, the rest mass energy of the electron can be determined.

In our experiment, we have measured the backscattered energy E_b using the scintillation detector gamma ray spectrometer. By knowing E_γ from the literature and E_b from the experiment, we have determined the rest mass energy $m_\mathrm{o}c^2$ of the electron.

3. Experimental details

The experimental arrangement to determine the rest mass energy of the electron is shown schematically in figure 1. It consists of a radioactive gamma source, a thick aluminium target and the detector spectrometer. The radioactive gamma sources, ^{203}Hg (279.197 keV), ^{137}Cs (661.660 keV), ^{54}Mn (834.855 keV) and ^{60}Co (1252.873 keV, which is the weighted average energy of 1173.237 keV and 1332.501 keV), used in our experiment are obtained from the Board of Radiation and Isotope Technology (BRIT), Mumbai, India. The gamma radiation emitted from the radioactive source at S is detected with a 2 inch diameter and $1\frac{3}{4}$ inch thick NaI(Tl) crystal coupled to a photomultiplier of the type 9656 KL (EMI). The output of the photomultiplier is fed to a linear amplifier and then to a 1 K multichannel analyser. In order to reduce the noise, we have placed the detector in a lead castle; the lead K x-ray from the lead shield (∼3 cm) can also produce a photopeak at 82 keV. To reduce the intensity of the lead x-ray, the inner portion of the lead shield is lined with a copper plate of the thickness 0.5 cm. It is interesting to note that for a large change in incident photon energy from 280 keV to 1200 keV, the backscattered photon energy changes from 130 keV to 220 keV. In view of

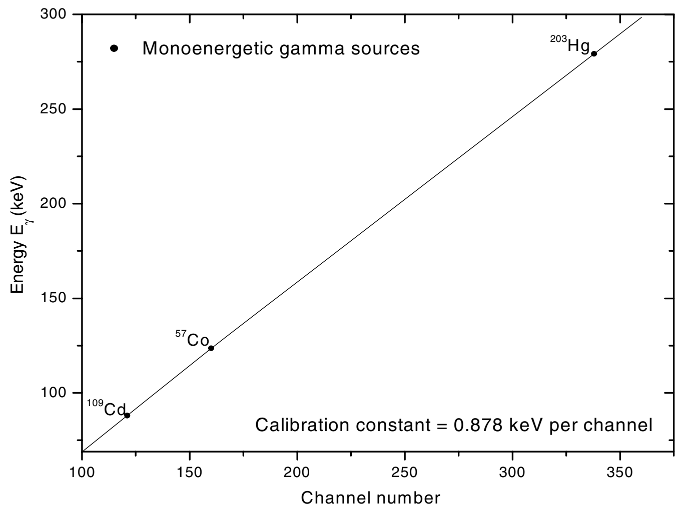

Figure 2. Calibration of the NaI(Tl) scintillation gamma ray spectrometer in the low energy region.

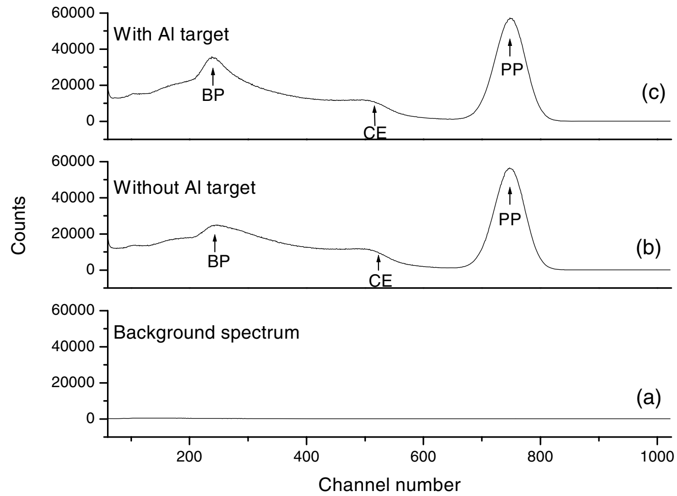

Figure 3. Typical gamma ray spectra of ^{137}Cs radioactive source with and without aluminium target. PP: photopeak, CE: Compton edge and BP: backscattered peak.

the change of the backscattered photon energy over a small energy interval, we have calibrated the detector spectrometer in the region from 80 keV to 300 keV, using monoenergetic gamma sources ^{109}Cd (88.034 keV), ^{57}Co (123.6 keV) and ^{203}Hg (279.197 keV). The calibration constant is found to be 0.878 keV per channel and is shown in figure 2. Our main objective in the present experiment is to measure the backscattered photon energies for the four different monoenergetic gamma sources. A typical experimentally measured gamma ray spectrum for ^{137}Cs (661.660 keV) is shown in figure 3(b). From the figure, we notice that the intensity of the backscattered photons produced in the detector is not pronounced. In order to obtain pronounced backscattered photon intensity for all the radioactive sources, we have placed a thick aluminium target (7.2 cm) over the source. In such a position, more gamma photons

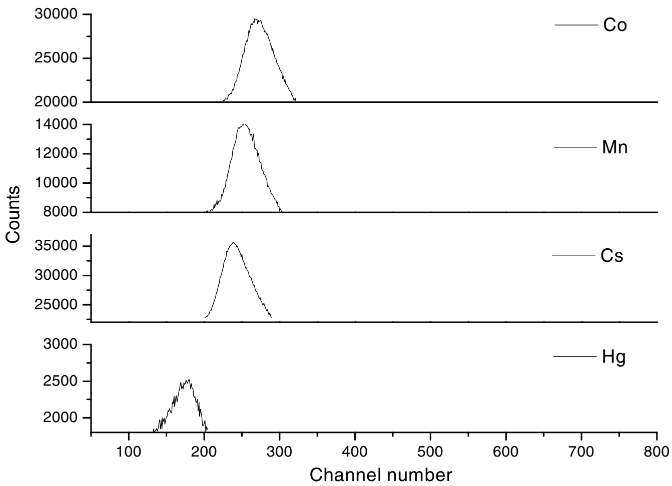

Figure 4. Typical backscattered peaks for ^{60}Co, ^{54}Mn, ^{137}Cs and ^{203}Hg with an aluminium target.

Table 1. Comparison of experimental values with standard value of the rest mass energy of the electron.

Sources	Photopeak energy energy E_γ (keV)	Backscattered peak energy E_b (keV)		Rest mass energy of the electron m_oc^2 (keV)	
	Literature[a]	Experimental	Calculated[b]	Experimental	Standard[c]
^{203}Hg	279.197	130.8	133.36	492.3	511.003
^{137}Cs	661.660	187.8	184.34	524.8	511.003
^{54}Mn	834.855	201.0	196.01	529.6	511.003
^{60}Co	1252.873	212.9	212.22	512.9	511.003

[a] Reference [4].
[b] Equation (5).
[c] Reference [6].

incident on the target, get backscattered into the detector leading to a pronounced backscattered peak at the lower energy region of the Compton continuum; this is shown in figure 3(c).

We have measured the backscattered photon energies for other radioactive sources of ^{203}Hg, ^{54}Mn and ^{60}Co by keeping the aluminium target over the sources. The experimentally observed backscattered peaks are shown in figure 4. In table 1, we give the list of radioactive sources used, the values of the incident gamma energies (E_γ) taken from the literature [4], the values of experimentally measured backscattered photon energies and also the calculated backscattered photon energies using equation (5). Using E_γ and experimentally measured E_b, we have determined the rest mass energy of the electron using equation (6); for each incident gamma energy, we see from column 5, the values lie close to one another. We have determined the rest mass energy of the electron using equation (4). In this case, we have plotted $1/E_b$ versus $1/E_\gamma$ which gives a straight line. From figure 5, we see that all the four points lie close to the least-square fit straight line. The rest mass energy of the electron is determined using the least-square fit value of the intercept. It is found to be 534.75 keV which is in agreement with the standard value of 511.003 keV within an error of 4.6%.

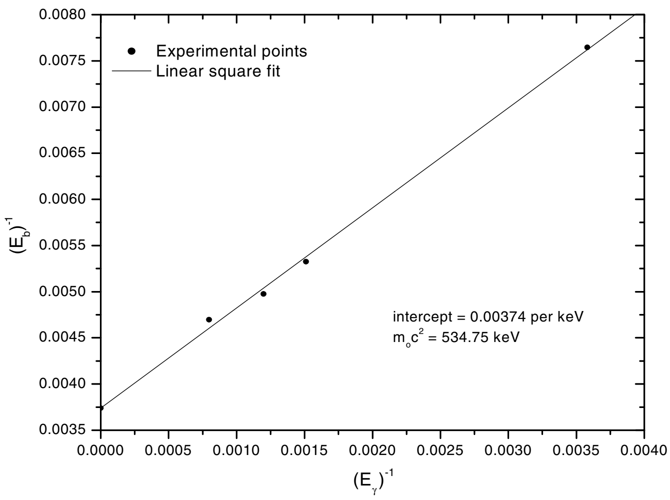

Figure 5. Plot of $\frac{1}{E_b}$ versus $\frac{1}{E_\gamma}$.

4. Conclusions

Here, we have set up a simple experiment for measuring the rest mass energy of the electron, as discussed above. We have measured the backscattered photon energy for determining the rest mass energy of the electron. From table 1, we notice that our experimental values of rest mass energy closely agree with the standard value within an error of 3.6%. Thus, we can say that this is an exclusively simple setup, which graduate and undergraduate laboratories can adopt, without much expense, to determine the rest mass energy of the electron, which is an important physical quantity. If the laboratories do not have four radioactive sources, they can determine the rest mass energy of the electron just by using a single radioactive source. Thus, in the present experiment, the student can also learn the important aspects of the interaction of gamma photons with a NaI(Tl) detector along with the determination of the rest mass energy of the electron.

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