Mass of the electron m_0

1   Objective

To determine the rest mass of the electron, m_e, via γ-ray interactions (mainly Compton scattering and photoeffect) in a *NaI* scintillation detector. Based on the enclosed article by Mudhole and Umakantha (Ref. [2]), you will perform this experiment as outlined there.

2   Theory and Procedure

You must become familiar with -ray interactions in matter, the Sodium Iodide (*NaI*) detector including the Photomultiplier Tube (PMT), and the Multichannel Analyzer (MCA) Universal Computer Spectrometer (UCS). See the enclosed handout (in Ref. [7]). The MCA is a computer-controlled spectrometer (UCS30) that digitizes the pulses in the range (0-10)V and with risetimes from (0.5-30)μs.

Review the manual of the UCS in Ref. [7]. Review the hardware properties on p. 7; connections in rear panel on p. 8; different analysis modes of operation on p. 10, specifically the "Pulse Height Analysis"; and the operation and settings of the amplifier/high voltage/ADC "Amp/HV/ADC" on pp. 16-22 for configuring system parameters for the HV and the amplifier gain. The manual contains useful advanced features for collecting and analyzing data such as region of interest (ROI) on p. 24 and file open/save functions on p. 35.

Warning! Check the polarity of the high voltage for the PMT, which is provided by the computer controlled UCS (see manual), and do not exceed the maximum HV, which should be indicated on the *NaI* detector. If in doubt, ask before turning on the HV!

The PMT output needs to be connected to the MCA input, which has an internal preamp/amplifier. Check the signals at various places with an oscilloscope. For instance, the raw anode output of the PMT should be a negative pulse (why?). The preamp/amp will integrate, amplify, and shape this pulse into a pulse that is required for the pulse to become digestible to the MCA.

Also observe the PMT output as you change the HV (gain of the PMT increases with increasing HV - make sure you understand why). Record the spectra from several -sources to familiarize yourself with the physics and the hardware. If the backscatter peak is weak try to enhance it by positioning some material appropriately. Use the photopeaks for calibration, i.e., channel number versus energy deposited. This relationship should be highly linear.

Perform a linear least squares fit. You can review least square fit in "Fit straight line with unequal errors" under additional resources or in 6.3 and 6.4 in Ref. [3].) Good sources for the calibration are ^{22}Na, ^{137}Cs, and ^{60}Co, resulting in a total of 5 photopeaks. Make sure your lab report/ lab notebook contains plots of all your spectra. The most useful sources, based on their longevity, are (with their half-life and most abundant E_γ):

^{137}Cs ($\tau_{1/2}$= 30.2 years; 0.662 MeV)

^{60}Co ($\tau_{1/2}$= 5.3 years; 1.17 MeV, 1.33 MeV)

^{22}Na ($\tau_{1/2}$= 2.6 years; 0.511 MeV, 1.275 MeV)

^{133}Ba ($\tau_{1/2}$= 10.5 years; 0.356 MeV)

Note that in case of ^{22}Na and ^{60}Co you might also see the sum peak at higher energies. Look for it and make sure you understand what is happening there. If you take data long enough with your detector close to a wall (no Pb bricks as shielding and no sources around!) you will likely see a peak at 1.46 Mev from ^{40}K in concrete, a well-known background line in concrete buildings. Identify this peak in a background spectrum.

Determine the resolution (FWHM) in % using your ^{137}Cs photopeak. Typical numbers for NaI detectors are 5%-10%. You may find useful to take data for a certain amount of time with a weak source, then remove the source, and take data for the same amount of time with the MCA in subtract mode, i.e. performing a background subtraction.

Using your calibration determine the Compton edge and the backscatter peak (both in keV) for as many sources as possible. Then calculate m_e and determine the uncertainty for m_e (in keV). It is important to collect as many data points for m_e as possible, at least four each from the Compton edge and from the backscatter peak. If, for example, you can't use the Compton edge from a particular source, try to still use the backscatter peak. An example for this is ^{60}Co - why can't you use the Compton edge in this case? For sources with two γ lines accumulate enough statistics so that you can use the sum peak and its Compton edge. In addition, take a long-enough background spectrum so that you can use the ^{40}K line, mentioned above.

Do your results from the Compton edges indicate whether the half-height point is really the best measure of the Compton edge? Is there any systematic difference in your results between the accuracy obtained for m_e using the Compton edges vs. using the backscatter peaks? If yes, can you think of a reason why?

Answer the question: why do the backscatter events show up in a peak, i.e. why are they not distributed over a much wider energy range?

3 References

[1] Melissinos and Napolitano, Chapter 8.

[2] Appendix: Determination of the rest-mass energy of the electron..., Am J. Phys Vol 45 No 11, Nov. 1977.

[3] Appendix : Interaction of Electrons and Photons with Matter

[5] G.F. Knoll, Radiation Detection and Measurement, 2nd ed., 1989, Wiley.

[6] W.R. Leo, Techniques for Nuclear and Particle Physics Experiments, 2nd ed., 1994, Springer.

[7] Multichannel Analyzer manual can be found in:
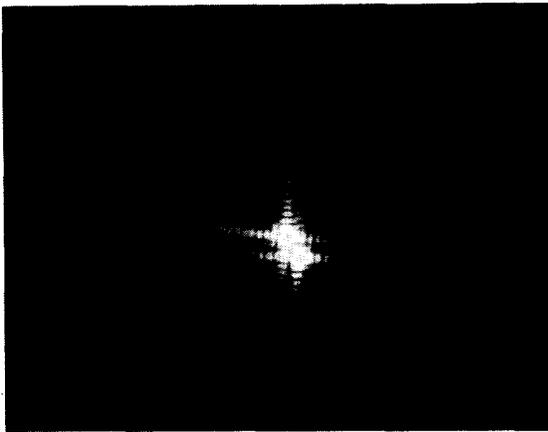http://www.spectrumtechniques.com/ucs30.htm

Fig. 1. The output of a misaligned double-beam interferometer illuminated through a square aperture.

this simple aligning technique. Such rotations cannot be tolerated in interferometric systems and may be troublesome also in other applications.

In noncoherent systems, rotational alignment is achieved by using some kind of reticle (i.e., cross hairs). Unfortunately, due to diffraction, a reticle does not solve the problem in a coherent system. We found it very useful to convert the whole laser beam into a "reticle." This can easily be done by inserting an aperture of some definite form in the beam in order to produce a diffraction pattern—the "reticle" of the desired form. For example, a circular aperture produces a set of concentric rings that are useful in accurate centering of the beam. In our laboratory[1] we used a square aperture in order to align an interferometric system with two laser beams exactly colinear and allowing no rotation between them. Figure 1 shows the output of the system with inaccurate alignment (a slight displacement of the beams was also introduced for clarity).

many cases this is adequate. However, when a larger number (over three) of reflections are involved they may introduce a rotation in the beam which is undetectable by

[1]J. Shamir, Appl. Opt. 15, 120, (1976).

Determination of the rest-mass energy of the electron: a laboratory experiment

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The rest-mass energy of the electron is an important quantity in physics and it is desirable to have a laboratory experiment to determine it. This can be done by making use of the Compton scattering in which an incident photon of known energy shares energy and momentum with an electron at rest. It can be shown[1] that in a head-on collision with an incident photon of energy E_γ, the electron receives the maximum possible energy given by

$$T_{max} = E_\gamma[1 + (m_0c^2/2E_\gamma)]^{-1} \tag{1}$$

and the back-scattered photon has the minimum possible energy given by

$$E'_\gamma = E_\gamma - T_{max} = m_0c^2[2 + (m_0c^2/E_\gamma)]^{-1}, \tag{2}$$

where m_0 is the rest mass of the electron and c is the velocity of light. Thus, by experimentally determining either T_{max} or E'_γ for a known E_γ the electron rest-mass energy m_0c^2 can be determined.

This experiment can be done in any undergraduate laboratory which is equipped with a gamma-ray spectrometer consisting of a NaI(T1) crystal coupled to a photomultiplier and a single- or multichannel analyzer to determine the pulse-height distribution due to monoenergetic gamma rays falling on the crystal. The photoelectric absorption of the incident photons lead to a peak called the photopeak whose

maximum corresponds to the energy E_γ of the incident photons. The Compton scattered electrons have a continuous distribution of energy from zero to T_{max} and these lead to the so-called Compton distribution in the pulse-height spectrum. Because of the finite resolution of the crystal, the Compton distribution has at the higher energy end a rapidly falling part called the Compton edge. The pulse height corresponding to the midpoint of the Compton edge may be taken as corresponding to the electron energy T_{max}. On the other hand, if the head-on collision takes place at the interface between the crystal and the glass envelope of the phototube, the electron would escape from the crystal and the back-scattered photon of energy E'_γ may undergo photoelectric absorption in the crystal. Such processes lead to a well-discernable peak called the back-scattered peak which is superposed on the continuous Compton distribution.[2] If, using a set of gamma sources of known energy, the spectrometer is calibrated so that the pulse height can be expressed in terms of energy, the pulse heights corresponding to the photopeak, the Compton edge, and the back-scattered peak can be directly expressed in terms of energy, and using Eqs. (1) and (2) the value of m_0c^2 can be determined.

We report the results we have obtained by using a NaI(T1) crystal of 1-in. diam. and 1-in. height coupled to
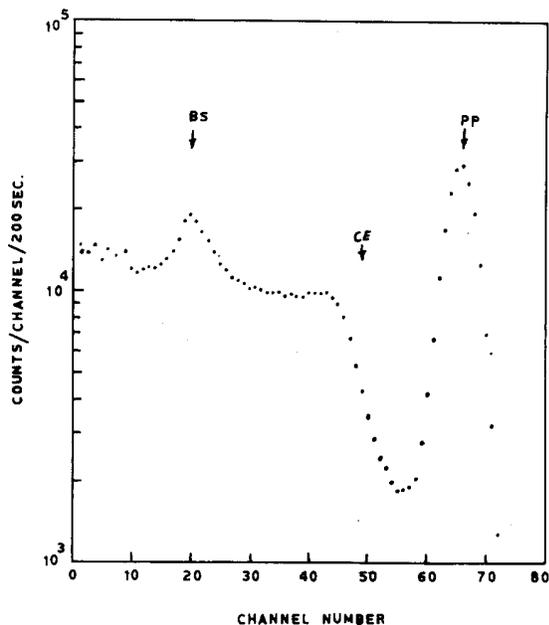
Fig. 1. A typical pulse-height distribution obtained with a ^{137}Cs source, where BS, CE, and PP indicate, respectively, back-scattered peak, the Compton edge, and the photopeak.

Table I. The values of the electron rest-mass energy (m_0c^2) calculated using the experimental values of the Compton edge (T_{max}) and the back-scattered peak (E'_γ) are given in columns 6 and 7, respectively, for the three gamma energies (E_γ) used. The error of ± 20 KeV corresponds to the uncertainty of $\pm 1/2$ channel (i.e., ± 5 KeV) in determining T_{max} and E'_γ from the pulse-height distributions. Mean value of $m_0c^2 = 516 \pm 20$ KeV.

Source	Halflife	E_γ KeV	T_{max} KeV	E'_γ KeV	m_0c^2 KeV	m_0c^2 KeV
^{137}Cs	30y	662	480	190	502	533
^{54}Mn	310d	840	640	200	525	525
^{65}Zn	245d	1114	910	210	499	517

an RCA-6199 photomultiplier. The pulse-height distribution is obtained by using a multichannel analyzer. A typical pulse-height distribution is given in Fig. 1. The gamma sources used, their half-lives, the values of E_γ, T_{max}, and E'_γ are given in Table I. The sources are of 10 μCi. In column 6 we give the values of m_0c^2 obtained by using Eq. (1), and in column 7 the values obtained by using Eq. (2). The

uncertainty in determining T_{max} and E'_γ from the observed pulse-height distribution is about $\pm 1/2$ channel, i.e., about ± 5 KeV. This leads to an error of about ± 20 KeV in the calculated rest-mass energy of the electron. The mean value of the rest-mass energy of the electron is found to be 516 ± 20 KeV which is close to the standard value of 511 KeV. Using the standard value of the velocity of light, the mass m_0 of the electron can be calculated. In our case it comes out to be $(9.20 \pm 0.35) \times 10^{-28}$ g comparable to the standard value of 9.108×10^{-28} g. Greater accuracy can be achieved by using a Ge(Li) detector, if available.

We are grateful to the University Grants Commission for the financial assistance.

[1] R. D. Evans, The Atomic Nucleus (McGraw-Hill, New York, 1955), p. 672.

[2] J. H. Neiler and P. R. Bell, "The Scintillation Method," in Alpha-, Beta-, and Gamma-Ray Spectroscopy, edited by K. Siegbahn (North-Holland, Amsterdam, 1965), p. 245.

Half-life of thorium-232: a laboratory experiment

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We report a simple laboratory experiment to estimate the half-life of ^{232}Th, which also familiarizes the students with the technique of absolute counting with a 4π geometry using a liquid scintillator.[1] The isotope has an abundance of 100% and its decay series is well known.[2] The longest lived product ^{228}Ra, has a half-life of 5.75 y. So, in any thorium sample which is more than about 35 y old, all the decay products would be nearly in secular equilibrium with thorium, leading to emission of six alpha particles in the energy range from 4 to 9 MeV and four beta particles belonging to beta spectra having endpoint energies from 0.012 to 2.25 MeV. In this experiment a known amount of thorium nitrate is dissolved in a liquid scintillator and a difference method is used to determine the counting rate due to

alpha particles only. As there are six alpha emissions in the series, one-sixth of this counting rate gives the disintegration rate of thorium in the sample. From this, the half-life of thorium can be calculated. The experiment can be done in 3–4 h using a single or a multichannel analyzer, or even a scaler-discriminator setup.

A liquid scintillator solution is prepared by dissolving 25 mg of p-terphenyl in 5 cc of dioxane. Of this 2 cc is poured into a flat-bottomed Pyrex glass cell of 2 cm diam and 2 cm height and an exactly weighed quantity of 2 mg of anhydrous thorium nitrate, $Th(NO_3)_4 \cdot 4H_2O$, is dissolved in the solution. In our experiment, we have used a sample which was purchased by our department 20 y ago. The cell is mounted on an RCA 6199 photomultiplier and covered

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