

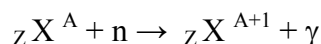
NEUTRON ACTIVATION

v2.1

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I. INTRODUCTION

The goal of this experiment is to gain some understanding of the principles of neutron activation and γ -ray spectroscopy. When exposed to a flux of thermal neutrons a nucleus has a finite probability of capturing a neutron. A typical reaction is of the form:



where the neutron is captured by some element, X, and some amount of energy is promptly released as a single photon, denoted γ . This type of "n-gamma" reaction is often abbreviated (n, γ). The probability that the reaction will occur is expressed in a geometrical quantity known as the total cross-section σ_γ having units of area. A typical unit is the *barn*, 10^{-24} cm².

An inspection of a nuclide chart (*e.g.* on the wall of the room housing the setup) will demonstrate that stable nuclei are often converted to unstable nuclei via the (n, γ) reaction. Neutron rich unstable nuclei β^- decay and produce daughter nuclei, often in excited states, which subsequently decay by emitting γ -rays of characteristic energies and intensities. (*Internal conversion* is a competing process that results in the emission of an electron rather than a γ -ray. See later discussion.) Analysis of a given spectrum can yield important information, such as the *flux* of the incident neutron beam, the *identity* of the target nuclide, the *half-life* of the unstable nucleus produced by neutron capture, *γ -decay branching ratios* of its daughter.

BEFORE conducting the experiments in this write-up, consult your instructor about laboratory *radiation safety* procedures.

II. BACKGROUND READING

The following references may provide useful background for the experiments and should be perused:

| <u>Reference</u> | <u>Sections</u> | <u>Topics</u> |
|---|---------------------------------------|--|
| Melissinos 2 nd Ed. ¹ | 8.6 8.4 Appendix D Chapter 8 | Half-Life measurements Scintillators & energy measurements Radiation safety Particle detectors in general |

| | | |
|--------------------------------------|---|--|
| Eisberg, Resnick ³ | 16.3, 16.5 | Beta and gamma decays |
| Krane ⁴ | 12.5, 20.1 | Neutron Activation Analysis |
| Firestone <i>et al.</i> ¹ | | Table of Isotopes, 8 th Ed. (web version via course website) |
| Bevington & Robinson ⁵ | 2.2, 2.3 3.2, 3.3 6.1-6.6 11.1 | Poisson and Gaussian distributions Error propagation Least-square fitting for a line Goodness of fit test |

III. EQUIPMENT

The basic components of the apparatus are a scintillator, a photomultiplier tube (PMT) with its high voltage power supply, an amplifier, and a PC-based pulse-height analyzer. Read appropriate sections of the instruction manual and get a demonstration from the instructor on the operation of the pulse height analyzer.

III.1. *Inorganic Scintillator Detector*

The interaction of γ -rays with matter produces three main types of phenomena: photoelectric effect, Compton scattering, electron-positron pair production. The three processes have different relative importance in different spectral regions, depending on the atomic number, Z , of the absorber.² From such considerations one can conclude that inorganic scintillators such as sodium iodide, NaI, or cesium iodide, CsI, have good efficiencies for γ -ray conversion due to their high effective Z . In this experiment you will use a NaI crystal of cylindrical shape which is about 2 inches in diameter and 2 inches deep.

Exercise 1: *Does the gamma-ray energy absorption in the scintillator in this experiment occur all in one spot, or is it distributed throughout the volume?*

III.2. *PMT and HV Power Supply*

The scintillator is optically coupled to a photomultiplier tube (PMT) which consists of a photocathode and a number of current gain stages. (See Melissinos.) Voltage is provided to the PMT base, essentially a voltage divider circuit, by the high voltage (HV) power supply. The maximum voltage to this PMT should never exceed 1200 V as indicated by the sum of the coarse and fine voltage control knobs. The detector operates well at about 1100 V. You can raise or lower this by a few tens of volts to fine-adjust the gain of the PMT if you wish. PMT's can take from minutes to hours to reach their optimal level of stability, therefore, leave the PMT turned on when you leave, so that the next users won't have to wait.

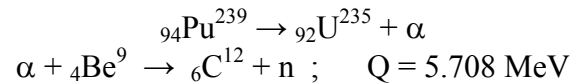
Exercise 2: Read about how a PMT and base work, and be prepared to explain your understanding to your instructor.

III.3. Amplifier

Signals from the PMT are filtered and amplified by a NIM module located in a “crate”. You can adjust the size of the output signal with the front panel controls, and you should examine and record in your log book the size and shape of the output signals on the oscilloscope. The signals should be negative-going from ground, with a positive over-shoot. Adjust the gain so that the photo-absorption peaks from Co^{60} are near the upper end of the DAQ histogram range (see below).

III.4. Neutron Source

The neutron source in the lab, known as an α initiated source, is composed of plutonium surrounded by beryllium. It is based upon the following nuclear reactions:



Q is the kinetic energy released in the reaction. To achieve a *thermal* neutron distribution, the source is placed in a tub of paraffin wax. By applying non-relativistic kinematics, one can show that an energetic neutron can lose an appreciable fraction of its energy by colliding with a free proton, of which paraffin has many. Furthermore, many subsequent collisions can reduce its energy to the thermal range. (See Segre⁵, Chapter 12 for an excellent discussion of reactor kinetics.)

III.5. Data Acquisition (DAQ) Computer

The pulses from the PMT are amplified and sent to the input port of a PC board which converts the charge in a pulse into a digital value. The more charge in the pulse, the larger the value, on a scale of 0 to 1024 (10 bits of resolution). In pulse-height analysis mode, the value corresponding to the charge in each pulse is used to increment a histogram in which the horizontal axis is the charge (energy) value, and the vertical axis counts the number of times an event with a given value was seen. To operate the software, to start and stop runs, to add up the counts in a given region, to convert values to energies, to save data files, etc., consult the manual for the device, or ask your instructor.

Exercise 3: Explain the difference between a histogram (such as you will be recording in this experiment), and a graph that plots a given function $y(x)$.

IV. ENERGY CALIBRATION PROCEDURE

Before using the system to measure unknown isotopes it is necessary to calibrate the NaI crystal. The calibration depends upon the applied voltage, the hardware and software gain settings, and factors such as the temperature in the room. This part of the experiment may take most of your first lab session.

1) Put a Cs^{137} source near the front of the counter. Connect the amplifier module's *Output* to the inputs of an oscilloscope (0.5 msec time base). Become familiar with the functions of the various knobs. You should note the effect a small variation in HV has on the amplified pulse shape and for which front panel knob settings the pulses become saturated (distorted).

2) Connect the amplifier to the DAQ board. Using the Co^{60} source, set the gain on the computer until the highest energy peak falls toward the right-hand side of the display. Use settings that will permit the accumulation of pulses corresponding to a γ -ray energy range as near to 0-2 MeV as possible. Initially the computer displays "channels" or "bins" on the horizontal axis. Eventually you may want a horizontal scale calibrated in either keV or MeV, but leaving it in "bins" is OK.

3) Return to the Cs^{137} source and accumulate a spectrum (similar to Fig. 8.21 of Melissinos) for a minute or so and observe the following features:

- i. the photo-peak and channel number around which peak is centered;
- ii. the full width at half maximum (FWHM) of the photo-peak;
- iii. the Compton edge and continuum.

Is the distance in channels between the photo-peak and Compton edge roughly what you expect?

Exercise 4: From the readings, determine the origin of the "width" of the peaks. Also, what is the origin of the "Compton edge"?

4) Locate the center of the 662 keV peak and record the channel number, n_γ . Also determine the full width at half maximum (FWHM), Γ_{FWHM} , for this peak expressed as a number of channels. Repeat using Na^{22} , Co^{60} , and Sn^{113} sources. The computer can now do a "two-point" or "three-point" energy calibration for you, but it cannot evaluate the goodness of the calibration. Therefore, plot the peak channel numbers versus γ energy yourself and confirm the linearity of the detector/counter system in response to the energy of the incident γ -rays. Do a linear least-squares fit using a function of the form

$$E_\gamma = a + b n_\gamma \quad (1)$$

and determine the values and associated errors of the coefficients a, and b. State what the expected error would be in determining the energy of an unknown photon line in the calibrated region if its associated bin number is well known.

Exercise 5: Before doing a computer-aided least-squares fit to your data, make a calibration graph by hand using pencil and ruler in your lab notebook. Make a best-fit by eye. Show this to your instructor.

5) Estimate the full width at half maximum (Γ_{FWHM}) of each significant peak, in keV. (This will be difficult for some peaks due to large background corrections.) Make a plot of Γ_{FWHM}^2 versus E_γ and perform a linear least-squares fit with the function

$$\Gamma_{\text{FWHM}}^2 = c E_\gamma + d \quad (2)$$

Explain why this functional dependence may be applicable.

The known gamma-ray sources you have available are

| | |
|-------------------|--------------------|
| Sn^{113} | (0.392 MeV) |
| Na^{22} | (0.511, 1.274 MeV) |
| Cs^{137} | (0.662 MeV) |
| Co^{60} | (1.17, 1.33 MeV) |

Exercise 6: Look up each of these isotopes in Reference [1]. Record in your notebook which transitions or reaction each of the above "known" gamma-ray energies come from. Discuss these with your instructor before the end of the second lab session.

The details of your energy calibrations should NOT be part of your journal article "Results" section. The reader will want to see at least a summary discussion of the calibration on the "Apparatus and Procedures" section. Nevertheless, all details should all be in your laboratory notebook.

V. ANALYSIS OF ACTIVATED INDIUM

In this part of the experiment you will activate Indium metal, determine the half-life of its unstable isotope formed by neutron capture, accumulate and analyze the resultant γ -ray spectrum. Using a nuclide chart with the aid of decay schemes from the *Table of Isotopes*¹, you will identify the dominant Indium isotope produced by neutron capture and trace the subsequent γ emission of its daughter nucleus.

The following is a suggested activation and data taking procedure:

- 1) Ask your instructor to help you prepare a vial of material for insertion into the PuBe irradiation container.
- 2) Fill a vial to nearly half capacity with pieces of Indium foil.
- 3) Load the vial and sample into an irradiation port, preferably the one closest to the source.
- 4) After a suitably long period of irradiation, remove the vial from the port. (What defines a suitable period?) Since the activity of the sample will be very low, place the vial

directly in front of the scintillator. Enclose both the scintillator and sample with a liberal amount of lead shielding.

5) Accumulate a spectrum of events in Pulse-Height Analysis (PHA) mode. Determine which of the observed peaks are likely to be from the activated source. Estimate carefully how precisely you can determine the centroids of the peaks, in units of energy. A second consideration is to see how closely your measurements match the handbook values of these gamma ray energies.

6) Develop a procedure to measure the number of decays observed per unit time using the Multi-Channel Scaling (MCS) mode of the data acquisition software. Note: plan to take data for at least two hours for this part of the experiment. This includes deciding what range of energies should be included in the counting region.

7) Determine from this data the half-life $T_{1/2}$ of the material. Estimate carefully how well you can make this measurement, and then compare your result, with uncertainty, to the handbook value for this material.

V.1. Peak Identification and Relative Count Rates

Determine the bin numbers of the peak centroids. Compute the corresponding γ -ray energies according to your previous calibration. Estimate the associated errors. Determine the relative intensity of each of the peaks you see; this requires that you sum up the number of counts in each of your peaks. Estimate the associated errors. Compare your values to those published¹. An example of the known decay scheme of an activated nucleus is given in Figure 1.

Exercise 7: Explain why it is necessary to sum up all the counts across a range of energies to get the total number of counts observed for one transition. Why is it not good enough to just use the number of counts in the highest channel?

Once the activated Indium isotope and its daughter have been properly identified, the relative efficiency of the detector as a function of energy can be estimated by comparing the relative intensities of the peaks observed to those published. (Refer to the decay schemes in the *Table of Isotopes*¹.) Determine the relative efficiency as a function of energy.

Exercise 8: Does the relative efficiency of the detector increase or decrease with increasing energy?

V.2. Determination of Half-Life

The counting rate due to decay is given by

$$R(t) = R_0 e^{-\lambda t} + R_b \quad (3)$$

where R_0 is the count rate at time $t = 0$, R_b is the background count rate, t is the time since $t=0$. Make an appropriate plot in which you expect the data to form a straight line. Extract the values of λ and R_0 . Compute the errors associated with these two parameters.

Convert λ to the half-life $T_{1/2}$ of the material. Compare the experimental half-life to the published value. (You will need λ for Section VIII.)

Exercise 9: Derive the relationship between the half life of the material, $T_{1/2}$, and the mean life, τ , which is defined as $\tau = 1/\lambda$.

VII. ANALYSIS OF ACTIVATED VANADIUM

Repeat the above analysis on Vanadium. The isotope formed has a comparatively shorter half-life; so you must work quickly and carefully. If the PHA mode of analysis does not work well enough, then try the alternative single-channel time-analysis mode.

VII. ANALYSIS OF AN UNKNOWN ISOTOPE

Your instructor will give you a sample which has been activated. Quantitatively analyze the sample. Determine the significant γ -ray energies. Determine the β -decay half-life. Use the *Table of Isotopes*¹, the wall-mounted *Chart of the Nuclides*, and resources on the web to determine the identities of the sample, the activated material, and daughter nuclei. Your result should be based on comparison of your observed energies (with associated uncertainties) and lifetimes (with associated uncertainties) with those listed in the reference materials. Make a statement about how well you think that all competing possibilities have been ruled out. In your final article, lead the reader through your chain of reasoning that leads to your final conclusion. It is crucial to understand how *precisely* you can make your measurements in order to identify the unknown with confidence; hence your work with the “known” materials is vital.

Exercise 10: Once you have identified the Unknown sample, look up the energy levels and decay scheme in the given references (available in the lab), and make a diagram of the unknown material in the simplified style of Figure 1 of this handout. Include this diagram in your logbook and in your journal article.

If time permits, you can try a second "unknown" isotope. If you have even more time left, you can activate (with help from your instructor) some substance of your choosing and attempt to identify its composition.

VIII. FLUX MEASUREMENT – *alternate project*

This part of the experiment actually investigates a property of the PuBe source which is used to activate materials, rather than the materials themselves. The "flux" of neutrons radiating from the PuBe source is defined as the number of particles per unit time passing through a unit area. It depends on the distance from the source. A practical method of measuring neutron flux is to measure the activity induced in a known amount of an element whose thermal neutron capture cross-section (σ_{nc}) is accurately known.

For low neutron flux (F_n) the change in the number of nuclei activated (N_{Act}) in time δt is given approximately by:

$$\delta N(t)_{Act} = (N_{nuc} \sigma_{nc} F_n - \lambda N(t)_{Act}) \delta t \quad (4)$$

where $N_{nuc} = N_{mole} A_o$ is the total number of nuclei in the sample, N_{mole} is the number of moles, and A_o is Avogadro's number. How would this equation be modified if there was a high neutron flux?

Assuming that no nuclei were initially activated, the solution of this equation is

$$N_{Act} = \frac{N_{Nuc} \sigma_{nc} F_n}{\lambda} (1 - e^{-\lambda t}) \quad (5)$$

which for $t \gg \lambda^{-1}$ yields the following simple relationship:

$$N_{Act} = \frac{N_{Nuc} \sigma_{nc} F_n}{\lambda} \quad (6)$$

Strips of Indium foil (8 to 10) will be used as a thermal flux monitor. At this point in your work, λ should be known. Before the flux can be calculated, however, N_{Act} must be determined. This quantity can be related to the integrated number of counts under prominent peaks but several complicating factors must be taken into account. These are:

- the detector has limited efficiency.
- the detector occupies a limited solid angle.
- the sample attenuates its own γ -rays: an effect that becomes important for source volumes on the order-of cm^3 or larger.
- not all of the decays will produce counts in the peaks of interest. Branching to unseen final states and internal conversion must often be considered.
- the number of integrated counts must be corrected for background events.
- the events were accumulated for a finite time interval.

VIII.1. *Detection Efficiency, Attenuation, and Solid Angle Corrections*

For quantitative measurements of γ -ray intensity one usually determines the number of counts in a photo-peak accumulated during a given interval of time. That

number can be determined by performing a linear background subtraction: Connect the minimum on the low energy side of the peak to that on the high energy side with a straight line and integrate above the line. If two peaks are not well resolved, you may wish to be more clever.

The correction factor accounting for efficiency, photon attenuation, and solid angle contributions can be estimated by placing the Co^{60} source at a number of sensibly chosen positions in the Indium stack and measuring the photo-peak intensities at each position. (The prominent peaks from Co^{60} and those obtained from activated indium decay nearly coincide.) For each photo-peak, that factor, η , is given by:

$$\eta = \frac{1}{M} \sum_j \frac{I_s}{I_j} \quad (7)$$

where M is the total number of positions, I_s is the source's photo-peak intensity and I_j is the observed intensity at the j th source position. Since the source's activity was measured several years ago, you must calculate the present-day activity from the date provided. To obtain the intensity from the decay activity, branching ratios and internal conversion corrections must be considered.

VIII.2. Branching Ratio Correction

The probability that β decay of the activated nucleus will produce a γ in the peak of interest depends upon the possible branches in the decay scheme. (See *Table of Isotopes*¹.) The branching ratio correction will be denoted (B).

VIII.3. Internal Conversion Correction

As stated in the Introduction, a nucleus in an excited state can perform a transition to a lower state by either emitting a γ or by transmitting energy directly to the electrons surrounding the nucleus. The latter process, called "internal conversion", results in the ejection of an electron from an atomic orbit. The energy of the ejected electron is equal to the energy lost by the nucleus less the binding energy of the electron in the atom. (Consult Blatt and Weisskopf, Theoretical Nuclear Physics.)

The total transition probability (P_{if}^{Tot}) from a nuclear state (i) to a nuclear state (f) is the sum of two terms:

$$P_{if}^{\text{Tot}} = P_{if}^{\gamma} + P_{if}^{\text{IC}} \quad (8)$$

where P_{if}^{γ} is the γ radiation probability and P_{if}^{IC} the probability of internal conversion. The *internal conversion coefficient* α is defined by:

$$P_{if}^{\text{IC}} = \alpha P_{if}^{\gamma} \quad (9)$$

so that we get:

$$P_{if}^{\text{Tot}} = (1 + \alpha) P_{if}^{\gamma} \quad (10)$$

The internal conversion coefficient depends upon the Z of the element, ΔE_{if} of the nuclear states, and the type of transition. (See Figures 7a-7j in the *Table of Isotopes*¹.) This correction has to be applied only to the final step of the decay sequence producing the γ -ray of interest. Corrections to intermediate steps in the decay sequence do not have to be considered. (Why not?)

VIII.4. Finite Time Correction

Since the events have not been accumulated from the instant the sample was removed from the activation container to time $t=\infty$, (the combined counts from all peaks considered) must be normalized to:

$$N_{Tot}' = K^{-1} N_{Tot} \quad (11)$$

where:

$$K = \frac{\int_{t_1}^{t_2} e^{-\lambda t} dt}{\int_0^{\infty} e^{-\lambda t} dt} \quad (12)$$

where t_1 and t_2 are the start and end times of the measurement.

Combining all of these factors, the total number of counts observed (N_{Tot}') is related to N_{Act} according to:

$$N_{Tot}' = N_{Act} \sum_j \left[\frac{\eta B}{1 + \alpha} \right]_j \quad (13)$$

where the sum is over the peaks being considered.

References

- 1) R. B. Firestone, V. S. Shirley *et al*, *Table of Isotopes, 8th Edition*, John Wiley & Sons, Inc., New York, 1996. See also the web site: <http://ie.lbl.gov/toi.html>, which contains much of the same information, and more.
- 2) A.C. Melissinos and J. Napolitano, *Experiments in Modern Physics, 2nd Edition*, Academic Press, New York, 2003.
- 3) R. Eisberg & R. Resnick, *Quantum Physics 3rd Ed*, J. Wiley & Sons, New York, 1985.
- 4) Kenneth Krane, *Introductory Nuclear Physics*, J. Wiley & Sons, New York, 1988.
- 5) P.R. Bevington and D.K. Robinson, *Data Reduction and Error Analysis for the Physical Sciences, 3rd Ed.*, McGraw Hill Book Company, New York, 2003.
- 6) E. Segrè, *Nuclei and Particles, Second Edition*, W.A. Benjamin, Inc., Reading, Massachusetts, 1977.

Simplified Level Diagram of Sn^{116} Showing Decay Gamma Rays From In^{116} Beta Decay

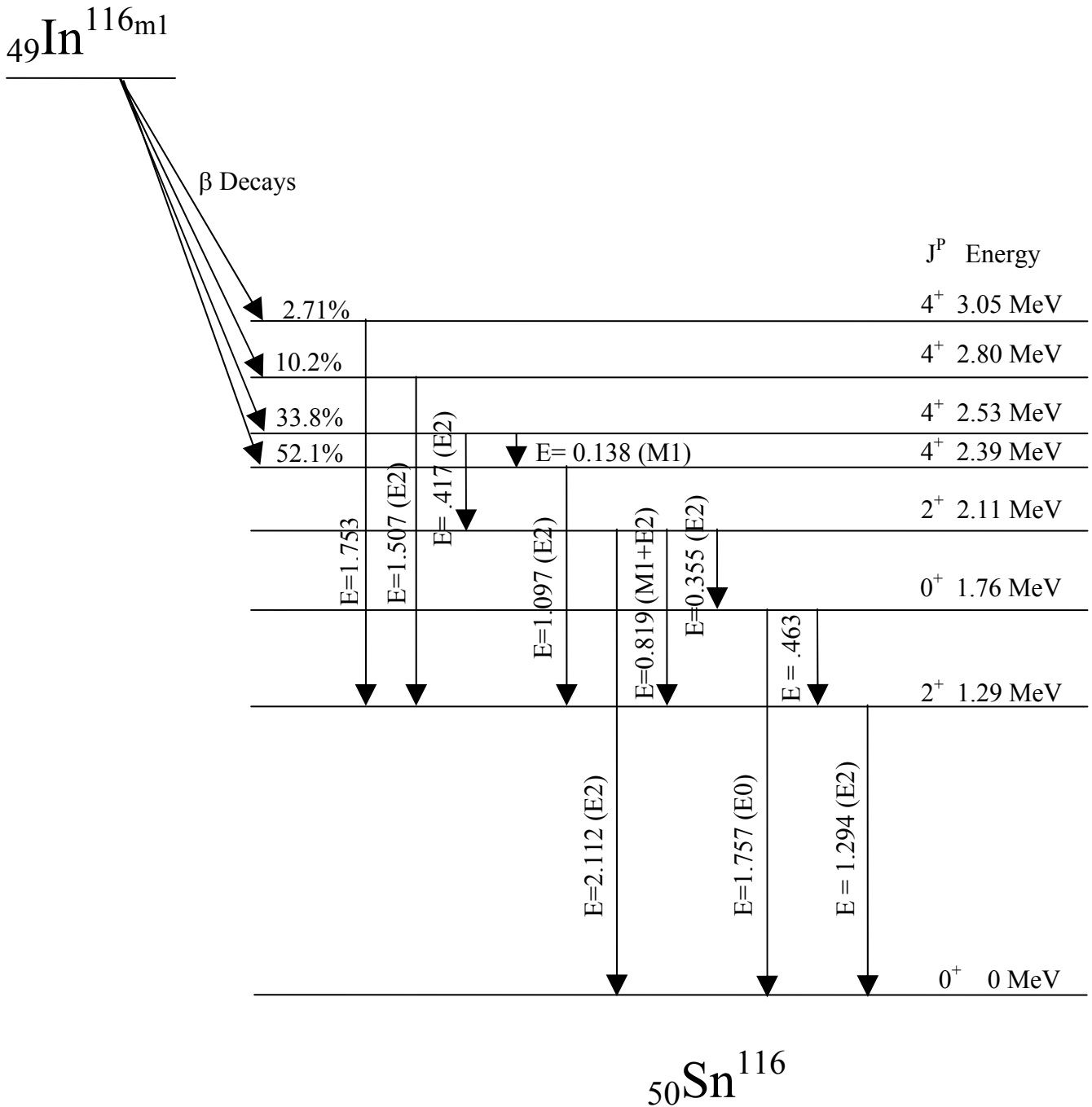


Figure 1: From the Table of Isotopes¹, this is an example of the (simplified) level-scheme relevant to beta decay followed by gamma emission of a nucleus used in this experiment.