Measurement of the Lifetime of the 59.5keV excited State of ^{237}Np from the Alpha Decay of ^{241}Am by delayed coincidence method

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---**ABSTRACT**---

The alpha decay scheme of ^{241}Am to the excited state of ^{237}Np and subsequently decay to the ground state of ^{237}Np have being studied. Delayed coincidence techniques have been employed and the lifetime of the 59.5keV excited state of ^{237}Np was measured to be 66nsec. This value obtain is very close to the accepted value which is 67nsec.

I.   INTRODUCTION

Nuclear structure is a complicated structure, which requires an increasing knowledge for more refined experimental equipment and techniques. During the fast decades, a significant progress has been achieved towards the understanding of nuclear structure through theoretical studies and experimental data acquisition. The decay of the excited state of any radioactive element happens so fast, and therefore requires a special technique to be able to understand and measure the life time of any excited states. An element can decay into several excited states, each having different energy level, angular momentum and parity. Different method and techniques have been employed in earlier experiments to measure the lifetime, energy, resolving time e.t.c. of the excited states of different elements. Coincidence technique is one the method used to measure the lifetime of excited state of an isotope. Coincidence counting rate were in earlier experiment observed as a function of delays inserted with mechanical delay lines or cables. Delayed coincidence provide greater efficiency of data collection, they are used in broad investigation such as the study of gamma-gamma ray angular distribution and gamma ray transition probability. The mean life of the second excited state of ^{42}Ca and the first excited state of ^{47}Sc have been measured using delayed coincidence techniques to be $4.8\pm0.3\times10^{-10}$sec and 5×10^{-12} respectively [1]. In another experiment using the same techniques, the half-life of the 74.6keV excited state of ^{239}Np was measured to be 1.2 ± 0.1mμsec [2].

In this experiment, I have employed the same delayed coincidence techniques to measure the half life of the 59.5keV excited state of ^{237}Np from the alpha decay of ^{241}Am.

The decay of ^{241}Am is essentially by alpha decay to the excited state of ^{237}Np in two energy levels. ^{241}Am can decay to the 103keV energy level of ^{237}Np via alpha decay, this decay happens 12.7% of the time. It can also decay via the same process to the 59.5keV energy of ^{237}Np, which occurs at 86.0% of the time. The 103keV excited state of ^{237}Np can also decay to the ground state of ^{237}Np by gamma-emission either directly to the ground state or through a decay branching to the 59.5keV then to the 33.2keV energy level and finally to the ground state of ^{237}Np. Both of the modes are short-lived, making it difficult to measure the lifetime of this excited state.

The most probable one and the long-lived decay is the decay of ^{241}Am to the 59.5keV excited energy level of ^{237}Np which occurs at 86.0% of the time then to the ground state of ^{237}Np by gamma-emission which occur 94.0% of the time. This decay mode is much slower compared to in particular the 103.0keV and the 33.2keV which occurs at 12.0% and 6.0% of the respectively. These are relatively faster and hard to measure due to their short-lived decay nature. The decay equation via this slow scheme and the general decay scheme of ^{241}Am to the ground state of ^{237}Np are shown below.

$$^{241}\text{Am} \xrightarrow[\text{86.0\%}]{\alpha} {}^{237}\text{Np*} \xrightarrow[\text{94.0\%}]{\gamma} {}^{237}\text{Np}$$
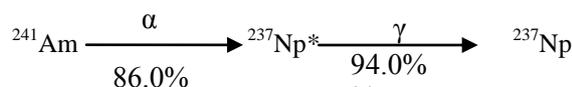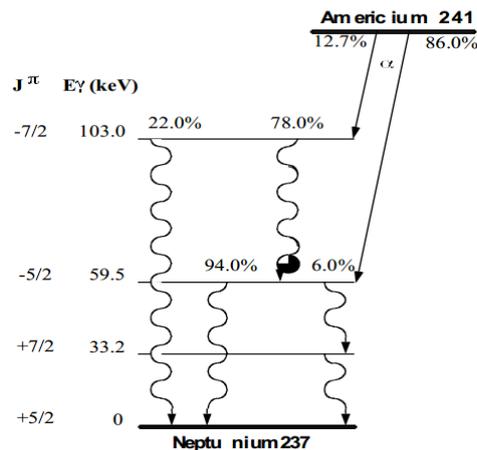
Figure 1: decay schemes of alpha particle decay of [241]Am via excited states
of [237]Np to the ground state of [237]Np with associated gamma-emission [3].

The lifetime of the 59.5keV excited state of [237]Np was measured by observing the time relationship between the emissions of the alpha particle by the decay of [241]Am and the emission of the 59.5keV gamma rays occupying the 59.5keV excited state of [237]Np. The [241]Am, which is the radioactive sample is placed between two plastic scintillators. One of the scintillators has a very thin sandwich organic material (10mm), this thickness is not sufficient for gamma ray interaction, therefore its only capable of detecting the alpha particle from the decay of [241]Am. The second plastic scintillators with appreciable thickness of about 50mm and 44mm in diameter, gives room for gamma ray interaction. It is therefore used in detecting our gamma rays from the decay of [241]Am. Plastic scintillators are used in this experiment despite their low light output, because they have fast response time. This fast response is therefore very important as the decay of happens so fast, i.e. the excited state of [237]Np have relatively short lifetime. To minimize the electron transit-time spread between the numbers of the dynodes present in the plastic scintillators used, the photomultiplier tubes are operated at a very high voltage. This high voltage will compensate the low light output of these scintillators.

II.   BACKGROUND THEORY

2.1. Plastic scintillation

Plastic scintillators are a class of organic scintillators. They utilize the ionization produced by charged particles to generate optical photons. They consist of a scintillation material which is optically coupled to a photomultiplier tube either directly or via a light guide. All plastic scintillators are sensitive to x-rays, gamma rays, fast neutrons and charged particles. For any material to be considered as good scintillators, it must be capable of converting a large amount of incident radiation into prompt fluorescence. As radiation passes through the scintillation, it excites the atoms and molecules making up the scintillators thereby causing light to be emitted. Among other types organic scintillators, plastic scintillators are by far the most widely used scintillation detectors. These detectors have densities ranges from 1.03 to 1.20gcm^{-3} [4]. These types of detectors have low light output, but have fast response time and their sensitivity to energy is high.

The scintillation material present in any scintillation detector produces three different types of emission [5]:
(i)   Fluorescence: This process describes the prompt emission of a photon in the visible spectrum from an excited subatomic state.
(ii)   Phosphorescence: The prompt emission in this process is also within the visible spectrum but has a longer wavelength and characteristic decay time.
(iii)   Delayed fluorescence: This process is similar to fluorescence but have a much longer wavelength decay time.

The operation of any detector basically depends on the process or ways by which the radiation interacts with the material of the detector.

2.2. Interactions of gamma rays with matter

Unlike alpha particles, gamma rays don't create ion pairs in matter by coulomb effect; this is because of their physical properties as quanta of energy which makes them interact mainly with the K- shell electrons. Among the large number of possible interaction mechanism a gamma ray undergo with matter, only three (3) among them have a major role to play in radiation measurement [6]. These interactions mechanisms include:

2.1.1. Photoelectric Absorption: In this process, a photon undergoes an interaction with an absorber atom in which the photon completely disappears. When this interaction occurs, an energetic photoelectron is emitted by the atom from one of its bound shells. The photoelectron appears with an energy given by:

$$E_{e^-} = h\nu - E_b \text{ ------------------------ (1)}$$

Where E_{e^-} = the electron energy

E_b = the binding energy of the atom

$h\nu$ = the photon energy

2.1.2. Compton scattering*:* In Compton scattering, the interaction takes place between the incident gamma ray photon and an electron in the absorbing material. The photon is deflected through an angle ϕ with respect to the photon original direction of travel. The reflected electron is known as **recoil electron**, the energy received by this electron from the incident photon ranges from zero to some appreciable fraction of the photon energy. The figure below shows how the electron is reflected after the interaction, and the equation below shows the photon energy after the interaction
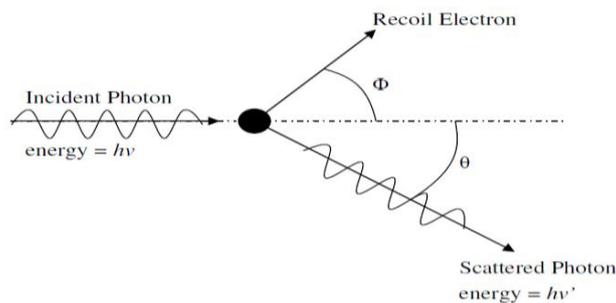
Figure 2: Diagram of Compton scattering process [5]

$$h\nu' = \frac{h\nu}{1 + \frac{h\nu}{mc \cdot c}(1 - cos\theta)} \text{ ------------------ (2)}$$

Where $h\nu'$ = the photon energy after the interaction

mc^2 = is the rest mass energy of the electron (0.511MeV)

2.1.3. Pair production: This happens to be the third among the most important interaction of gamma rays with matter. In this process, the incident gamma ray of certain energy interacts with the coulombic field of the nucleus and degrades into two particles; one of matter and the other of anti matter.

2.3. Radioactive decay theory

Rutherford and Soddy in 1902 postulated the theory of radioactive decay. All radioactive elements or substances are unstable; they will therefore have to disintegrate in a later time. They explained that a radioactive substance transformed into another substance in a way the atoms changed from a parent nuclei to a daughter nuclei, and that this decay is a random process. The fraction of atoms dN that disintegrate in a small interval of time dt, is described by the decay equation

$$dN_o = -\lambda N(t)dt \text{------------------ (3)}$$

Integrating the above equation gives

$$N(t) = N_o exp(-\lambda t) \text{------------------ (4)}$$

Where N = the number of excited nuclei

N_o = the initial number of the excited nuclei

t = the time since excitation and

λ = the decay constant which is express as:

$$\lambda = ln2/T_{1/2} \text{----------------------- (5)}$$

Where $T_{1/2}$ = the half-life of the excited state

2.3. Coincidence System

All coincidence measurement employs similar techniques, by converting the analogue signal from the detectors to a logic signal [6]. A coincidence system is designed basically to measure or determine when two pulses, or generally when two events occur within a given time period. The coincidence of two events is quite complicated than it appears, the associated statistical nature of this system makes it impossible to analyze with 100% confidence level. In principle, a coincidence system sums up the two input signals, and a resultant pulse is generated whenever the two pulses overlap.

Resolving time, which describes the period of time in which the two input signals can be accepted, is determined by the width Γ of the pulses. If the system detects the overlap of the pulses of width say Γ_o each, the resolution time is then express as $2\Gamma_o$ [7]. Assuming the rate of the pulse from alpha particle detector is n_1 and the pulse from the gamma detector represented by n_2, the probability or chance of coincidence is given by $2\Gamma_o n_1 n_2$ per second [8].

The life time of a nuclear state is related to its energy by Heisenberg uncertainty principle [9].

$$\Delta E \Delta t = \hbar \text{ --------------------- (6)}$$

ΔE = uncertainty in the energy associated with a state

Δt = uncertainty in time associated with state and

$\hbar$ = planks constant, which has a value of 1.05×10^{-34}joules.sec

In describing nuclear lifetime, equation one is best express as

$$\tau = \frac{\hbar}{\Gamma} \text{ ------------------- (7)}$$

Γ = energy width associated with a level

τ = mean lifetime, which is the average time for the nuclei to decay to a lower energy level.

The half-life and the mean life are related by

$$\tau = \frac{T1/2}{\ln 2} \text{ ------------------- (8)}$$

III. EXPERIMENTAL APPARATUS

The apparatus used in this experiment includes two plastic scintillators, a crate consisting of a dual discriminator (model T105/N), a dual high voltage supply unit (red-fronted CAEN supply module), an uncalibrated variable delay unit (multipulser: Model WD300/N), a coincidence unit (dual two fold AND: Model C102A/N), delay boxes, pulse generator, stop watch, 0.5m and 1m coaxial cables, an oscilloscope, T-junction and some numbers of 50-ohms terminators. A block diagram of the experimental set-up is shown in figure 2. Some of the major components of the experimental set-up are discussed below.

3.1. Dual Discriminator

An ideal dual discriminator is expected to perform the following functions

The most important function of the discriminator is to produce a standard logic pulse of fixed height and adjustable width for each variable height scintillators pulse larger than a set threshold voltage. It is also capable of counting narrow pulses at very high counting rates. It is very good at marking the precise arrival time of the pulses.

3.2. Multipulser Unit

A Multipulser is designed to have some variable delay unit. The multipulser used in this experiment has four (4) switchable delay ranges: 50-200nsec, 0.2-2msec, 2-20msec and 20-200msec.

IV. EXPERIMENTAL PROCEDURE

4.1 Dual Discriminator Calibration

Decay measurement of any kind involves some background noise; this noise is as a result of several factors like the electronic noise and cosmic muons interference. It is therefore necessary to calibrate all those components of the experiments that need to be calibrated so as to obtain a more concise result. The apparatus used in the calibration of the dual discriminator includes: a digital oscilloscope, bipolar pulse generator, the dual discriminator itself, standard length coaxial cables and a number 50-ohms terminator with a T-junction. The pulse generator is connected to both the digital oscilloscope via a 2m coaxial cable and the dual discriminator. The discriminator is connected to both the pulse generator and the digital oscilloscope via a 1m cable each. It is important to make sure that both the cable going directly to the oscilloscope and the one passing through the discriminator to the oscilloscope are of equal length. This is because, distance affect the amount of signal travelling through longer cables. The dual discriminator potentiometer setting was set to 1.5; the amplitude of the pulse generator was then increased gradually until just a point before the pulse freezes. The value of the pulse amplitude was determined from the display on the digital oscilloscope. The value obtained was recorded as the discriminator threshold setting corresponding to the output voltage observed. This process was repeated varying the potentiometer setting at an interval of 0.5 for 15 other measurement. The results obtained are presented in table 1. The graph of the actual voltage (mV) plotted against the discriminator threshold setting is presented in shown in figure 3.

4.2. Multipulser Calibration

The apparatus used in this section are similar to the ones used in calibrating the dual discriminator. The connection is the same, but multipulser in place of dual discriminator in this case. All the unused ports of the multipulser were terminated by a 50-ohms terminator. The multipulser range was set at 20-200nsec. The potentiometer was then set to its minimum value, 0.0. Both the input and the output logic pulses were seen on the oscilloscope. The delay was characterized by a horizontal time sweep between the input and the output logic pulse. At the minimum value of the potentiometer, the delay was 48.0nsec. The potentiometer was the varied at an interval of 0.5 up the maximum value of the knob. The corresponding delays were observed and record as shown in table 2. A graph of delay (nsec) was plotted against the potentiometer setting as can be seen in figure 4.

4.3 Coincidence Measurement

The apparatus for this measurement are set up as in figure 4 below
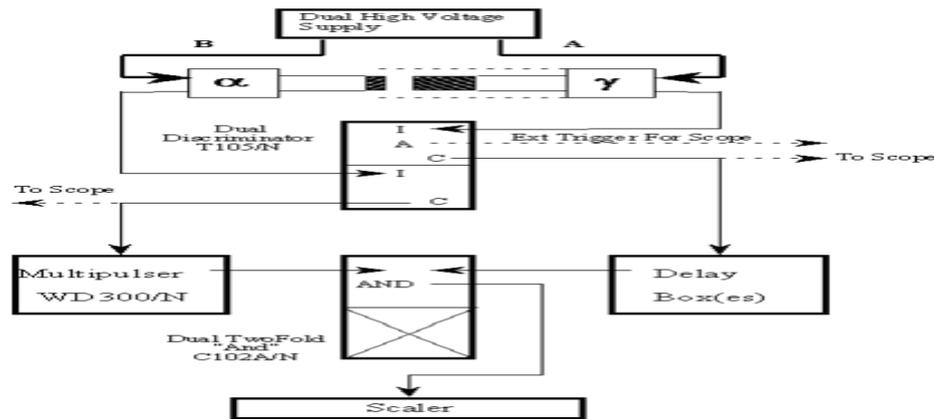
Figure 3: Experimental setup and circuit diagram [3].

The gamma detector and the alpha detector voltage were both set to about 2500V, with both discriminator A and B threshold set to 1.2. Both the alpha and the gamma signals are connected to the counter via an AND gate. A 62nsec delay was created using the delay boxes; this is the best delay which provides the maximum coincidence count rate. Starting from zero, a suitable multipulser width steps were choosing up to about 10 (the maximum value of the multipulser). Each step is observed for about 360sec and the number of counts is recorded as displayed on the counter. The main reason for observing the counts rate over a quite long time scale is to obtain a result with reasonable statistical accuracy. The result obtained in each steps are given by table 3. The graph of the number of counts was plotted against the delay using linux with error on delay of 0.03%, the graph shows an exponential curve. The slope of the graph, which is the decay constant (λ) was determine and hence used to calculate the half-life of the excited state of ^{237}Np.

V. Result and Discussion

5.1. Results

Table 1: result obtained in calibrating the dual discriminator

Discriminator A (Threshold)	Voltage (mV)
1.5	160
2	190
2.5	245
3	300
3.5	340
4	390
4.5	440
5	490
5.5	540
6	570
6.5	610
7	670
7.5	720
8	780
8.5	840
9	1000
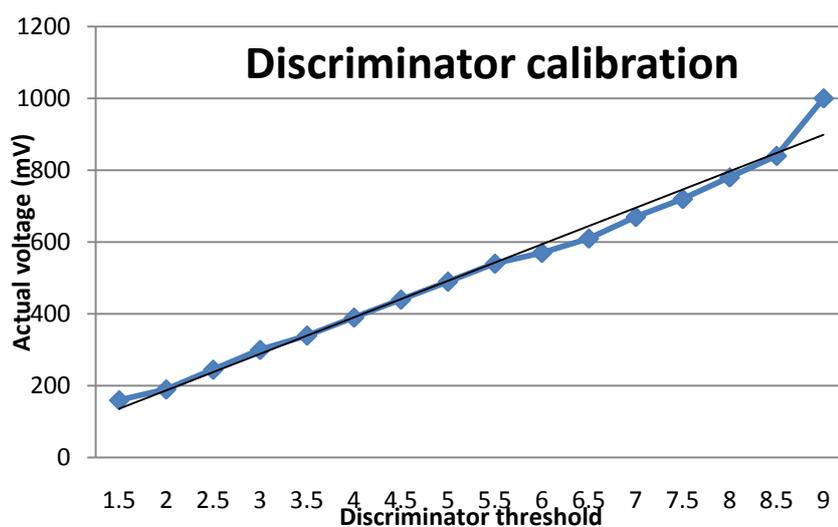
Figure 4: A graph of the actual voltage (mV) versus discriminator threshold for calibrating the dual discriminator.

Table 2: Result obtained in calibrating the multipulser

Potentiometer Setting	Delay time (nsec)
0	48
0.5	59
1	70
1.5	80
2	92.5
2.5	105
3	115
3.5	125
4	137.5
4.5	147.5
5	157.5
5.5	167.5
6	177.5
6.5	190
7	200
7.5	210
8	220
8.5	230
9	240
9.5	250
10	265

Multipulser calibration
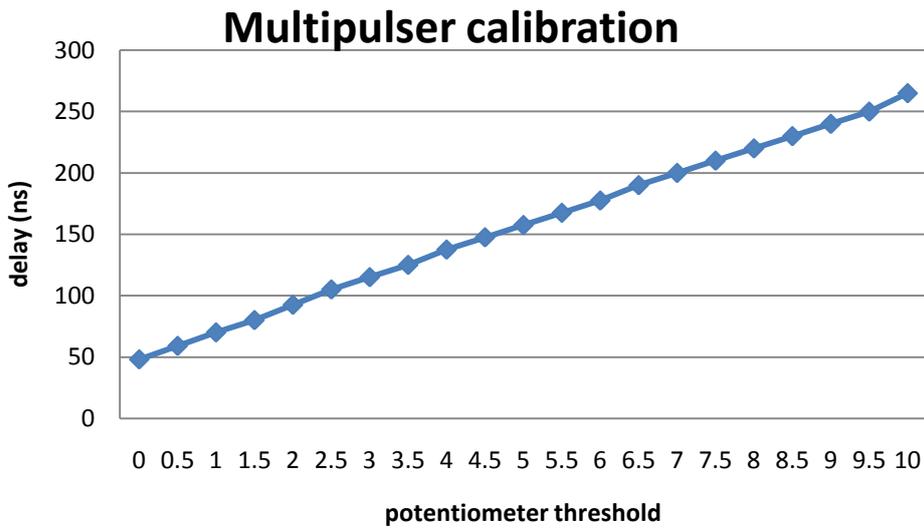
Figure 5: A graph of the readings obtained during the calibration of the multipulser

Table 3: results obtained during the coincidence measurement

Delay (nsec)	Error Delay	Counts/6 min	Error on counts
48	3	284	16.8
92.5	3	503	22.4
105	3	441	21
115	3	373	19.3
125	3	318	17.8
137.5	3	315	17.7
147.5	3	249	15.7
157.5	3	231	15.1
167.5	3	217	14.7
177.5	3	216	14.6
190.5	3	187	13.6
200	3	158	12.5
265	3	0	0
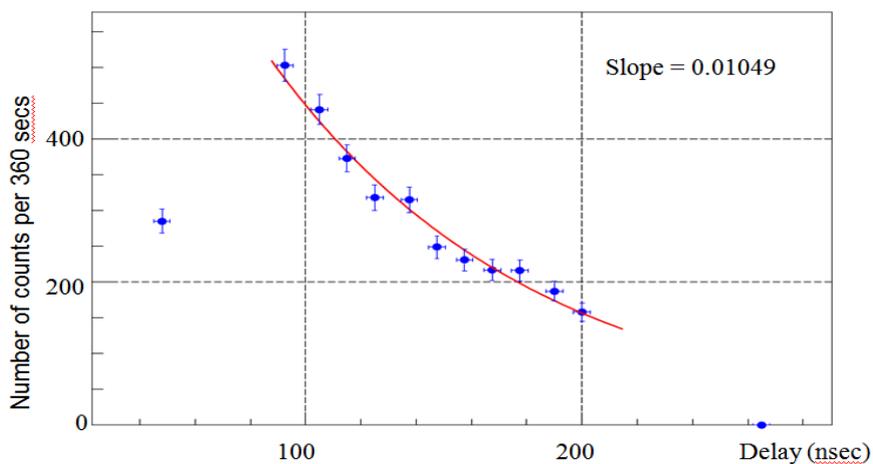
Figure 6: A graph of the number of counts versus the delay in nsec for the coincidence measurement

5.2. Discussion

From the graph of the coincidence measurement shown in figure 6, the decay constant (λ); whish is the slope was determined to be 0.01049. This value was the substituted into equation (5) and the lifetime of the excited state of ^{237}Np was found to be 66nsec with error on the delay of about 0.03%. The background was also subtracted throughout the number of count to reduce the experimental uncertainty. Figure 4 and 5 are graphs for the calibration of the dual discriminator and the multipulser unit respectively. The straight line obtain in the calibration of the discriminator indicates that the actual voltage increases with increase in the discriminator threshold value.

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