IOSR Journal of Applied Physics (IOSR-JAP)
e-ISSN: 2278-4861.Volume 8, Issue 2 Ver. I (Mar. - Apr. 2016), PP 66-73
www.iosrjournals

Measurement of Lifetime of an Yrast $I^{\pi} = 2^{+}$ state in ^{152}Sm via γ – γ coincidences usingNaI(Tl) Scintillators

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Abstract: *An experiment was conducted to study the performance of thallium doped sodium iodide (NaI(Tl)) scintillators in measuring the lifetimes of nuclear excited states that are just above 1 ns. A bench top setup with two similar NaI(Tl) detectors was used to measure the lifetime of Yrast $I^{\pi} = 2^{+}$ state in ^{152}Sm via γ – γ coincidences. Results showed high precision of the timing system used and the accuracy of measurement confirming the suitability of NaI(Tl) scintillators in measuring lifetimes longer than 1 ns.*

Keywords:*Accuracy, Coincidence, Lifetime, Nuclear State, Precision, Yrast state*

I. Introduction

As one of essential nuclear observables, the lifetimes of nuclear excited states are needed to determine the reduced transition probabilities which offer the model independent information useful in understanding the nuclear structure. For instance, even the simplest information on the lifetimes of the first $I^{\pi} = 2^{+}$state in even-even nuclei and the corresponding extracted B(E2:2^{+} to 0^{+}) can be employed to show nuclear collectivity and in a model independent way extract parameters such as the transition quadrupole moment (Q_0) and nuclear deformation, β_2 [1]. However, precision measurement of lifetimes of nuclear excited states can prove to be a very difficult task. One of important techniques used to measure the lifetimes of excited states is the electronic fast timing technique. This technique has the ability to measure lifetimes in the picosecond region which gives it a huge advantage over other methods such as Recoil Distance technique and Coulomb Excitation technique [2]. Nevertheless, precision and accurate measurement of lifetime of nuclear excited state depends on the rise times of the detectors usedas well as the electronic devices employed [3]. Normally, scintillators such as BaF_2 and $LaBr_3$ are employed due to their relatively fast rising times as described in Table 1. However, in some conditionsboth BaF_2 and $LaBr_3$might be eithertoo expensiveor hard to get. In such conditions, especially when lifetimes longer than 1 ns are to be measured, NaI(Tl) scintillators can make a good substitutionfor BaF_2 and $LaBr_3$. In this work an experiment is set to study the performance of NaI(Tl) detectors in measuring the lifetime of a 121.78keV state of ^{152}Sm which is known to have a lifetime just a little longer than 1 ns. The 121 keV yrast state of ^{152}Smhas been chosen sinceits lifetime of 1.400(11) ns is well known from literature and ^{152}Eu is a common calibration source.

Table 1. Characteristics of some scintillation detectors. Information from reference [1].

Scintillator	Light Output(photons/MeV)	Principle decay time (ns)	Energy resolution (%)
NaI(Tl)	3.8×10^4	230	6 – 7
BaF_2	1.0×10^4	0.6 ; 620	10 – 12
$LaBr_3$	8.0×10^4	16	3 – 4

II. The Fast Timing Electronic Technique

The electronic technique involves measurement of time difference between coincident decays of two successive states. This is done by isolating the discrete gamma ray transitions which feed into and out of the level of interest which is the intermediate state of the gamma cascade selected [3]. This requires the use of a pair of two detectors which are gated such that one detector records the gamma ray that feeds the intermediate state while the second detector records the gamma ray from decay of the intermediate state. Both of the signals are processed and fed into the Time to Digital Converter (TDC) module which can be used to obtain the time difference between the two signals. Fig. 1 illustrates this timing technique. The obtained time distribution is in turn used to determine the average lifetime of an excited state via a technique called Delayed Coincidence method. The normalized delayed coincidence time distribution is the convolution of the Prompt Response Function (PRF) of the setup P(t), with an exponential decay as given in equation (1), [4].

$$D(t) = n\lambda \int_{-\infty}^{t} P(t' - t_0) e^{-\lambda(t-t')} dt' \quad \text{with } \lambda = 1/\tau \qquad (1)$$

where, n is the total number of detected γ – γevents in the time difference spectrum, λ is the transition (Decay) probability and τ is the mean lifetime of nuclear excited state interconnected by the selected γ – γ cascade while t_0 is the centroid of the PRF peak.

If the lifetime to be measured is greater than the Full Width at Half Maximum (FWHM) of the PRF, a log plot of time difference against counts is Gaussian shaped [3]. In this case, the Centroid shift method is used to determine the lifetime of the state. On the other hand, for lifetimes longer than the FWHM of the PRF, a log plot of time difference versus counts is observed to be Gaussian shaped distribution with an exponential tail to either side. In this situation the lifetime is obtained from the straight part of the tail using a method called the slope method. Usually, the centroid shift method is used for lifetimes in picosecond range while the slope method is applied for lifetimes in the nanosecond region.

Hence thetwo key points to be considered when setting a lifetime measurement experiment are energy resolution and time resolution of the detection system employed [5,6]. Energy resolution is important for placing clean energy gates for the detectors to give information of only the transition of interest. Besides, time resolution of the system, which depends on the rise time of detectors and the goodness of electronic components used has a big influence on the width of the PRF peak [2]. For long time, BaF_2 scintillators have been employed in timing experiments due to their superior rise time as shown in table 1. However, these detectors offer poor energy resolution compared to other detectors such as $LaBr_3$ scintillators which are both fast and have very good energy resolution making them the current best option for these experiments [3].

As shown in Table 1, NaI(Tl) scintillatorsare remarkably slower than the previous scintillators, but have good detection efficiency and better resolution than BaF_2. This makes NaI(Tl) scintillators suitable for simple lifetime measurement experiments in the range of nanosecond. In this work, the accuracy of NaI(Tl) scintillators in measuring lifetimes ranging between 1 and 2 ns is studied.

III. Experimental Setup

A 'bench-top' coincidence setup with two "2 x 2" cylindrical NaI(Tl) ORTEC 905-3 detectors was used in this experiment. These detectors were labelled B1 and C1 and made to face each other with their faces separated by a distance of 5 cm. The radioactive source (^{152}Eu) is stationed at the central point between the detectors faces. The Photomultiplier Tubes (PMT) attached to the detectors were powered by a Power supply module which offers two separate channels for HV outputs. The signal from each detector was fed to the splitting module and then other electronic devices as illustrated in Fig. 1(a). The CAMAC system was used for data acquisition.

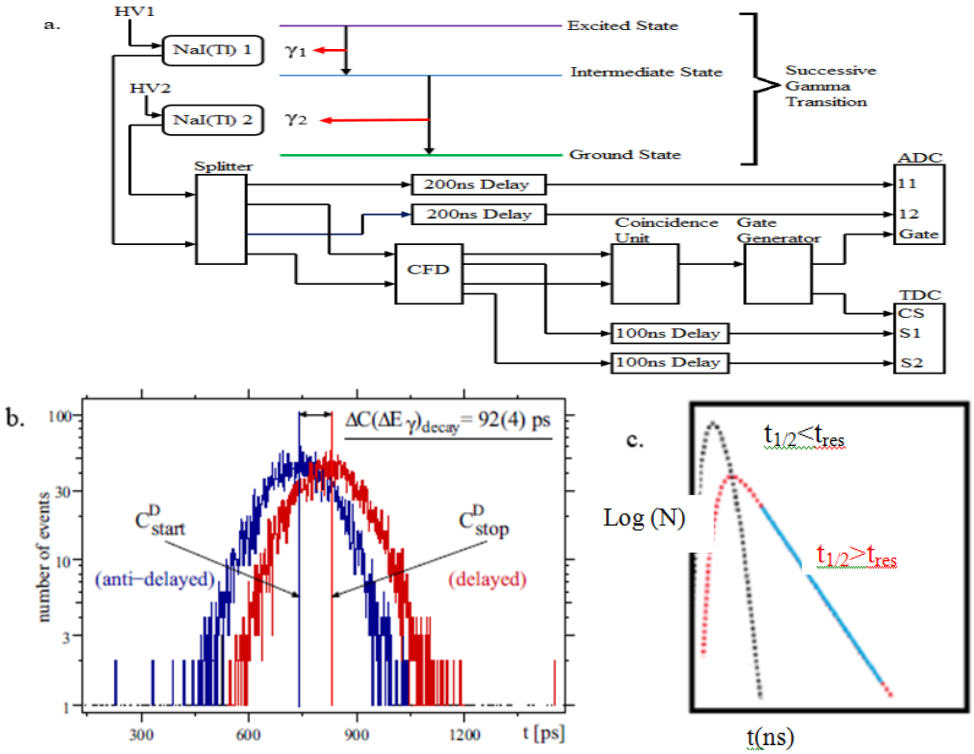

Figure 1. (a) An illustration of the electronic γ – γ fast timing circuit using the Constant Fraction Discriminator (CFD) and the Time to Digital Converter (TDC). A schematic decay gamma cascade is also shown. (b) Time difference Spectra showing the centroid shift when the detectors' functions are reversed [1]. (c) Schematic

picture of the time difference spectra showing the prompt peak (black) for vey short lifetimes and the prompt peak with an exponential tail to its side (red) for longer lifetimes. Lifetime is related to the slope of the linear part (the blue line).

In order to study the timing performance for lifetimes ranging between 1 and 2 ns, ^{152}Eu source was employed. ^{152}Eu decays by electron capture to excited state of ^{152}Sm which then undergoes several gamma transitions to attain stability. The yrast state $I^{\pi} = 2^{+}$ is the first excited state of ^{152}Sm with energy 121.7keV and lifetime of 1.400 (11) ns [7]. ^{152}Eu was an ideal source for this experiment since the lifetime of 121.7keV state is well known in literature and it falls in the range between 1 and 2 ns which is the requirement for this study. Besides, as Fig. 2 shows, the 121keV state is coincident with three different higher states thus offering 4 choices of consecutive gamma transitions. In this work, the chosen transitions are identified as Transition1, 2, 3 and 4. $2^{-} \rightarrow 2^{+} \rightarrow 0^{+}$ is referred to as Transition1, where $3^{+} \rightarrow 2^{+} \rightarrow 0^{+}$ is referred as Transition2, $2^{+} \rightarrow 2^{+} \rightarrow 0^{+}$ is referred to Transition3 and $4^{+} \rightarrow 2^{+} \rightarrow 0^{+}$ is referred as Transition4. Time difference spectrum from each of these coincident transitions is used to determine the lifetime of 121keV state. The mean value of lifetime is determined and the four values of lifetime obtained are then used to determine the average lifetime of a state, accuracy of measurement as well as the precision of timing system.

Since both detectors see the same gamma ray source, time distribution from each detector is obtained in the offline analysis by setting energy gates (narrow energy windows) on the full energy peak of the transitions of interest.In this work, the TDC start signal is given by the gate generator while the first stop signal comes from detector B1 and the second stop signal from detector C1.Energy gates are selected such that detector B1 always see the 121.7keV state's decay transition while detector C1 sees the transitions that feeds the 121.7keV state as selected during data analysis.

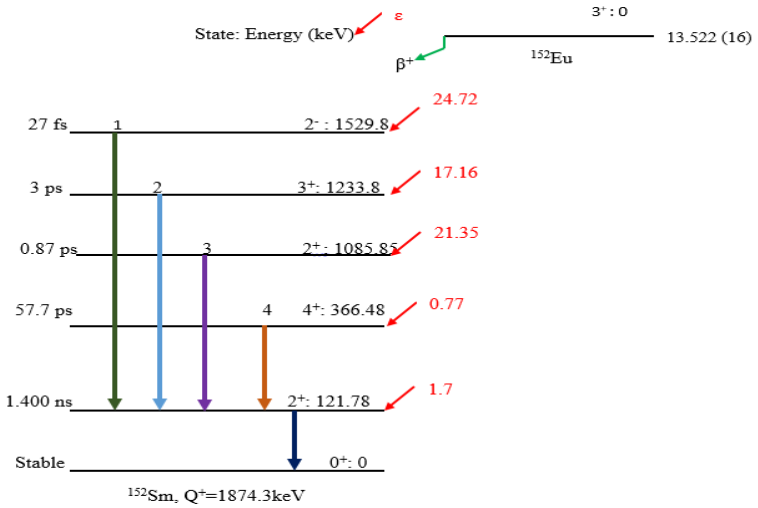

Figure 2. Partial decay scheme of ^{152}Sm showing the gamma transitions considered in this study [7]. 1, 2, 3 and 4 are different transitions used in this study to measure the lifetime of 121.78keV state.

The feeding and decaying transitions used in this study are shown by bold lines in Fig. 2. The time difference spectrum is obtained by substituting the B1's time spectrum from that of C1. The obtained time difference spectrum is in turn used to determine the lifetime of the 121.7keV state by the slope method. The width of the energy gates are calculated using the expression in (2). Root and RooFit software are used to assess the performance of the detectors and to evaluate the lifetime.

$$W = 1.6449\sigma$$
$$R = \left[\mu - W/2, \mu + W/2\right] \qquad (2)$$

where, W is the gate width, σ is the standard deviation and μ is the mean position of the peak.
However, when selecting the gates for these transitions, the background contribution to these peaks and to the time difference spectrum cannot be taken for granted and have to be discussed in details. In all cases, the time spectrum lies on top of significant background contributions mainly from the Compton-scattered events from the higher energy transitions [3]. In order to subtract this background contribution, the energy gates are placed at the center of the peaks involved and then shifted to the right sides of the respective energy peaks. Fig. 3 shows a sample of background subtraction from the $2^{-} \rightarrow 2^{+} \rightarrow 0^{+}$ transition. The gamma energy peaks involved in this transition are 1408keV and 121.8keV peaks. Raw and background time difference spectra are generated. The raw time difference spectrum is obtained by placing the energy gates at the center of 121.8keV peak and

1408keV peak (Raw). Then the energy gates were shifted to the right side of 121.8keV peak and on the 1408keV peak forming the part 1 of background contribution (BG1). Again, the energy gates were placed on the 121.8keV peak and to the right of the 1408keV peak forming the background spectrum 2(BG2) and finally the energy gates were set to the right sides of 121.8keV peak and 1408keV peak to obtain background spectrum 3 (BG3). The final time difference spectrum which is used to determine the lifetime of the 121.8keV state is obtained by taking (Raw) – (BG1) – (BG2) – (BG3). Similar analysis is done for other three choices of gamma transitions considered in this work.

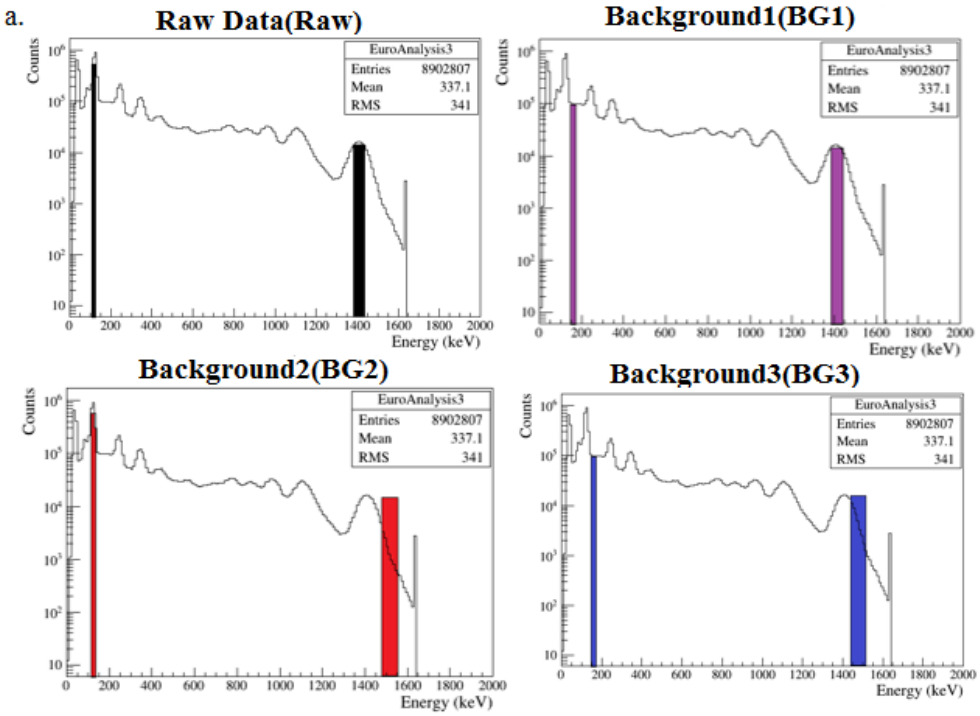

Figure 3. a) Gates used for background analysis from the ^{152}Eu experiment

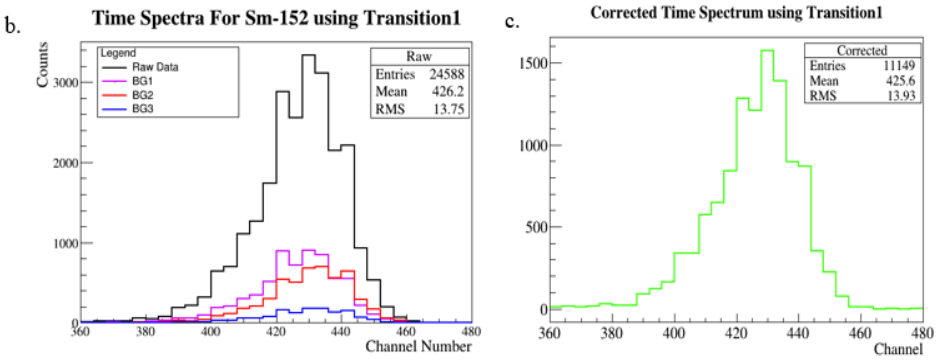

Figure 3 b) Time difference spectrum with background contribution c) Time difference spectrum after subtraction of background contribution. This spectrum is used to extract the lifetime of a given state.

IV. Experimental Results And Discussion

The energy calibration curve is described by a second order polynomial function as shown in Fig. 4. The energy spectrum as measured in this experiment is also shown Fig.5. This calibration curve reveals the good linearity of the NaI(Tl) detectors used in this experiment. Energy spectrum is presented in Fig. 5.

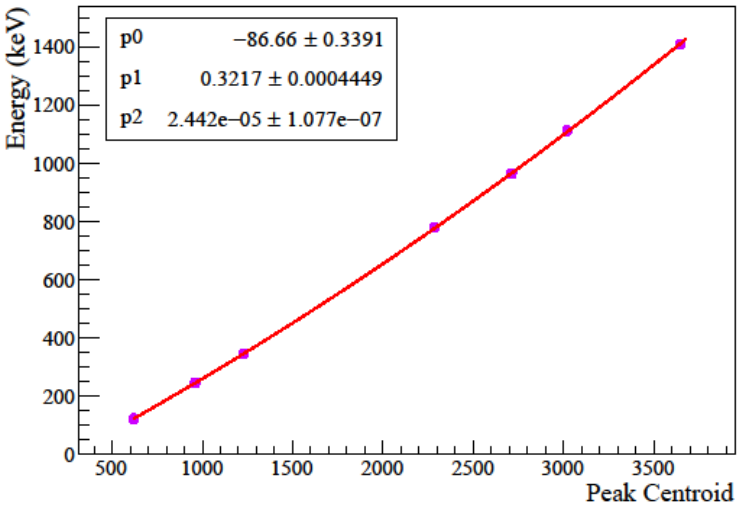

Figure 4. Energy calibration curve for one of the detectors used in this experiment.

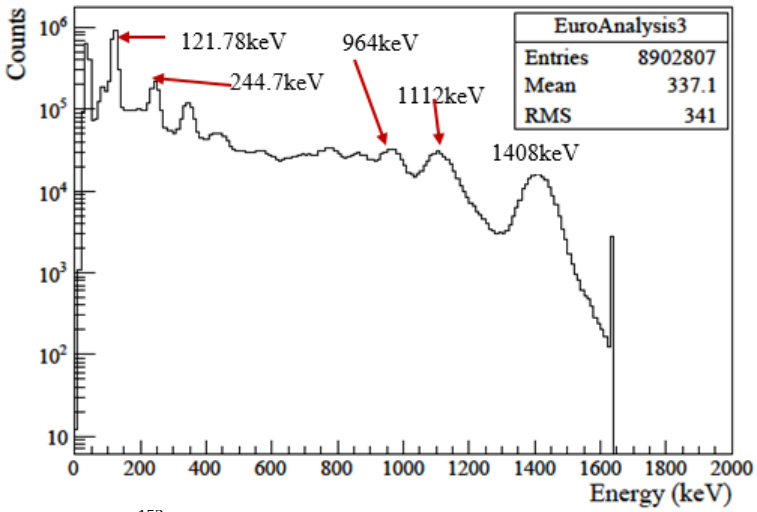

Figure 5. Energy spectrum of ^{152}Eu as measured by detector C1. Gamma ray peaks used to determine the lifetime of 121.8keV state in this experiment are indicated.

On the other hand, Fig. 6 is a logarithmic plot of the measured full width at half maximum (FWHM) versus energy for one of these detectors. It was observed that the FWHM merely depends on $\sqrt{E_{\gamma}}$ although the slope is not -0.5 as (3) suggests since energy resolution is also affected by other factors such as the charge collection statistics by the detector, electronic noise, fluctuation in PMT gain, variations in the detector response over its active volume and drifts in parameters over the course of the measurement [8].

$$\ln R = \ln K - \frac{1}{2}\ln E \qquad (3)$$

As discussed in section II of this article, another important parameter in lifetime measurement experiments is the time resolution of the system which depends on both the rise time of detectors as well as electronic devices employed for signal processing. In this experiment, the time resolution of the system was determined by using the time difference spectrum obtained from measurement of ^{60}Co source. The lifetime of 1173keV state of ^{60}Co is known to be 0.713 ps [7]. Since this time is too short to be resolved by our electronic system, ^{60}Co source was used to determine the time resolution of the system used in this experiment. A plot of time difference versus counts for ^{60}Co source is a Gaussian shaped peak as shown in Fig. 7. The time resolution of the system is evaluated from the FWHM of this peak using the formula;

$$R(\%) = \frac{FWHM}{\mu} \times 100\% \qquad (4)$$

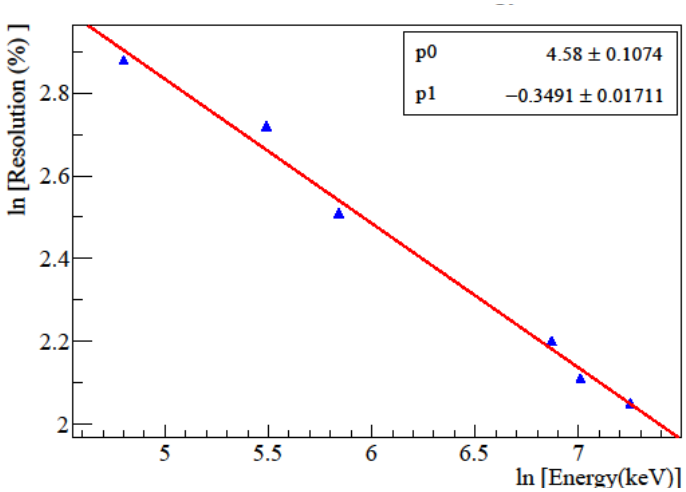

Figure 6. The dependence of resolution on energy is shown. The slope is not -0.5 as it should be, indicating the presence of other factors that influence the energy resolution.

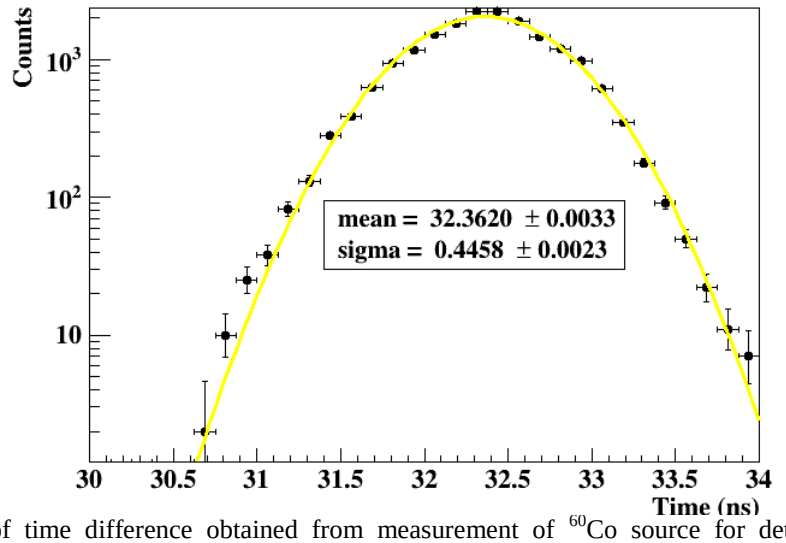

Figure 7.A plot of time difference obtained from measurement of ^{60}Co source for determining the time resolution of the system. Yellow line is the Gaussian Model used to fit data points. The FWHM of the prompt peak was found to be 1.050 (5) ns. This shows the system has a time resolution of 3.24 (87) % indicating the capability to measure lifetimes that are longer than 1 ns.

In order to determine the lifetime of a given state, the gamma transition which includes the state of interest as the intermediate state is selected. As this experiment aims at determining the lifetime of the 121.78keV state of ^{152}Sm, four transitions are selected and labelled as 1, 2, 3 and 4 as described by Fig. 2. In all transitions, the 121.78keV state is the intermediate state thus giving four values of lifetime of this state. The final lifetime is then calculated from the average of these values. Fig. 8 shows the time difference spectrum obtained from the transition labeled 1 which involves the $1529.8keV \rightarrow 121.78keV \rightarrow 0keV$ transition. The energy gates are placed around the 1408keV and 121.78keV gamma peaks. As the time distribution is Gaussian with an exponential tail to the left side, a convolution model is developed using RooFit so as to fit the distribution. This convolution is constructed using the Gaussian and the Exponential Decay PDFs developed in RooFit. The time difference distribution from each transition is fitted to the convolution model and the respective lifetime is determined from the fitting parameters. In this way, the lifetimes for different transitions are as indicated in Table 2.

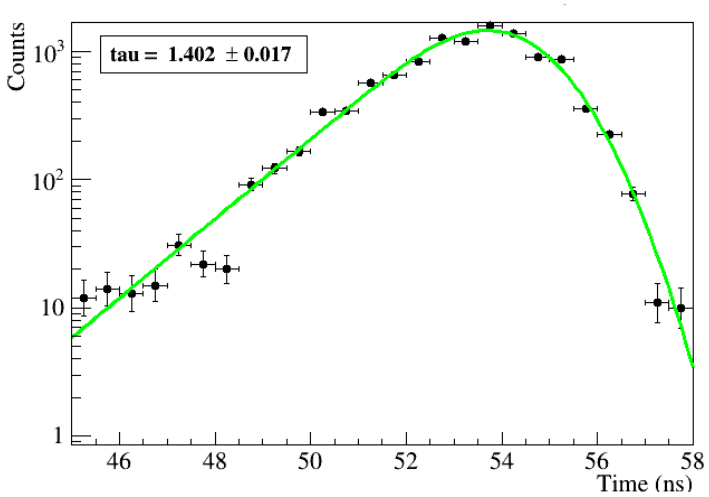

Figure 8. A log plot of time difference versus counts for transition 1 indicated in figure 2. Here the 1408keV and 121.78keV peaks are used to obtain the time difference spectrum. Black points are experimental data points whereas the green line is the convolution model developed for fitting the experimental data so as to extract the lifetime given in the distribution.

Table 2. Values of lifetime of 121.78keV state as obtained using different transitions as shown. The values in brackets are the statistical errors and correspond to last digit of the measured value.

Transition ID	States Involved	Lifetime (ns)
1	$1529.8keV \rightarrow 121.78keV \rightarrow 0keV$	1.402(17)
2	$1233.86keV \rightarrow 121.78keV \rightarrow 0keV$	1.401(32)
3	$1085.85keV \rightarrow 121.78keV \rightarrow 0keV$	1.404(32)
4	$366.48keV \rightarrow 121.78keV \rightarrow 0keV$	1.401(21)

Comparison between the mean lifetime values obtained from each transition show that the discrepancies from the literature known value ranges from 1 to 4 ps. This shows that the measurements are experimentally accurate. On the other hand the average divergence of the measured values from the true value was found to be 2 ps showing the good precision of the timing system used in this study. Fig. 9 demonstrates the accuracy of the measurement and precision of the timing system.

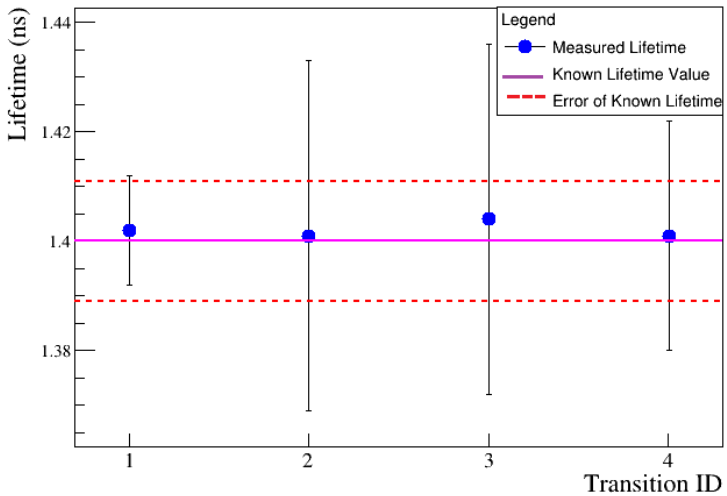

Figure 9. Comparison of the lifetime values measured in this experiment (blue circles) as well as the known value from literature (Violet line) with their respective uncertainties (black bars and the dotted lines)

The final lifetime value of the 121.78keV excited state of ^{152}Sm measured in this experiment is presented as the weighted mean of the lifetimes extracted from different transitions. The weighted mean is derived from the method of maximum likelihood and is given by equation 5 while its respective uncertainty is given by equation 6 [8].

$$\mu = \frac{\sum_{i=1}^{n} \overline{X}_i / \sigma_i^2}{\sum_{i=1}^{n} 1/\sigma_i^2} \qquad (5)$$

$$\sigma(\mu) = \sqrt{\frac{1}{1/\sigma_i^2}} \qquad (6)$$

Where, μ is the weighted mean, $\sigma(\mu)$ is the uncertainty of the weighted mean, $\overline{X}_i$ and σ_i are the measured mean values with their respective uncertainty values.

Results from equations 5 and 6 showed that the mean lifetime of the 121.8keV state is 1.402 (11) ns. This value is very close to the literature value which is 1.400 (11) ns. Besides, the uncertainty of measurement in this study is just 0.78 % offering more evidence of the goodness of the measurement.

V. Conclusion

It is therefore acceptable to say that this study has successfully measured the lifetime of yrast $I^{\pi} = 2^{+}$ state in ^{152}Sm via γ – γ coincidences using NaI (Tl) Scintillators. The study have shown that NaI(Tl) scintillators have fairly good energy resolution suitable for offline placement of energy gates which is important for selecting the gamma rays of interest. Besides, the system used in this experiment have been observed to have the FWHM value of 1.05 ns indicating good timing resolution and showing that the system can be used to measure the lifetimes that are longer than 1.05 ns. The timing system used in this experiment is also found to be precise enough with the average divergence from the known value being 2 picosecond.

The average measured value of lifetime in this experiment is1.402 (11) ns. While the discrepancy from the known value of lifetime of this state is just 2 picoseconds, the uncertainty of the measurement is only 0.78% cementing the idea that the measuring system used in this study is worthy. Hence, this study has confirmed that in a situation where other faster scintillators are too expensive or hard to find, NaI(Tl) detectors can make a good substitute in measuring the lifetime of nuclear states which are in the nanosecond region.

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