Experimental study of lifetimes of excited states in the $K^\pi = 0^-$ octupole band and γ-vibrational band in ^{228}Th.

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Abstract. Lifetimes of excited states in the $K^\pi = 0^-$ octupole band and γ-vibrational of ^{228}Th have been measured using the fast timing setup at the University of the West of Scotland (UWS). The setup consists of two cerium doped LaBr$_3$ fast scintillators placed equidistant from the radioactive source ^{232}Th. The states of interest have been analysed by doing the triple $\gamma - \gamma - time$ coincidence analysis and using the fast-timing technique, mirror-symmetric centroid difference method. Octupole collectivity in ^{228}Th nucleus is also investigated by calculating the enhanced electric dipole moments and transition rates in excited states followed by lifetime measurements in octupole band.

Introduction:

Lifetime measurements of nuclear excited states is important in defining the observables like intrinsic dipole moments and transition rates in order to explain the nuclear structure [1][2][3]. Such measurements have been done using different methods and types of detectors. The Mirror-symmetric centroid difference method is a well suited fast-timing technique [4][5][6] for lifetime measurements in the few picoseconds regime is used in this work. The lifetimes of excited states are used to determine the octupole collectivity in nuclei by measuring the enhanced dipole moments between those states. Much of theoretical work have been done to investigate the octupole collectivity in actindes including the Th isotopes [7] [8][9][10][11][12]. Such collectivity in ^{228}Th has also been predicted by previous calculations and density functional models [13, 14, 15, 16, 17, 18]. The present work aims at investigating the octupole collectivity in ^{228}Th nucleus following the lifetime measurements of excited states in the $K^\pi = 0^-$ octupole band.

Negative-parity states in octupole bands of actinide nuclei are important due to their implications on the octupole collectivity of nuclei in this region with $A \approx 226$ [8][13][17][20]. Nuclear octupole deformation can result in large intrinsic dipole moments in excited states in these heavy nuclei [8][13][17][23]. The stable octupole deformation in nuclei in this region has also been confirmed due to the presence of such E1 states and also a strong E3 state in octupole band which lead to the conclusion of having a pear-shaped nucleus [19][20] . Such enhanced intrinsic dipole moments are calculated from the lifetimes of these states. The dipole moment measurements have been done earlier for octupole band states in neighbouring ^{228}Ra nucleus which indicated the presence of octupole collectivity in it [20][18].

The nucleus of interest in this work, ^{228}Th, is populated as a result of the ^{232}Th decay chain and the states belong to it are populated via β^- from ^{228}Ac and subsequent γ-rays decay[22]. There are no lifetimes measurements have been reported in octupole band of this nucleus. Only the lifetimes of the first 2^+ and 4^+ states in ground state rotational band have been measured earlier. Similarly, lifetimes of 2^+ state in γ-vibrational band have also been measured first time in this work.
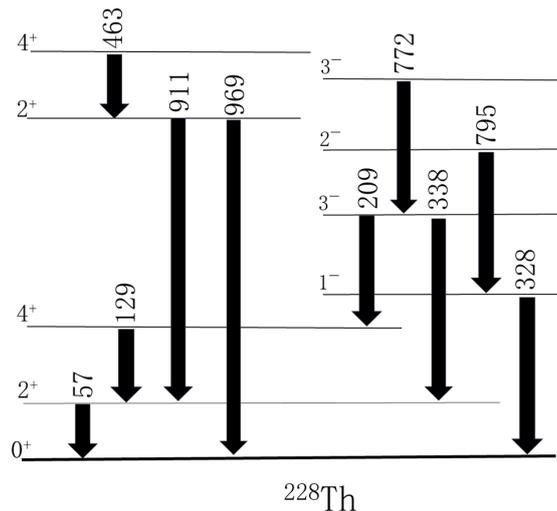

Figure 1. A partial level scheme for ^{228}Th is shown in the figure including the levels belong to octupole band, ground state rotational band and γ-vibrational band populated via β^- decay from ^{228}Ac . The figure is taken and modified from [22].

Experimental setup:

The experiment was performed at University of the West of Scotland by keeping the radioactive source, ^{232}Th foil with radioactivity $\approx$ 6 kBq, at equidistant (d=5mm) from two $1'' \times 1''$ LaBr$_3$(Ce) detectors. These detectors are used due to their compatibilities with the fast timing measurements and advantages over other kind of detectors [2][23][14]. The electronics used in the experiment consists of two CFD's (constant fraction discriminators), two Fan In/Out logic units and a TAC (Time to amplitude converter) [24].

A Caen digitizer V1725 [25] is used to record the energy and timing signals from the detectors and TAC respectively where the waveform data is stored using MIDAS [26] software and analysed offline. The setup works on the principle of mirror symmetric centroid difference method [4, 5, 6] where delayed and anti-delayed time distributions are obtained by selecting the populating and depopulating transitions as start and stop signals respectively and vice versa. The lifetime of the state is then measured by taking the difference between the centroids of two time distributions [4, 5].
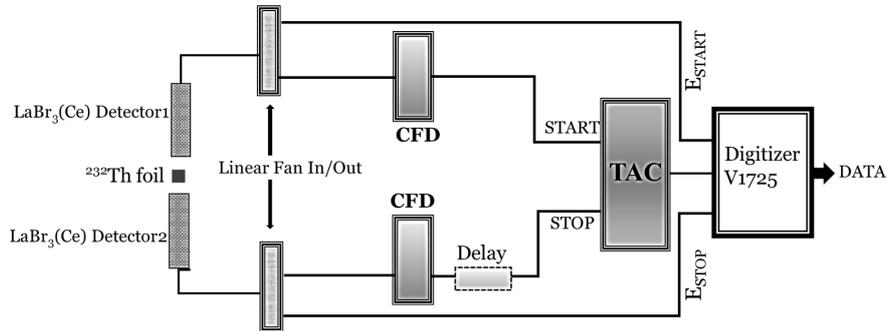
Figure 2. A schematic representation of the experimental setup used in this experiment is shown in the figure.
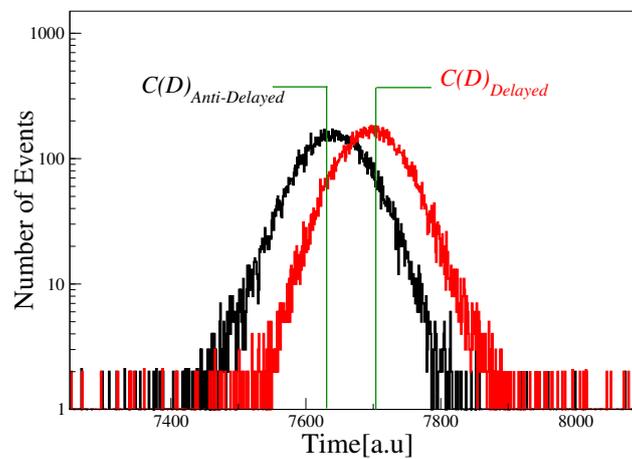
Figure 3. The delayed and anti-delayed time distributions as a result of setting the incident transition as start and stop respectively.

The difference between delayed and anti-delayed time distributions is written as,

$$\Delta C = C(D)_{Delayed} - C(D)_{Anti-delayed}$$
$$\Delta C = C(P)_{Delayed} + \tau - C(P)_{Anti-delayed} + \tau$$
$$\Delta C = 2\tau + C(P)_{Delayed} - C(P)_{Anti-delayed}$$

which gives the lifetime as,

$$\Delta C = 2\tau + PRD \tag{1}$$

$$\Rightarrow \tau = \frac{1}{2}\left[\Delta C - PRD\right] \tag{2}$$

Since the correct lifetimes of the states are subject to background corrections [4, 5, 7] so background corrections are also done for the above mentioned states in this work. It is done by correcting the centroid difference between the timing distributions. The background corrected ΔC_{FEP} (centroid difference between full energy peaks) is calculated as,

$$\Delta C_{FEP} = \Delta C_{Exp.} + \frac{1}{2}\left[t_{COR}(feeder) + t_{COR}(decay)\right] \tag{3}$$

Where $t_{COR}(feeder)$ and $t_{COR}(decay)$ are the correction terms in the feeding and decaying transition respectively [5].
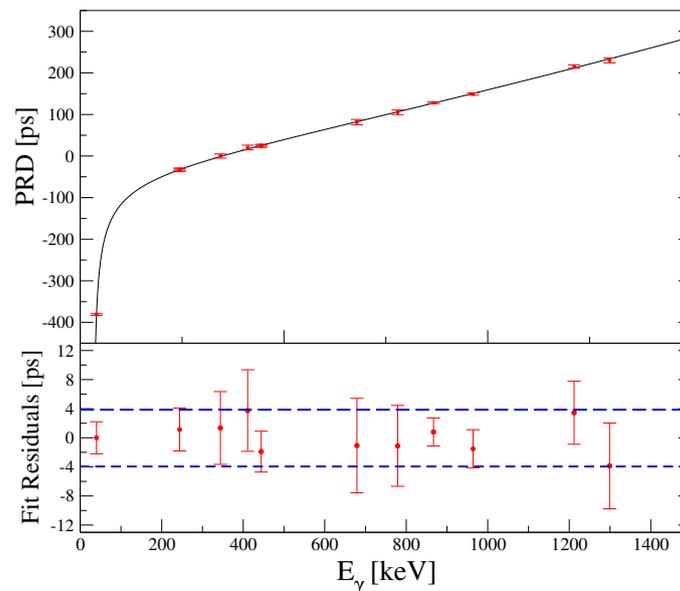
$$t_{COR}(feeder) = \left[\frac{\Delta C_{EXP} - \Delta C_{BG}}{P/B}\right]_{(feeder)} \tag{4}$$

And,

$$t_{COR}(decay) = \left[\frac{\Delta C_{EXP} - \Delta C_{BG}}{P/B}\right]_{(decay)} \tag{5}$$

where $\frac{P}{B}$ is the peak to background ratio for the feeding and decaying transitions and ΔC_{BG} is the centroid difference of the background contribution which is determined by the fitting the background data points. The lifetime is then measured by using the relation;

$$\tau = \frac{1}{2}\left[\Delta C_{FEP} - PRD\right] \tag{6}$$


Figure 4. The PRD curve for the $\gamma - \gamma$ time-walk characteristics of the setup is shown in the figure on top. The bottom figure shows the difference between the data and fitted prompt response function residuum..

The PRD is prompt response difference function of the setup and actually related to the time-walk of the detector setup. It is calibrated by a standard ^{152}Eu source which provides different combinations of transitions with fast lifetimes in picoseconds regime. The procedure to get the PRD curve which is used to read the PRD values for any sequential $\gamma - \gamma$ cascade within the energy range of 40-1400 keV [4, 5]. The PRD curve obtained in this work is shown in Figure 4.

Results:

The lifetime of the 1^- state in $K^\pi = 0^-$ band is measured by taking the 795 keV γ-ray as a feeding transition to this state and 328 keV as a decay. By measuring the centroid difference between them and carrying out the background subtraction, a lifetime of 1^- state is deduced. Similar procedure is applied to get the lifetime for the 3^- state in $K^\pi = 0^-$ band where 772 keV and 338 keV are used as start, stop
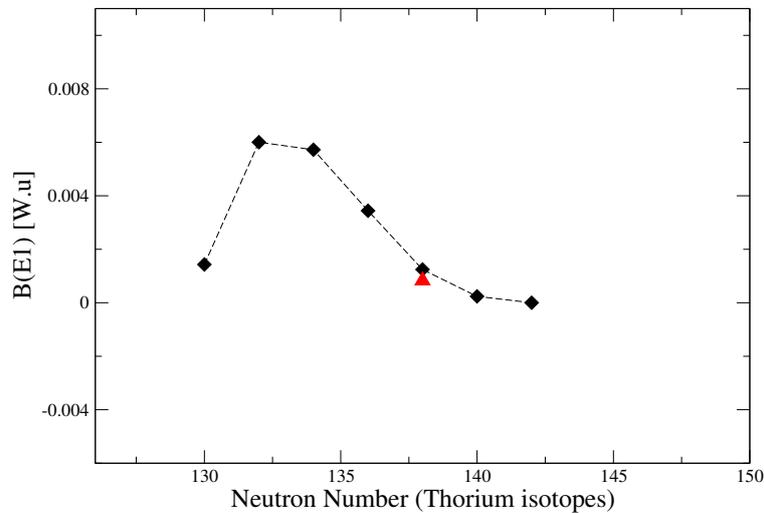
Figure 5. The preliminary transition rate result (in red) for first excited state 1^- in octupole $K^\pi = 0^-$ band of ^{228}Th is compared with the previous calculations.

and vice versa for delayed and anti-delayed time distributions respectively.

Similar analysis were performed to measure the lifetime of the 2^+ state in γ-vibrational band with 463 keV transition as feeder and 969 keV as decaying transition. There is a second independent measurement which is also possible by taking the 911 keV as decaying transition at 2^+ as well.

The intrinsic dipole moments and transition rates for the 1^- and 3^- states are also deduced on the basis of measured lifetimes. The preliminary results for $BE1$ transition rate for first excited state 1^- is compared and found in agreement with the calculations by Robledo et al. for even-even Th isotopes [19] as shown in Figure 5.

Similarly, electric quadrupole moments and reduced probabilities for the 2^+ state in γ-vibrational are also deduced. The dipole moments due to E1 transitions in octupole band suggests the presence of sizeable octupole collectivity in ^{228}Th nucleus. The results also confirm the theoretical predictions made about the octupole collectivity in this nucleus. The measurements about quadrupole moments for 2^+ state in γ-vibrational band are also compared with similar calculations done for other actinides and rare earth nuclei and further analysis are ongoing in order to draw a conclusion.

Conclusion:

Lifetimes measurements have been carried out for the first time in octupole and γ-vibrational bands of ^{228}Th nucleus. According to the preliminary results obtained so far, the quantities, intrinsic dipole/quadrupole moments and transitions rates are found in very good agreement with the previous measurements, theoretical models and predictions. However, more data is being taken by inserting a HPGe detector in the current setup for a better resolution in order to measure the more lifetimes. The analysis are ongoing.

Aknowledgement:

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