Segmented YSO scintillation detectors as a new β-implant detection tool for decay spectroscopy in fragmentation facilities

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Abstract

A newly developed segmented YSO scintillator detector was implemented for the first time at RI-beam Factory at RIKEN Nishina Center as an implantation-decay counter. The experiment demonstrates that this detector is a viable alternative to conventional silicon-strip detectors with its good timing resolution and high detection efficiency for β particles. A Position Sensitive Photo-Multiplier Tube (PSPMT) is coupled with a 48 × 48 segmented YSO crystal. To demonstrate its capabilities, a known short lived isomer in 76Ni and the β decay of 74Co was measured by implanting those ions into the YSO detector. The half-lives and γ rays observed in this work are consistent with the known values. The β-ray detection efficiency is more than 80 % for the decay of 74Co.

The study of β-decays far from stability is essential to understand the evolution of nuclear structure and nucleosynthesis processes. It has been shown that,
$\beta$-decay properties of neutron-rich nuclei heavier than iron impact $r$-process calculations that determine the solar abundance of elements \cite{1,2}. Typically, $\beta$-decay experiments with such exotic nuclei involve intense cocktail beam from fragmentation facilities. The role of an implantation detector in these experiments is to measure the energy and the positions of both heavy ion implantation and $\beta$-ray emission in order to correlate the identified ion with $\beta$-decay events. Conventionally, implantation detectors developed for the beams of fragmentation facilities use double-sided silicon-strip detectors (DSSDs) such as AIDA \cite{3} or WAS3ABI \cite{4} which were used recently with the BRIKEN \cite{5,6,7} neutron counter array at the Radioactive Ion Beam Factory (RIBF).

The idea of a new implantation detector using segmented scintillator crystals was proposed previously \cite{8} aiming to use it as a fast $\beta$-trigger for the neutron time-of-flight (ToF) array, VANDLE \cite{9}. Neutron ToF measurements of $\beta$-delayed neutron emitters provide neutron energy information \cite{10}. The DSSD cannot be used in this application because of its slow response. A new fast-timing implantation detector made of scintillator crystal is expected to enable neutron ToF techniques in advanced fragmentation facilities that can provide high-intensity exotic beams. The prototype plastic scintillator based detector described in Ref. \cite{8} was used as the fast trigger in the fast-timing investigations at NSCL \cite{11}. Plastic detectors however suffer from low stopping power for beta particles which adversely impacts the ability to make ion-decay correlation.

In this paper, development of a new implantation detector using segmented YSO (Yttrium Orthosilicate, Y$_2$SiO$_5$) crystals is presented. There are several advantages of using YSO crystals compared to DSSDs other than its fast timing response (42 ns decay time \cite{12}) and much better energy resolution than plastic scintillator detectors. The effective atomic number ($Z = 35$) and the density ($4.4 \text{ g/cm}^3$) of the YSO crystals are higher than silicon, resulting in a better stopping power, and therefore shorter range of $\beta$ particles emitted by the ion implanted into the detector. Due to these properties, YSO detectors are expected to have a higher detection efficiency and better position resolution for high-energy $\beta$ rays than silicon-strip detectors. Another advantage of using YSO
scintillators are that they can be used with higher implantation rates since they are radiation hard and the fast scintillation enables rapid re-triggering. The YSO is non-hygroscopic, relatively cheap and easy to make into pixelated arrays. The design presented here is very easy to implement in an experiment: it requires only 5 detector signals for processing. The smaller light yield for heavy ions is common to inorganic scintillators reduces the required dynamic range of the light sensor, which records signals induced by beta particles and high-Z implants.

The segmented YSO detector was implemented for the first time at the RIBF to measure β decays of nuclei around and beyond 78Ni. Analysis and results on the isomer of 76Ni and the β decay of 74Co nuclei are presented as a demonstration of the capability of this new implantation detector. The β efficiency for the 74Co decay and γ-ray absorption for the 76Ni isomer are also shown.

The detector unit consists of segmented YSO crystal coupled to a flat panel multi-anode photomultiplier by Hamamatsu, H12700. The YSO scintillator is a high-granularity matrix of 1 × 1 mm segments arranged into a 48 × 48 array in the x-y plane. Each segment, as well as the face and the sides, is isolated by ESR (3M) reflector material. The thickness of the crystal is 5 mm which is designed to stop all the ions of interest in the 78Ni region produced by fragmentation at the RIBF. A 2 mm thick quartz light diffuser between the YSO crystal and the PSPMT was required in order to achieve sub-anode position resolution by spreading the light from one pixel onto several anodes of the PSPMT. The detector unit was enclosed in a 3D-printed light-tight box with a thin light shielding black tape covering the face of the detector. The 64 anode channels of the photomultiplier are read out by a resistive-network Anger-logic for x and y position determination. The dynode signal is used to determine the time and the total energy. Each of the four signals from the anodes and the dynode are split into channels with two different gain settings. One set of signals is amplified by a high bandwidth 20x amplifier for β-ray counting and the other is for heavy-ion implantation.
The YSO implantation detector was implemented together with the BRIKEN neutron counter system [5, 6] at RIKEN, RIBF in order to study $\beta$ decays of the nuclei around and beyond $^{78}$Ni. The neutron-rich nuclei are produced by in-flight fission of a 345 MeV/nucleon $^{238}$U$^{86+}$ beam on a 4-mm thick $^9$Be production target. The typical intensity of the primary beam was $\sim$60 pnA during the run. Fission fragments are separated and identified in the BigRIPS in-flight separator [13] on an event-by-event basis by their proton numbers ($Z$) and the mass-to-charge ratio ($A/Q$). These quantities are obtained by the measurement of the $B_\rho$, time of flight (TOF), and energy loss ($\Delta E$) in BigRIPS. A detailed explanation of the particle identification at the BigRIPS is found in Ref. [14, 15]. The result of the particle identification plot is shown in Fig. 1. There are $2 \times 10^5$ $^{76}$Ni and $1.5 \times 10^4$ $^{74}$Co ions implanted into the YSO detector in $\sim$ 140 hours of run.

The secondary beam was transported to the final focal plane, and implanted into the YSO detector. Four layers of double-sided silicon-strip detectors
(DSSDs) from WAS3ABi were installed upstream of the YSO detector. The DSSDs consist of sixteen 3-mm wide strips in both the x and y directions. The typical rate of the ion implantation in YSO during the run was \(\sim 60\) cps.

The YSO and WAS3ABi detectors are placed in the center of the BRIKEN high-density polyethylene moderator. The BRIKEN detector was operated in hybrid mode, which is composed of 140 proportional counters filled with \(^3\)He gas for neutron detection and two ORNL clover-type HPGe detectors on the sides for high-resolution \(\gamma\)-ray detection.

As a result of the implementation of YSO detector at the RIBF, we obtained position images for \(\beta\) and implantation events in the detector and successfully achieved correlation between recoil and decay events. The \(x-y\) image for \(\beta\) events in the YSO detector is shown in Fig. 2 (a). Each dot in the plot corresponds to a 1 \(\times\) 1 mm segment of the YSO crystal. The horizontal dip along \(y \sim 0.5\) is caused by the structure of the YSO segmentation. The array is made of two parts of 24 \(\times\) 48 segmented crystals and the ESR between those two in the middle distorts the image due to less light sharing between the two pieces. The image has the resolution sufficient to distinguish segments for most of the active region. Figure 2 (b) shows the image of the implantation events occurring in the 1 s before \(\beta\) events observed in one of the segments marked with a red circle in Fig. 2 (a). The full-width half-maximum of the peak corresponding to the correlated implants shown in Fig. 2 (d) is 1.3 mm.

In \(^{76}\)Ni, an isomeric state is reported by Mazzocchi et al. produced by fragmentation of a \(^{86}\)Kr beam in a \(^9\)Be target at NSCL. Figure 3 shows the delayed \(\gamma\)-ray spectrum after \(^{76}\)Ni implantation at the YSO detector. The energy of the four \(\gamma\) peaks agrees with the literature. The half-life of the isomer is obtained as \(520(15)\) ns by fitting the decay curve of all the four \(\gamma\) peaks, which is also consistent with the literature value, \(590^{+180}_{-110}\) ns.

Isomeric \(\gamma\)-ray spectra of \(^{76}\)Ni implanted into YSO and WAS3ABi are compared in order to check \(\gamma\)-ray absorption in each detector material because YSO is expected to have higher absorption than silicon due to its higher effective atomic number and thickness. The ratio between the two peak areas, that of
143 keV and 930 keV, is \( \frac{49(8) \text{ counts}}{12(3) \text{ counts}} = 4.3(15) \) for WAS3ABi, where the ratio for YSO is \( \frac{701(30) \text{ counts}}{191(14) \text{ counts}} = 3.7(3) \). This shows that \( \gamma \)-ray absorption in YSO detector of the 143 keV line with respect to the 930-keV line is 1.2(4) times larger than that in DSSSDs, which is not drastic.

\( \beta \)-\( \gamma \) spectrum of \( ^{74} \text{Co} \) was first reported by Mazzocchi et al. \cite{17} and then by Go et al. \cite{18} and recently by Morales et al. \cite{19} with improved statistics. Xu et al. \cite{20} and Hosmer et al. \cite{21} reported the half-life of \(^{74} \text{Co} \) decay. Hosmer et al. also measured \( P_n \) branching ratio with BF\(_3\) neutron counters \cite{21}.

Figure 4 shows the decay curve of \(^{74} \text{Co} \) \( \beta \) events. The fit function includes the parent, daughter (\(^{74} \text{Ni} \)), grand-daughter (\(^{74} \text{Cu} \)), and neutron-daughter (\(^{73} \text{Ni} \)) decays along with a linear background. The half-lives of \(^{74} \text{Ni} \), \(^{74} \text{Cu} \), and \(^{73} \text{Ni} \) are fixed to the literature values, 0.5077 s \cite{20}, 1.59 s \cite{22}, and 0.84 s \cite{23}, respectively. The \( P_n \) branching ratio of \(^{74} \text{Co} \) is fixed to 18 \% \cite{21}. The \(^{74} \text{Co} \) half-life obtained in this work is 30.8(6) ms, which is consistent with the literature values, 30(11) ms \cite{21} and 31.6(15) ms \cite{20}. A \( \beta \)-decay branch from isomeric
state in $^{74}$Co is reported by Morales et al. [19] with a 28(3) ms half-life.

Figure 5 shows the $\gamma$-ray spectrum of $^{74}$Co decay detected within 100 ms after implantation. All the $\gamma$ rays in our spectrum are consistent with the reported values in Ref. [18, 19]. We also observed $\gamma$ rays at 2588 and 3611 keV which are reported as decays from the isomeric state in $^{74}$Co [18, 19].

The main purpose of using the segmented YSO detector in this experiment was to demonstrate and exploit its high beta-detection efficiency. Figure 6 shows the $\beta$ efficiency curve as a function of the maximum correlation distance between $\beta$ events and implant events. The correlation distance is calibrated to mm from the fact that the distance between two segments is 1 mm. The $\beta$ efficiency is calculated by dividing the integral of the parent decay curve obtained from fitting by the total number of $^{74}$Co implants. The main source of the dead time is due to blocking $\beta$ triggers for 200 $\mu$s after ion implantation in order to wait until the signal recovers from the large pulse from heavy ions. This corresponds
Figure 4: The decay curve of the $\beta$ rays from $^{74}$Co decays. The solid blue curve represents the fitting function. The dashed red curve shows the decay component of the parent nucleus, $^{74}$Co. The dashed-dotted green curve is the sum of the daughter and neutron-daughter branches. The dotted black line shows the linear background. The plot at the right top of the figure shows the difference between the data points and the fitting function.

to 1.2% of dead time when the implantation rate is 60 cps. The dead time of the data acquisition system during the run is neglected since it was much smaller than 1%. The $\beta$ efficiency of the YSO detector for $^{74}$Co decay is more than 80% when we take the maximum correlation distance $>3$ mm as shown in Fig. 6. This correlation range can be linked to the energy of the $\beta$ particles in YSO.

In summary, we implemented the new segmented YSO detector for the first time in a $\beta$-decay experiment at RIBF, RIKEN. As a demonstration, data on the isomer in $^{76}$Ni and the $\beta$ decay of $^{74}$Co are shown. The implant-$\beta$ correlation by the YSO detector was successful and obtained 30.8(6) ms half-life for $^{74}$Co which is consistent with previous reports [20, 21]. We also confirmed the $\gamma$-rays of the $^{74}$Co decay reported in Ref. [18, 19]. The $\gamma$-ray absorption in YSO is affecting the $\gamma$-ray detection efficiency, but not more than by a factor of 1.2(4) at 143 keV,
Figure 5: The γ-ray spectrum from the β decays of $^{74}\text{Co}$. Energies of the peaks decaying by a similar half life to that of $^{74}\text{Co}$ ($\sim 30$ ms) are labeled in keV.

compared to the silicon-strip detector, WAS3ABi. The β-ray detection efficiency for $^{74}\text{Co}$ is $\sim 80\%$ with 3 mm radius of the correlation window. We have demonstrated that the YSO detector can be, in many cases, a better alternative to DSSD detectors for β-decay study at fragmentation facilities.

acknowledgments

The present experiment was carried out at the RI Beam Factory operated by RIKEN Nishina Center, RIKEN and CNS, University of Tokyo. This research was supported in part by the Office of Nuclear Physics, U.S. Department of Energy under Award No. DE-FG02-96ER40983 (UTK).

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