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A new neutron detector with a high position resolution for the study of the (p, pn) reaction on rare isotopes

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Abstract. We are developing a neutron detector with a position resolution better than 3 mm to study the single particle properties of nuclei by the knockout (p, pn) reaction at intermediate energies. We constructed a prototype detector consisting of scintillating fibers and multi-anode photomultiplier tubes (PMTs). A test experiment using 70-MeV proton and 68- and 50-MeV neutron was performed for characterizing its performance. In preliminary results, a position resolution of about 3 mm, is realized, as designed. The resulting separation-energy resolution would be 1 MeV, when using this system at a distance of 2 m from the target for measuring the (p, pn) reaction.

1 Introduction

Nucleon-knockout $(p, 2p)$, (p, pn) reactions at intermediate energies (200–300 MeV) provide a powerful probe of the single particle nature of nuclei[1]. Exclusive measurements of the $(p, 2p)$, (p, pn) reactions allow one to determine the separation energies, becoming one of hot topics in studies of unstable nuclei.

The first goal of our $(p, 2p)$, (p, pn) studies is to deduce the single-particle energy spectra on oxygen isotopes of $^{14\text{–}24}$O at the RIBF. Especially, measuring the neutron-knockout (p, pn) reaction channel is a difficult challenge because of the poor position resolution of neutron detectors, say ~ 3 cm. In the present study, we are developing a prototype detector as a new neutron detection system to achieve a position resolution better than 3 mm for neutrons with kinetic energies ranging from 50 to 200 MeV. This position resolution, when the detector is placed at a distance of 2 m from the target, corresponds to a separation energy resolution of 1 MeV, a reasonable resolution for distinguishing neighboring single particle states.

2 Prototype detector

Figure 1 shows a schematic view of the prototype detector. A proton scattered by an incident neutron looses part of its energy while crossing the scintillator and scintillation photons are generated along its

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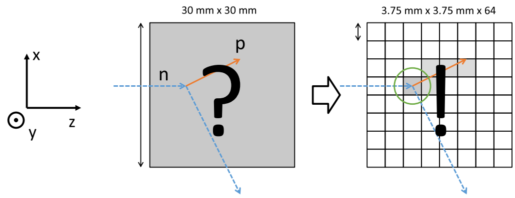

Figure 1. An idea to improve the position resolution. Blue dashed lines and red solid lines show trajectories of incident neutrons and scattered protons.

trajectory. In the prototype detector, we segmented a scintillator of 30×30 mm^2 total cross section to an array of 64 plastic scintillators each with sizes of 3.75×3.75 mm^2, so that we can see the trajectory of the proton as the hit pattern of the segments. By analyzing the hit pattern, the reaction point can be determined within the sizes of a segment and the uncertainty of position can be improved from 30 mm to 3.75 mm by a factor of 8.

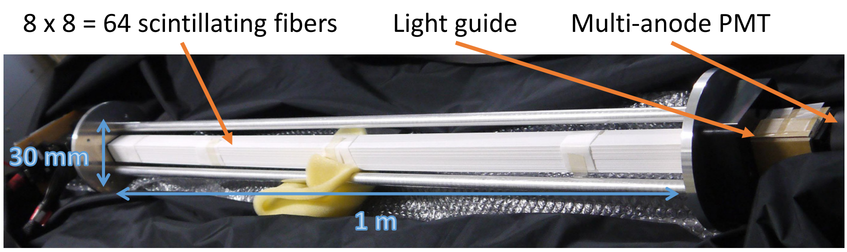

Figure 2. A photograph of a prototype detector, consisting of the neutron detection part comprised of 64 plastic scintillation fibers, two multi-anode PMTs for reading out the scintillation light from both ends of each fiber, through optical fibers.

Figure 2 shows a photo of the prototype detector, which has a total effective volume of $30.0 \times 30.0 \times 1000$ mm^3 consisting of 64 scintillating fibers ($3.75 \times 3.75 \times 1000$ mm^3). Scintillation photons generated in each fiber are transported via pitch conversion fibers with a diameter of 2 mm having no scintillation ability, to the photo-cathode planes of a multi-anode PMT (Hamamatsu H7546B). We use the dynode signal for determining the reaction timing and the reaction position along the y-direction, as well as the anode signals for the hit pattern analysis on (x, z)-plane.

3 Experiment

Test experiments of the prototype detector consisting of two measurements were performed in November 2012 at the Cyclotron and Radioisotope Center (CYRIC), Tohoku University. In the first experiment, a faint proton beam accelerated up to the energy of 70 MeV by the 930-type azimuthally-varying-field cyclotron was used for evaluating the time resolution (Δt), the position resolution along the y-direction (Δy) and the proportion of the effective volume in the total volume of scintillators (P_{eff}). In the other experiment, monoenergetic neutron beams at 68 and 50 MeV produced through the ^{7}Li$(p,n)^7$Be(g.s. + 0.43 MeV) and ^{12}C$(p,n)^{12}$N(g.s.) reactions at 0 degrees, respectively, are used for determining the position resolution along the x- and z-direction (Δx) and the detection efficiency (ϵ). Li and C targets with natural isotopic abundances were used and their thickness were 0.18 and 0.27 g/cm^2, respectively. The intensity of the proton beam was about 10 nA and the rate of neutrons bombarding the detector was typically 10^6 particles per second.

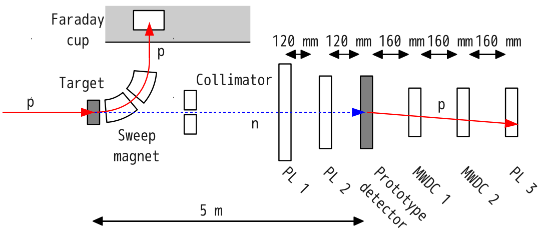

Figure 3. A schematic view of the setup for neutron measurement.

Figure 3 shows the setup of all the detectors for the second experiment with neutron beams. After passing through the target, the proton beam was transported to a Faraday cup in the wall by the sweeping magnet, where the electric charge of the beam was collected and sent to the current integrator. Neutrons produced by the (p, n) reaction, after going through the collimator, bombarded the detectors located 5 m away from the target. A plastic scintillator with a thickness of 13 mm (labeled as PL1) was used for vetoing charged-particle. A plastic scintillator with a thickness of 100 mm (PL2) covering the same solid angle as the prototype detector, was used for normalizing the absolute magnitude of the neutron flux with its calculated detection efficiency. A plastic scintillator with a thickness of 3 mm (PL3) was used as a trigger of multi-wire drift chambers (MWDCs). The MWDCs were used for determining the reaction point in the prototype detector, which was reconstructed by a backward extrapolation and compared to those given by the hit pattern in the prototype detector.

4 Results

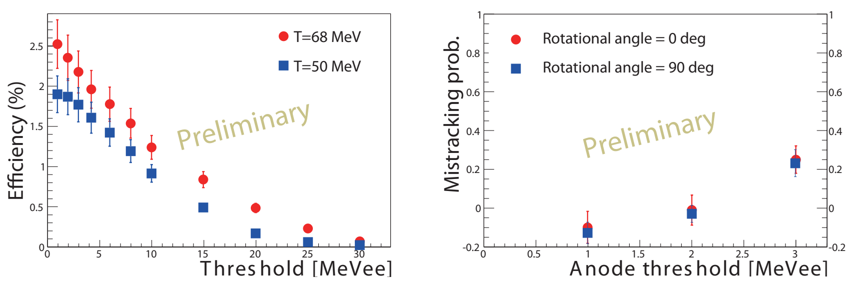

Figure 4. The left panel shows the detection efficiencies for 68- and 50-MeV neutrons as a function of the dynode threshold. The right panel shows the mistracking probability. Two different marks show the different rotational angles of the prototype detector around the y-axis.

The left panel of Fig. 4 shows the preliminary results for the detection efficiency as a function of the dynode threshold. The detection efficiency of $\epsilon = 2.5\%$ was achieved for 68-MeV neutron with a dynode threshold of 1 $\mathrm{MeV_{ee}}$. It is sufficient to perform the (p, pn) experiment. This value is about 30% smaller than that of a conventional detector having same thickness of 30 mm. This reduction is considered to be due to the ineffective area such as cladding, light shielding and gaps surrounding each scintillating fiber.

The right panel of Fig. 4 shows the mistracking probability as a function of the anode threshold. A major source of mistracking is an oversight of the starting point of the hit pattern, which is strongly affected by the anode threshold. This value was derived from the detection efficiency of each fiber

Table 1. Summary of the items characterizing the performance of the prototype detector, the requirements on the items to achieve $\Delta S = 1$ MeV with the detector position of 2 m apart from the target, and their results. Resolutions are written in a full-width at half-maximum.

Items	Requirements	Results
Detection efficiency ϵ	–	2.5%
Position resolution Δx	5 mm	2.6 mm
Position resolution Δy	70 mm	55 mm
Timing resolution Δt	700 ps	300 ps
Effective volume P_{eff}	–	70%

assuming the toy model that the mistracking always involves neighboring fibers and its probabilities along the x-direction and z-direction are the same. Within this toy model, the position resolution Δx turns out to be almost the same as the size of a segment, if the mistracking probability is less than 0.3 (30%). With the setting of the anode threshold below 3 MeV_{ee}, the effect of the mistracking on the position resolution is negligible.

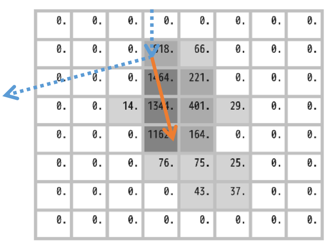

Figure 5. An example of hit pattern. 8×8 numbers indicate the light output in each segment. Blue dotted lines and red solid line show the supposed trajectory of incident/scattered neutrons and proton, respectively.

Figure 5 shows the hit pattern for a neutron-detection event with the QDC value of each segment. In this event, the segment where the reaction due to the incident neutron can be easily identified, implying that the uncertainty of the neutron detection position, ± 1.8 mm, can be achieved. The detailed analysis for establishing the method of the hit-position reconstruction is under progress.

Table 1 shows the result of the performance test. The requirement of achieving the separation energy resolution of $\Delta S = 1$ MeV is fully satisfied.

5 Summary and outlook

We constructed the prototype detector with a high position resolution of ± 1.8 mm for intermediate-energy neutrons consisting of scintillating fibers and multi-anode PMTs. The test experiment using 70-MeV proton and 68- and 50-MeV neutron was performed in CYRIC for characterizing its performance. The results show the required separation-energy resolution of 1 MeV can be realized when the detector is located 2 m apart from the target.

Due to the limitation of the accelerator, the performance was characterized only in the energy region of 50–70 MeV and there is no data in the energy region of 70–200 MeV, which is the most important for (p, pn) measurements. We are planning to perform further experiments in the energy region of 100–200 MeV at Research Center for Nuclear Physics, Osaka University.

References

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