Development of a Next-generation Neutron Detector Array HIME

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Abstract

We propose to make a test experiment to investigate the performance of a newly developed high-resolution neutron detector array HIME (HIgh resolution detector array for Multi-neutron Events). The HIME which is composed of 100 rods of 2x4x100 cm^3 plastic scintillators, makes use of a new scheme of fast neutron detection using a tracking of recoiled protons. With this new scheme, momentum resolution and capability of multi-neutron detection is expected to significantly improve. Here, we use the quasi-monoenergetic neutron beam produced by the $^7\mathrm{Li}(p,n)^7\mathrm{Be}$(g.s.+0.43 MeV) reaction at 100 MeV and 250 MeV to determine the timing resolution, energy dependence of the neutron efficiency, and the angular resolution of the recoiled proton at HIME.

1 Introduction

One of the goals of nuclear physics is to describe any many-body nucleonic systems in a universal way from the β-stability line to the drip-lines, and even beyond. In this respect, “unbound nuclei” in the vicinity of the neutron drip line play an important role in nuclear physics. Such nuclei are used to make a rigorous test of the modern nuclear structure theories, such as ab-initio calculations as well as Gamow shell models. Such nuclei are also important in investigating the tensor forces/correlations, and the isospin dependence of the nuclear force, dineutron correlation, due to the large neutron/proton ratio and low-dense properties. Four neutron correlation, which could be important in tetra neutron and ^{28}O, is also a central issue. It is noted that these properties in extreme neutron rich nuclei could be useful in understanding the neutron star.

Such an unbound nucleus can be produced using a reaction with an RI beam, and its level structure can be determined by the invariant mass spectroscopy, where momenta of all the outgoing particles including neutron(s) following the decay of the intermediate resonance of the unbound nucleus are measured to reconstruct the invariant mass. However, due to the experimental difficulties, partly because of those in neutron detection, there remain a lot of key unbound nuclei, whose level structures are still not well known. Even for the lightest ones, such as ^{5}H and ^{10}Li, the data obtained so far are in controversial situations. Main difficulties of neutron detectors are attributed to those in detecting two or more neutrons, where the cross talk due to scattering of neutron(s) often occurs. To solve these problems, we are now developing a new neutron detector array HIME, which has sufficiently high granularity, and is expected to have the capability of detecting multi-neutron events unambiguously by using a new scheme of tracking the recoiled proton.

The HIME is composed of 100 pieces of plastic scintillator modules, each of which has the size of 2x4x100 cm^3, and is coupled to two phototubes at both ends of the longest direction. In the proposed test experiment, 90 pieces of modules, out of 100, are arranged into 7 pieces x 3 layers and 12 pieces x 2 layers, *i.e.*, total 5 layers. In addition 3 pieces of VETO modules are installed in front of the HIME modules as in Fig.1.1 [*1]. Each detector module of HIME is thin enough for the recoiled proton to penetrate more than one layer at 100 MeV–300 MeV. In particular, if a neutron leaves three or more signals by the recoiled proton by penetrating three or more layers, one can track this proton, as shown in Fig. 1.2. We call such an event "tracked event", hereafter.

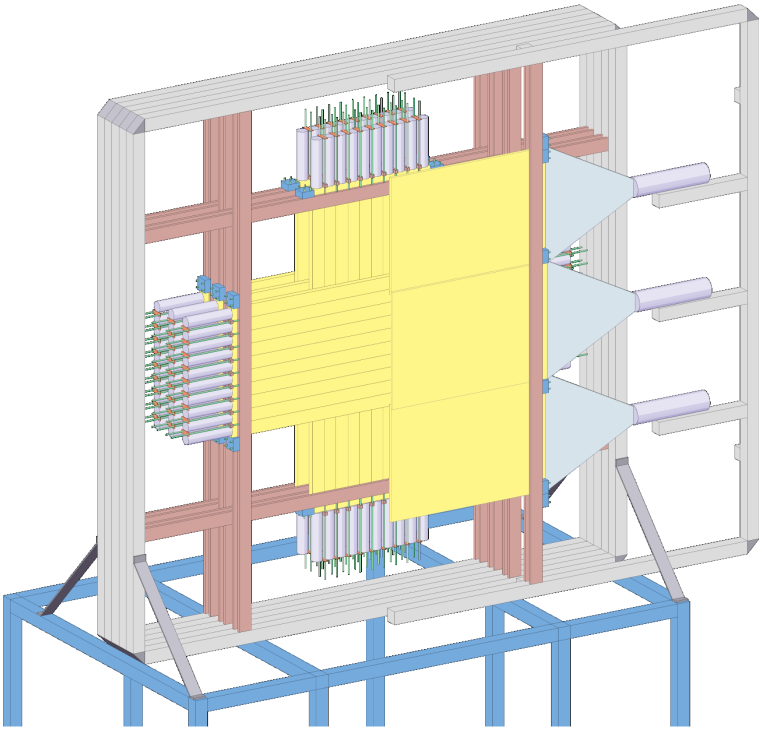

Figure 1.1 Schematic view of the HIME. Only half of the VETO modules are drawn.

Advantages of using this new scheme are: 1) One can select recoiled proton events out of other events (γ, α *etc.*), 2) Significant improvement of position and timing resolutions and thus the excitation energy resolution, and 3) One can efficiently and reliably eliminate cross talk events.

[*1] In the experiment using the RI beam, the similar setup is planned to be used

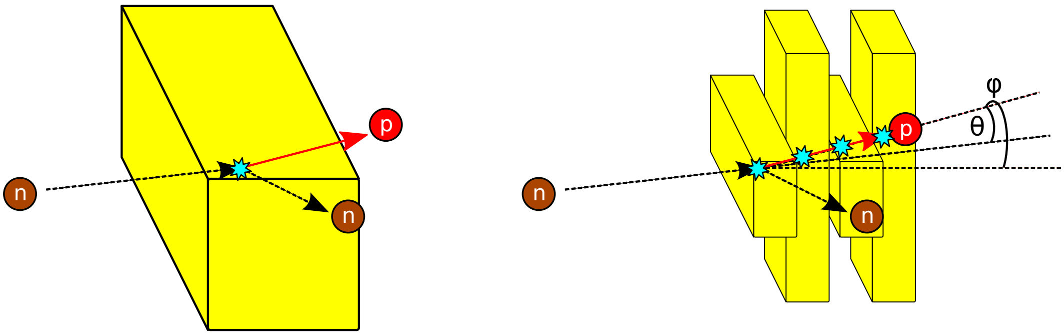

Figure 1.2 Schematic view of analysis method of usual neutron detector and the next-generation neutron detector HIME. Usual neutron detector detect recoiled charged particle only by one module, while the HIME detect recoiled proton which is main projectile of reaction between neutron and plastic by several modules. This makes the HIME able to track recoiled proton. Detail of advantage of tracking is described in the text.

In a tracked event, one requires three or more signals in three or more layers, as mentioned. As such, one can eliminate dominant background due to γ rays since such requirement does not meet the condition of the γ related event, which leaves small signals in one or two layers. One can also eliminate the recoiled heavier-residue events such as α, ^{12}C, or ^{11}B since it leaves none or small signal only in one layer. Hence, the requirement of such three signals restrict the event to the one related to the recoiled proton produced in the $n+p$ elastic scattering or knockout reaction such as $^{12}\mathrm{C}(n,np)$.

The advantage 2) can be understood in the following way. The tracking improves the position resolution by the fitting procedure. The hit position is better determined, compared to the width of the plastic scintillator. The timing resolution improves roughly by $\sqrt{(\text{number of penetrated layer})}$. The energy loss correction for the recoiled proton is possible by considering the kinematics of the reaction. The conventional neutron detectors using information from only one layer has a limited timing resolution due to the ambiguity of the hitting position, which is also improved in this scheme.

In the current scheme of HIME, cross talk events can be excluded by making use of the tracked events. One possible scheme is shown in Fig. 1.3. The kinematics and causality can be used in a more efficient way in this detector, compared to the conventional detectors such as LNEUT and NEBULA at RIBF at RIKEN, LAND at GSI, MoNA at MSU. Although the current HIME setup has still very low efficiency for multi-neutron events, we expect the $4n$ detection efficiency of about 5% when the full setup is realized in a few years.

As the first physics experiment using the HIME array, we plan to measure the excitation energy spectra of ^{10}Li accurately by using the invariant mass spectroscopy at SAMURAI at RIBF. The main purpose is to distinguish the p-wave doublet states $(1^+,\ 2^+)$[1, 2], which has been a long-standing issue. The identification of such a doublet is in particular important to make a stringent test of modern nuclear theories such as ab-initio calculations and tensor-optimized shell model by Myo et al.[1]. Figure 1.4 shows the result of the Monte Carlo simulation for this case, when we use the two-proton knockout reaction of ^{12}B. Here we compare the result obtained by the HIME with that by LNEUT(conventional

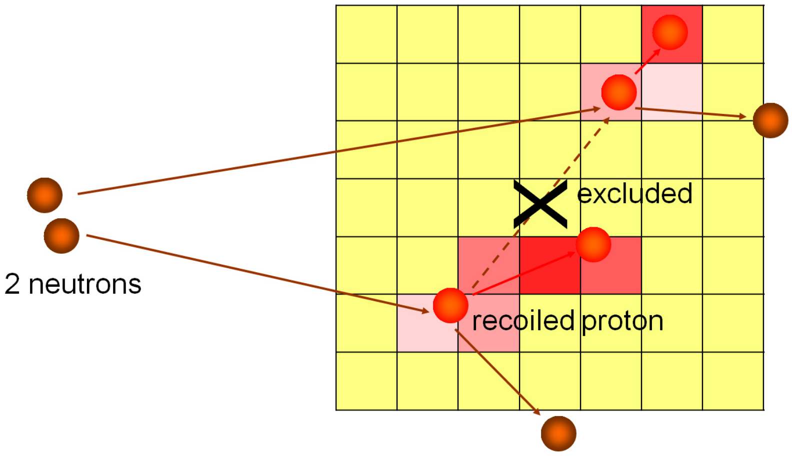

Figure 1.3 Schematic view of an analysis method to distinguish the $1n$ event from the $2n$ event. By tracking the recoiled proton, kinematics of neutron is restricted to a small solid angle (about 0.5 sr in the center-of-mass system). This allows us to exclude such cross talk $1n$ event.

neutron detectors at RIPS at RIBF). Moreover, we expect to identify much more new levels for other cases in the near future, owing to the highest resolution for the neutron detection, and high capability of multi-neutron detection. We will also make use of the RI beam produced at RIPS facility around 100 MeV/nucleon. The RIPS facility still provides good intensity for the light neutron-rich nuclei. In the near future, at SAMURAI/RIBF, we also plan to measure most sought-after unbound nuclei $4n$, ^{5}H, and ^{28}O using HIME.

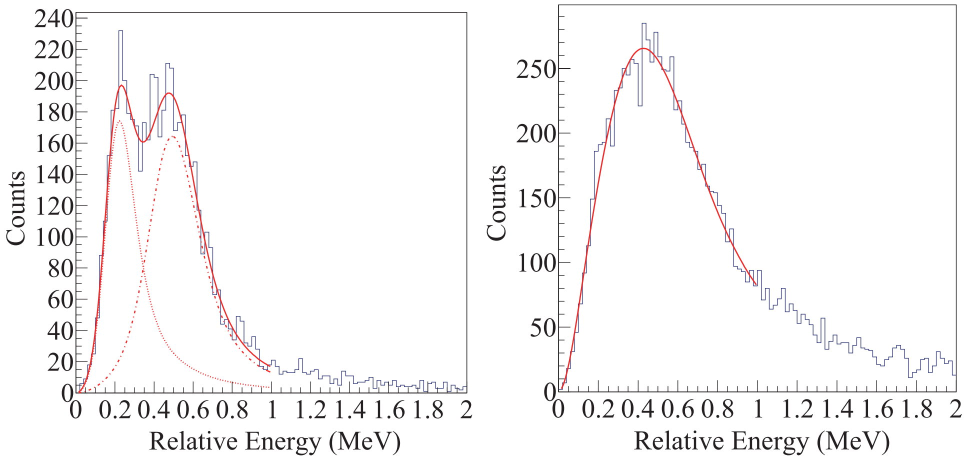

Figure 1.4 The simulated result for the invariant mass spectrum of ^{10}Li produced by the $2p$ knockout from ^{12}B. Left: The spectrum expected for the HIME setup (analysis of tracked events). Energy resolution is about 200 keV (FWHM). Right: The spectrum expected for the LNEUT setup (conventional detectors at RIPS). Energy resolution is about 500 keV (FWHM). It is found that the doublet peaks can be distinguished by the HIME array.

In this proposed test experiment, we aim at establishing this new detection scheme of fast neutrons.

For this purpose, we need to confirm the validity of the selection method of “tracked events”. We also measure the basic properties of HIME, *i.e.*, timing resolution, position resolution, and angular resolution of the recoiled proton. The result can be used to determine the energy resolution of planned experiments for the unbound nuclei. In addition, we measure the neutron detection efficiency, which is necessary to determine cross sections, in order to extract the spectroscopic factor, and to study the reaction mechanism for production of unbound nuclei. Since the efficiency depends on incident energies, as described later, we will use two incident energies, 100 MeV and 250 MeV. The former is relevant to experiments at RIPS at RIBF, and the latter is to those at SAMURAI at RIBF. The results are also compared with a Monte Carlo simulation to evaluate its validity. The simulation is also used to assess the capability of the multi-neutron detections.

2 Experiment

We use the quasi mono-energetic neutron beam, produced by the reaction ^{7}Li$(p,n)^7$Be(g.s.+0.43 MeV) at 100 MeV and 250 MeV. These neutrons are used to confirm the selection capability of the tracked event, and to measure the timing resolution, position resolution, and the angular resolution of the recoiled proton, as well as intrinsic efficiencies for these incident energies.

As shown in Fig.2.1, we use two experimental setups. In the 1st setup (top panel), a plastic beam detector at about 1 m upstream of the target is installed, while the HIME is located at 7 m downstream. The counting rate of protons is restricted to about $5{\times}10^5$ cps due to the limitation of the beam detector. For gaining the yield, we set the HIME at a shorter distance (7 m), where the acceptance of the HIME is $2.7{\times}10^{-3}$ sr. Since we can obtain start timing of TOF and the number of protons by the beam detector, event by event, this setup is primarily used to determine the TOF resolution and the accurate proton counts. The timing resolution of the beam detector is expected to be about 80 ps,

In the 2nd setup (bottom panel), the plastic beam detector is removed, and the HIME is located at a longer distance of 45 m downstream of the target. In this case, one can take advantage of much higher intensity of the proton beam, and energy resolution of neutron improves significantly due to the much longer TOF. On the other hand, estimated timing resolution becomes worse ($\sim$ 400 ps (FWHM)) since the start timing of TOF is determined by the RF signal. Hence, it is not appropriate to use this setup for determining the timing resolution. The acceptance of HIME is 6.6x10^{-5} sr at 45 m downstream. Such a long distance is possible since the 2nd setup can accept much higher intensity of the proton beam.

As mentioned, the timing resolution is measured by the 1st setup with HIME at a shorter distance (7 m), combined with a beam detector. According to the simulation, the timing resolution does not depend on the incident energies as shown in Fig. 2.2. The expected resolution for the tracked event is about 100 ps (1σ), which is better by a factor of about 3, compared to LNEUT used at RIPS ($\sim$300 ps).

The efficiency is determined by combining results from the two setups. The cross section for the ^{7}Li$(p,n)^7$Be(g.s.+0.43 MeV) reaction has the form

$$\sigma(q) = \sigma_0 \exp\left(-q^2 \frac{<r^2>}{3}\right), \tag{2.1}$$

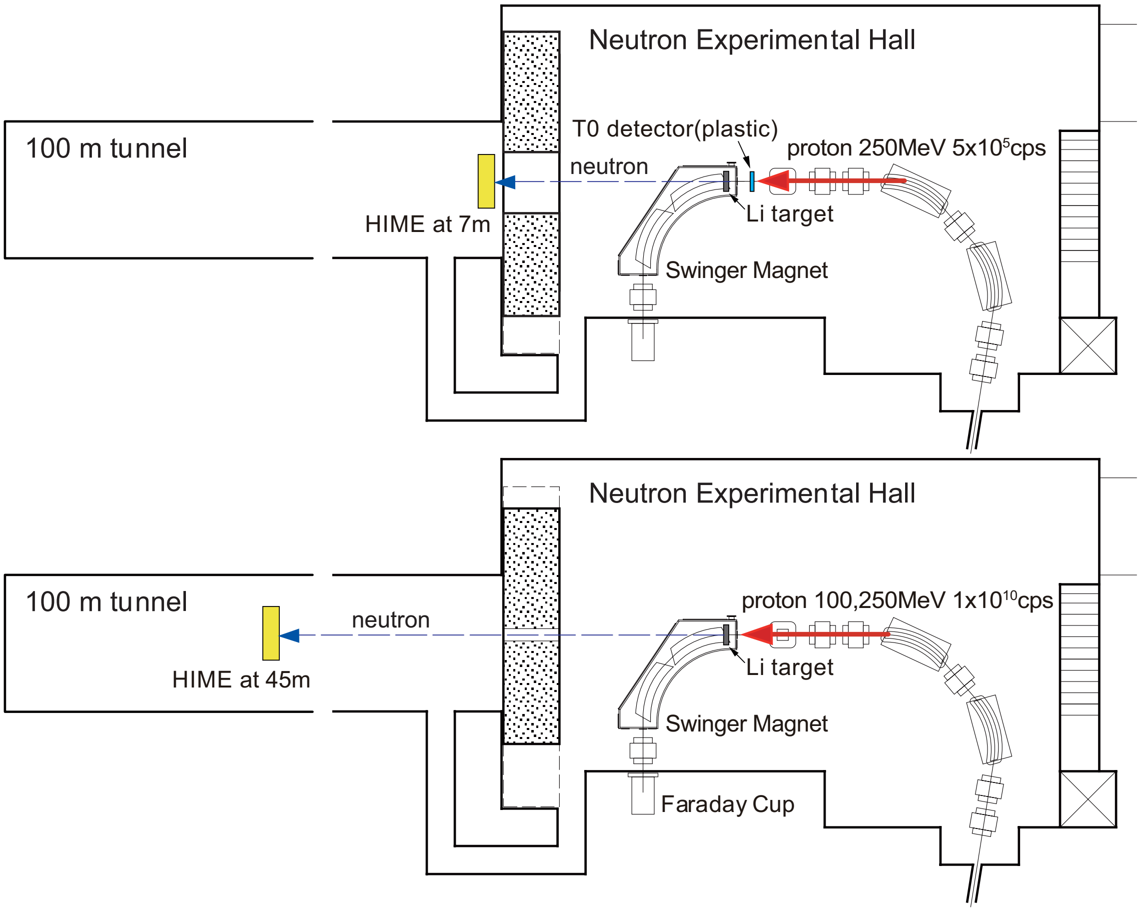

Figure 2.1 Upper panel: The experimental setup when we measure neutron event-by-event. In this setup, TOF resolution and accuracy of beam rate is higher. Lower panel: The experimental setup when we use high intensity proton beam. In this setup, energy resolution and event rate is higher.

where the cross section at θ=0 is 26 mb/sr in the c.m. system, and about 35 mb/sr in the laboratory system at the current energies [3]. Since there exist higher excited states in ^{7}Be (E_x >0.43 MeV), the energy resolution (6.6 MeV FWHM), expected for the 1st setup, is not sufficient to distinguish the peak (g.s.+0.43 MeV) from the higher energy background, as illustrated in Fig. 2.3

On the other hand, the 2nd setup can distinguish the peak from the background due to its higher resolution, while the event-by-event determination of the beam counts is not applicable. To obtain the high accuracy for the efficiency less than 5%, we use the 2nd setup for determining the shape of the energy spectrum. Energy resolution for the neutron in the 2nd setup is 1.2 MeV (FWHM) at 250 MeV, and 0.27 MeV (FWHM) at 100 MeV for the expected timing resolution of 400 ps (FWHM). By folding this spectrum by the resolution for the 1st setup, one can determine the portion of the g.s.+0.43 MeV states in the spectrum for the 1st setup accurately. We make the measurements both in the two setups for 250 MeV. For 100 MeV, we only use the 2nd setup since we know that relative beam rate in the 2nd setup can be reliably extracted and we can calibrate the Faraday cup using the 250 MeV run. The

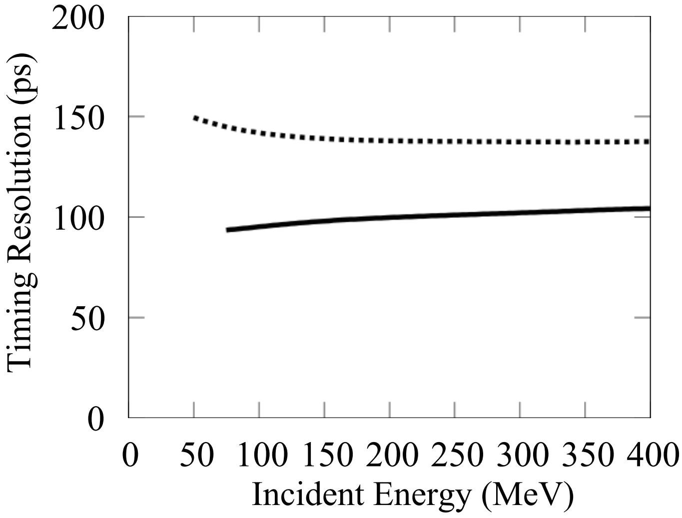

Figure 2.2 Energy dependence of the timing resolution of the TOF. Dotted curve (upper) shows the resolution obtained by the conventional method (use of only one layer), and used the resolution corresponding to that of γ ray (130 ps 1σ). Solid curve (lower) shows the resolution obtained by the tracking method. In this case, the intrinsic timing resolution of 110 ps obtained for the proton is assumed. The resolution for proton and γ in HIME was measured at the HIMAC experiment.

energy dependence of the efficiency obtained by the simulation is shown in Fig. 2.4. For the "tracked event", the efficiency is expected to be about 1% at 100 MeV, while about 3% at 250 MeV.

The proton angular resolution is measured by using the 100 MeV proton beam itself (faint beam). By using the 1st setup, and by changing the HIME angle from 0 to 60 degrees with 15-degree steps, one can mimic the recoiled proton events at finite angles. We expect the resolution to be 120 mrad (1σ) on average.

The experimental setup and evaluated event rates are summarized in Table 2.1. For the 1st setup, we need to keep the primary beam rate as low as 5x10^5 cps due to the limitation of the beam detector. For the 2nd setup, the primary beam rate is restricted due to the limitation of the DAQ counting rate of ~1000 cps. To avoid pile-up events in the plastic scintillator and to reduce the single rate of the HIME, we use the beam chopper with a suitable repetition rate. The target thickness of Li is chosen, as shown in Table 2.1, to optimize the resolution, yield, and background.

Distance	Energy	Intensity	After pulsing	Thickness	$\int d\sigma(\Omega)$	Yield
7m	250 MeV	3.5x10^6 cps	5x10^5 cps	1 g/cm^2	94 μb	380 cph
45m	250 MeV	1.5x10^{11} cps	1x10^{10} cps	0.5 g/cm^2	2.3 μb	88000 cph
45m	100 MeV	1.5x10^{11} cps	1x10^{10} cps	0.5 g/cm^2	2.3 μb	29000 cph

Table 2.1 Summary of the experimental setups, estimated event rates for the ^{7}Li$(p,n)^7$Be(g.s.+0.43 MeV) reaction.

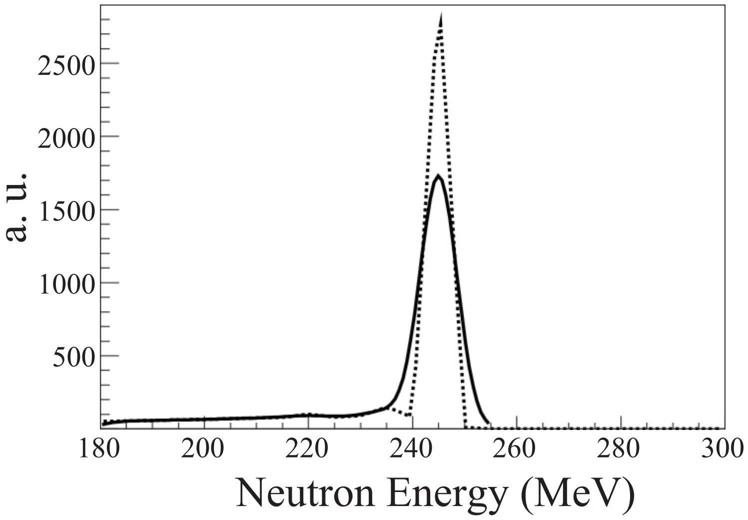

Figure 2.3 The comparison of the expected energy spectra for the 1st setup (dotted curve) and the 2nd setup (solid curve) for the $^7\mathrm{Li}(p,n)^7\mathrm{Be}$ reaction at 250 MeV. The spectrum for the 2nd setup is based on Ref.[4]. For the 1st setup, the energy resolution is estimated to be 6.6 MeV (FWHM), which is folded.

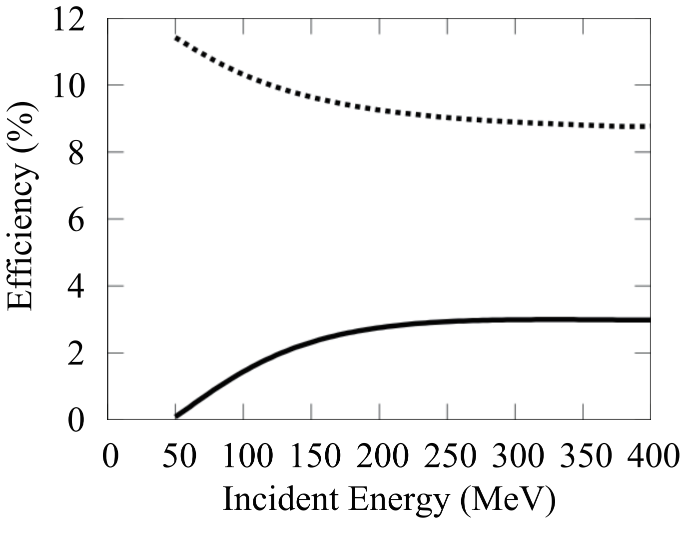

Figure 2.4 Incident energy dependence of the intrinsic efficiency of the neutron detection for the threshold energy of 4 MeVee. Dotted curve represents the case for the conventional method (one layer analysis), while solied curve corresponds to the one using the tracking (”tracked event”). It is noted that the efficiency changes rather rapidly up to 150 MeV for the latter case.

3 Estimation of beam time requested

Based on the estimated beam intensity and event rates shown in Table 2.1, we request 2 days in total, whose detail is shown in Table 3.1.

energy	position/aim	Target-in	Target-out	Total
250 MeV	7m	16h	4h	20h
	45m	2h	1h	3h
	electronics tuning			9h
	exchange of setup			4h
Total				1.5days
100 MeV	45m	2h	1h	3h
	7m	3h	—	3h
	electronics tuning			2h
	exchange of setup			4h
Total				0.5days
				2days

Table 3.1 Days to be requested based on the estimated beam intensity and event rates.

For the 1st setup at 250 MeV, we will accumulate about 6000 events of the tracked events (3 hits/ 3 layers or more), where one can get the statistical error of 1.3%. With this, we expect about 3000 events for the 4 hits in the 4 layers, and about 1500 events for the 5 hits in the 5 layers. These can be used to evaluate even higher-resolution modes. For the 2nd setup, we request 2 hours/each at 100 MeV and 250 MeV, and 3 hours for angular resolution measurements using the proton beam itself.

4 Readiness

We use the newly-developed HIME neutron array, which will be installed at the N0-course. In addition we also install the beam detector upperstream of the target (1st setup). The HIME neutron detector array and beam detector are now being constructed and to be ready by the end of April 2012. In summary, we request 2-day machine time to determine experimentally the performance of the high-resolution neutron detector array HIME.

References

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