Measurements of Hydrogen and Helium Isotopes Emission Spectra from Neutrons Induced Reaction at Ten's of MeV

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Abstract

We have developed a wide dynamic range spectrometer for the measurements of (n,xZ) double differential cross sections (DDXs) for ten's of MeV neutrons at TIARA. The spectrometer consists of a 40-cm diameter vacuum reaction chamber and three counter telescopes. Each telescope consists of a gas proportional counter, an SSD and a BaF_2 scintillator. By using the spectrometer, we achieved simultaneous measurements from ~MeV α particles to 75MeV protons with an acceptable counting rate.

1. Introduction

Charged particle emission double differential cross sections (DDXs) for Ten's MeV neutrons are of prime importance for accelerator applications, such as the high intensity neutron sources for material research, accelerator cancer therapy and accelerator-based transmutation systems.

For the reason, we have continued the measurements of DDXs for (n,xZ) reactions at 40-80 MeV mono-energetic neutron source facility in TIARA (Takasaki Establishment, JAERI) [1]. Last year, we reported the (n,xp) and (n,xd) DDXs of Al and C at 5 angles, and compared the data with theoretical calculation codes of ISOBAR and GNASH [2] for the (n,xp) DDXs. The two codes agrees each other and trace our data above the detection threshold (Ep~10MeV), but show differences in magnitude below 10MeV. Thus, marked low threshold measurements for (n,xp) reactions are desirable to validate the calculations. In addition, α particle spectra are also needed because the (n,xα) reactions are major components of neutron KERMA (Kinetic Energy Released in MAterials)[3] and a He accumulation effect plays an important role in material damage.

In order to expand the measurement to lower energy protons and α particles, we have developed a new spectrometer. In the present paper, we report the design of the spectrometer and the results of test experiments for a low detection threshold, wide range particle identification of hydrogen and helium Isotopes and a better signal-to-noise ratio (S/N). Thick sample correction methods now under research are also mentioned.

2. Design of the New Spectrometer

2-1. wide Range Measurements

In the energy region above 20MeV, many kind of hydrogen and helium isotopes are emitted from neutron induced reactions. Therefore, particle identification (PI) is expected to be needed over a wide energy range from ~5MeV up to 80MeV at TIARA. For PI, the ΔE-E method is widely applied utilizing a counter telescope which consists of a transmission detector and a stop detector. It is difficult to achieve the PI over the wide energy range because the ΔE value of 5MeV α particles are more than 100 times as large as that of 80MeV protons. To achieve such a wide range particle identification, we choose a ΔE1-ΔE2-E method, which utilizes two transmission detector ΔE1 and ΔE2, and treats the ΔE2 as the stop detector for particles which stop in ΔE2. The schematic view of the telescope with a vacuum reaction chamber is shown in fig. 1.

To measure ~MeV α particles, the ΔE1 detector must be thin to reduce energy loss. In the ordinary (p,xZ) DDX measurements, silicon surface barrier detectors (SSD) of 20~25μm thick are used as the ΔE1 detector[4]. For (n,xα) measurements, even thinner SSDs (< 10μm) with a large effective area is desirable. The latter is required because the neutron flluence (1~2$\times 10^4$ /cm^{2}s) at sample (20cm^2) was lower than ordinary proton experiment (1nA) by four order of magnitude. In order to reduce the energy loss and obtain large acceptable area, we chose a low pressure gas proportional counter as the ΔE1 counter. The counter is of ordinary cylindrical shape (5.4cm long, 4.3cm in diameter) and the area of the entrance window is 1200mm^2. As the operation gas, 0.1~0.2atm Ar+5%CO_2 is used in gas-flow mode. With 0.1atm a gas pressure, the detection threshold of α particles can be low as ~2.4MeV. The gas pressure is automatically regulated by a mass-flow controller (STEC PCU2000 and PIEZO valve). The entrance window of the gas counter was a 5.4μm thick mylar film which was supported by a stainless wire grid (0.1mm in diam., 4mm spacing) to withstand a gas pressure up to ~0.4atm. As for the ΔE2 detector, we employ a SSD (CANBERRA PIPS) 150μm thick and 900mm^2 wide, that was proved to be useful for PI of proton and deuteron up to 75MeV[1]. As for the E detector, a BaF_2 scintillator (2.2cm thick, 4cm in diameter) are selected owing to its chemical stability requiring no entrance window and its fast timing feature is needed to measure time of flight of particles.

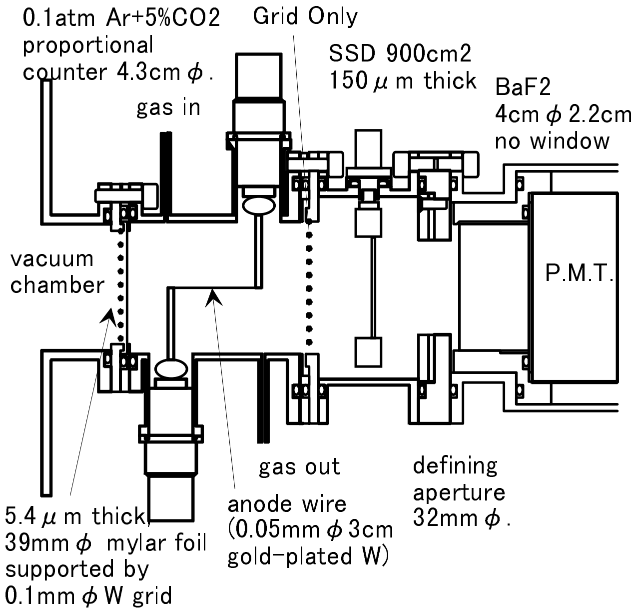

Fig. 1: Schematic View of Wide Range Telescope

2-2. Counting Efficiency and S/N

In addition to the extension in an energy range, the improvement of counting efficiency and S/N is also considered. In order to improve the counting efficiency without deteriorating angular resolution, we adopted multi telescope system shown in fig. 2. The three counter telescopes are set on the vacuum reaction chamber (37cm in diameter) every 20°. The detection angles can be set 25-150° with 10° steps by turning the chamber around sample without breaking the vacuum. In the previous work[2], the (n,xp) and (n,xd) measurements suffered from backgrounds from nitrogen and oxygen in the air environment. Thus we expect the reduction of background by adopting the new vacuum chamber (< 5Pa). To avoid neutrons bombardment of the chamber, an taper shaped iron collimator (80cm long, inner diameter at the exit is 5.5cm) is used to neutron collimation and neutron entrance port is 72mm in diameter. A thin aluminum plate (2mm) was used as the entrance window. The disk-shaped sample (5cm in diam.) was located at the center of the chamber and to be exposed to direct neutrons from the Li target.

2-3. Data Acquisition circuit

For the data acquisition, we employ the CAMAC systems to gather three sets of six parameter data described below. The schematic view of the circuit is shown in fig. 3. Good events are chosen either by gas-SSD coincidence or SSD-BaF2 coincidence. To simplify the circuit, two-out-of-three condition is adopted using a majority coincidence module (Philips 755). The energy signals of BaF_2 were obtained by charge integration methods with $2\mu s$ gate. The ΔE (or E) signals from SSD and gas counter was integrated with pre-amplifiers, and amplified, then converted into digital values by peak ADCs. The time of flight of the charged particles are also measured at BaF_2 and SSD.

To enhance PI, the SSD pulse heights were acquired with two gain: high gain is for the hydrogen Isotope separation and low gain is for the Isotope separation.

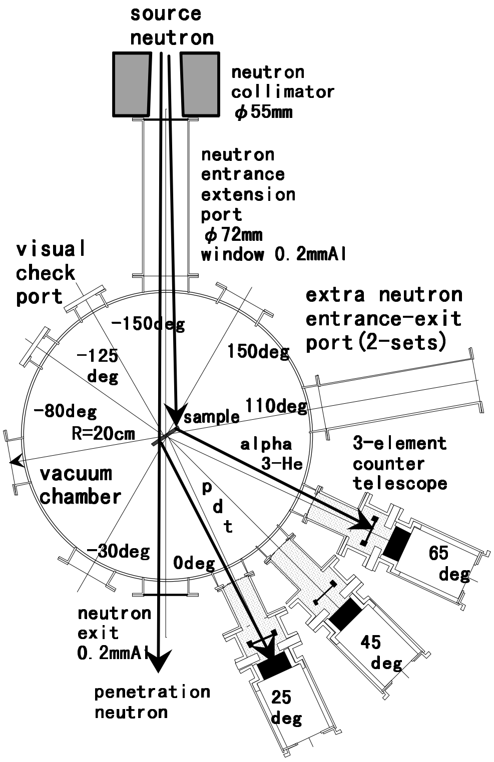

Fig2: Multi telescope system

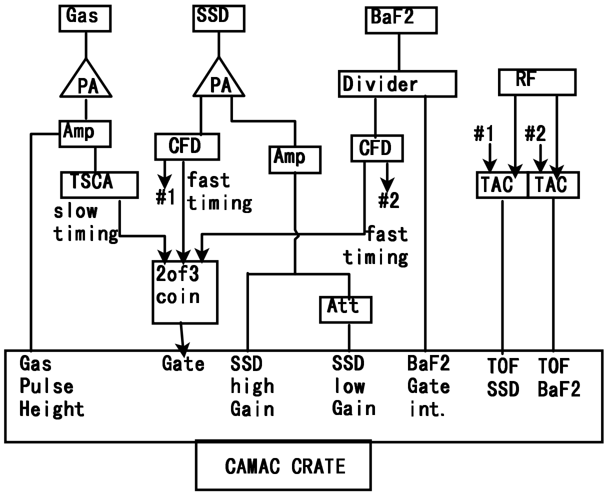

Fig. 3: Data Acquisition System

3. Test Experiments and Results

3.1. Experiment

PI over a wide range and S/N were tested. A sheet of polyethylene, carbon and iron samples were set at the center of the vacuum chamber and irradiated by 75MeV neutrons. Emitted charged particles (proton, deuteron, triton ^{3}He and α) were detected by the counter telescopes. In addition, an ^{241}Am calibration α source was also incorporated in the chamber to obtain to determine the energy scale of the detector pulse heights. The pressure of the gas counter was set 0.1 atm.

3.2. Particle Identification

In fig. 4, two dimensional spectra are shown for BaF_2-SSD (high gain), BaF2-SSD (low gain) and SSD (high gain)-Gas. In the BaF_2-SSD (high gain) plot, proton , deuteron and triton spectra are clearly separated, while He spectra are out of range of SSD axis. For the He isotope separation, BaF_2-SSD(low gain) spectra are used. Although the separation of hydrogen isotopes from electrical noise is poor, ^{3}He and α particle are clearly identified. Few data has been reported for such good separation of He isotopes for the ten's MeV neutron experiments[5][6] except for a specialized spectrometer for α particles measurements.[7] In the SSD(high gain)-Gas spectra, helium are separated clearly from hydrogen and detector noise, but an isotope separations of helium are not be visible because of limited resolution of gas counter due to low energy loss and a low yield. The peaks in the spectra is α particles from the ^{241}Am source (5.6MeV). It assures the detection threshold for α particle measurements is lowered well below 5MeV.

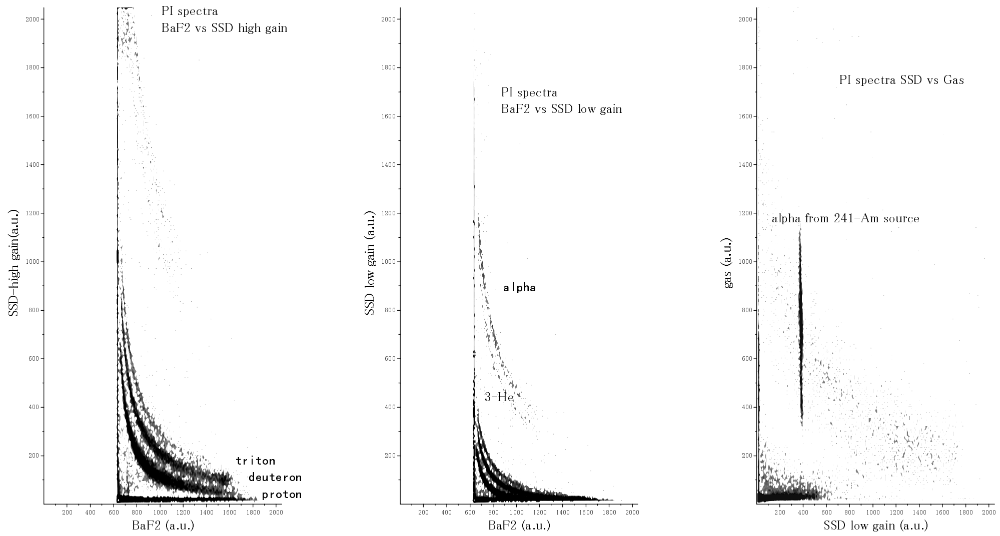

Fig. 4: 3-mode Particle Identification Spectra

The energy scales of the spectra are determined by the α particles from the ^{241}Am, and peak spectra of secondary proton and deuteron from H(n,xp) and C(n,xd) reaction, respectively.

P.I. mode	SSD(high gain)-BaF_2	SSD(low gain)-BaF_2	Gas-SSD(high gain)
Particles and Energy Range	Proton > 5MeV Deuteron > 6MeV Triton > 7.5MeV	^{3}He > 16MeV α > 18.5MeV	He 2.5-19.5MeV

3.3. Improvement of S/N

In order to examine the effect of the vacuum chamber, neutron collimator and neutron entrance window, we compared the S/N in the present C(n,xp) measurements with that in the air environment[2]. The S/N values are compared about the total yields of secondary protons normalized to the sample weight. The results are shown in fig. 5. By the present aparatus, the S/N values are enhanced more than decades than conventional telescopes in the air environment.

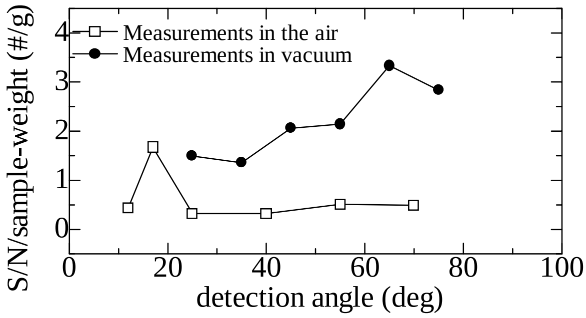

Fig. 5: S/N improvements

4. Thick Sample Condition

The sample for the spectra measurements should be much thinner than the shortest charged particle range in the sample, because the energy loss distorts the spectra. However, we often must use samples which is too thick for α particle (large dE/dX) measurements to obtain acceptable counting because of limited neutron flux. Therefore, a data correction method to correct the charged particle spectra for the effect of energy loss is desirable. We are considering to apply Baysian theorem for the corrections (unfolding).

<u>4-1. Response Function</u>

In order to apply unfolding methods, the response function should be examined. We calculate it for a sample(fig. 6). For protons, the energy of detected particles is very close to the primary energy, but it differs largely in the α particle measurements because of large energy loss.

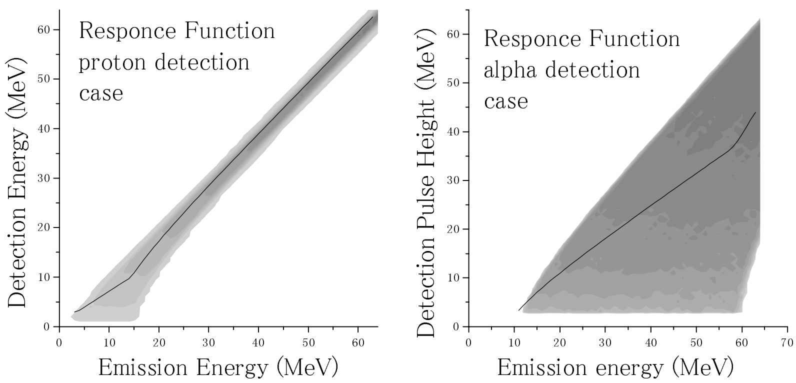

Fig. 6: Response Function of thick sample measurements

The measured spectrum dY/dH is the folded spectra of Reaction spectrum dY/dE by the response function.

$$\frac{dY}{dH}(h) = \int r(e \to h) \frac{dY}{dE}(e)de$$

To solve this Fredhorm integral equation, a simple approximation such as “average detected energy” (solid lines in fig. 6) are currently used[8]. However it usually results in the overestimation of the maximum energy of the spectra. Therefore, another unfolding methods are needed.

<u>4-2. New Unfolding Methods based on Bayes’s Theory</u>

Let the d_i(i=1,m) be the measured spectra corresponding to pulse height bin h_i , and p_j(j=1,n) be the primary spectra corresponding to energy bin e_j . Then r_{ij} is defined as the probability that a particle of e_j is measured as pulse height h_i. When we know the prior $est^{(l)}_j$ to the p_j, if we have measured one particle of pulse height h_i, then the estimated spectrum $est^{(l)}_j$ is improved by Bayes' theory. After successive iteration, the primary spectrum can be estimated.

$$est_j^{l+1} = \frac{est_j^l \times r_{i,j}}{\sum_j^n est_j^l \times r_{i,j}}$$

Then we expand the theory to the present case: the measured spectrum d_i.(i=1,m) is given.
In this methods, we assume the flat spectra as the initial prior spectrum $est^{(0)}_j$, then repeat the improvement calculations until convergence.

$$est_j^{l+1} = \sum_i^m d_i \frac{est_j^l \times r_{i,j}}{\sum_j^n est_j^l \times r_{i,j}}$$

4-3. Tests of Unfolding Capability using simulated spectra

We test the unfolding capability using simulated spectra (fig. 7). The ideal primary spectra is the solid line and the triangles are folded spectra by the response of α particle measurements in fig. 6. The dots are the unfolded spectra obtained by 30times correction calculations. As the results, while the peak separation is poor, the total yield and overall spectral shape are reproduced. This result indicates the potential of the Baysesʼ unfolding methods to solve the thick sample condition in the charged particle spectra measurements.

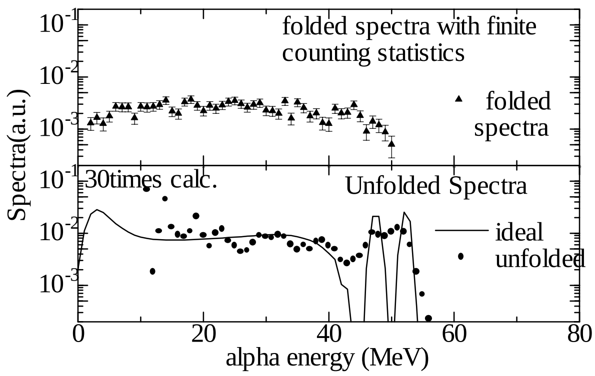

Fig. 7: unfolding tests using simulation calculation

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