CROSS SECTION MEASUREMENT FOR THE $^{147}Sm(n,\alpha)^{144}Nd$ REACTION AT E_n = 5.0 AND 6.0 MeV*

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Abstract

Cross sections of the $^{147}Sm(n,\alpha)^{144}Nd$ reaction were measured at E_n = 5.0 and 6.0 MeV. Experiments were performed at the 4.5 MV Van de Graaff accelerator of Peking University. Neutrons were produced through the $D(d,n)^3He$ reaction with a deuterium gas target. A twin gridded ionization chamber was used as charged particle detector and two large area $^{147}Sm_2O_3$ samples placed back to back were employed. Absolute neutron flux was determined by a small ^{238}U fission chamber. Present cross section data are compared with existing results of evaluations and measurements.

1. Introduction

^{147}Sm is a fission product nucleus. The Q value of the $^{147}Sm(n,\alpha)^{144}Nd$ reaction is as big as 10.13 MeV. Study of this reaction is important in astrophysics, in determination of the parameters of optical model potentials and in the research of nuclear reaction mechanisms. Several experimental and theoretical works have been done for this reaction [1-6], but existing measurements are only confined in the resonance and in 14 MeV neutron energy region. In the MeV neutron energy region, however, there is no experimental data up to now mainly due to the small cross section of this reaction and low intensity of neutron flux. Thus, for the $^{147}Sm(n,\alpha)^{144}Nd$ reaction cross section very large discrepancies exist among different evaluated data libraries such as ENDF/B-VII, ENDF/B-VI, JENDL-3.3 and JEFF3.1.

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Since the cross section of the $^{147}Sm(n,\alpha)^{144}Nd$ reaction is small in the MeV neutron energy range and the sample should be thin enough to allow alpha particles to escape without too much straggling, it is necessary to use relatively large area samples for measurement. Furthermore, charged particle detector with large detection solid angle and high detection efficiency should be employed. By using a twin gridded ionization chamber and two large area $^{147}Sm_2O_3$ samples, cross sections of the $^{147}Sm(n,\alpha)^{144}Nd$ reaction were measured at $E_n = 5.0$ and 6.0 MeV in the present work.

2. Details of experiment

The experiment was performed at the 4.5 MV Van de Graaff accelerator of Peking University. The setup of our experiment is shown in Fig. 1 which mainly consists of three parts: neutron source, neutron flux detector and charged particle detector.

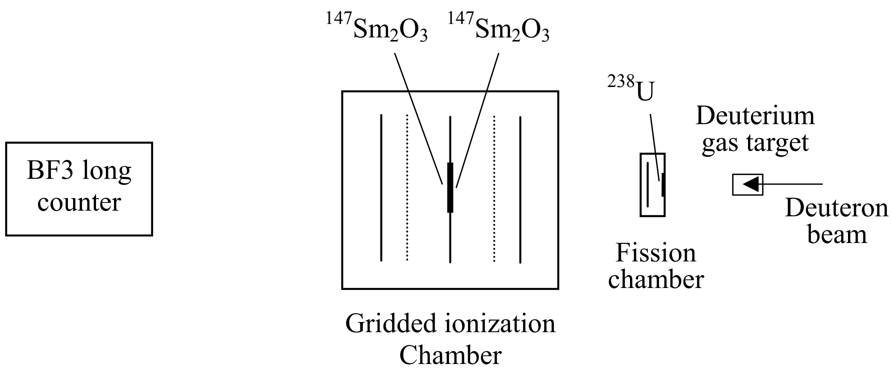

Fig. 1. Setup of the experiment.

In the present experiment, quasi-monoenergetic neutrons were produced through the $D(d,n)^3He$ reaction with a deuterium gas target. The length of the gas cell is 2.0 cm and it was separated from the vacuum tube by a molybdenum foil 5.0 μm in thickness. The pressure of the deuterium gas was 3.0 to 2.9 atm during experiment. The energies of the deuteron beam after accelerating before entering the molybdenum foil were 2.46 and 3.26 MeV. By Monte Carlo simulation the corresponding neutron energies were 5.0 and 6.0 MeV, with neutron spread 0.16 and 0.12 MeV, respectively.

A BF_3 long counter was used as the neutron flux monitor. The axis of the long counter was set along the beam line, and from the front side of the BF_3 long counter to the gas target was about 3.0 m. The absolute neutron flux was determined through a small parallel plate ^{238}U fission chamber with flowing Ar+3.73%CO_2 (a little more than 1.0 atm) as working gas. The abundance of the ^{238}U sample is 99.997%. The diameter of the round-shaped ^{238}U sample is 2.0 cm, and the weight is 547.2 (1 ± 1.3%) μg. The ^{238}U sample was placed perpendicularly to the beam line, and the center of the sample was at 0° to the beam line. The distance from the ^{238}U sample to the center of the gas target was 3.4 cm.

A twin gridded ionization chamber was used as the charged particle detector. It is composed of two symmetry sections with a common cathode. The cylindrical-shaped chamber is made from aluminum and the thickness of the wall is 2.0 mm. The diameter and height of the chamber are 37.0 and 29.0 cm, respectively. The shape of the electrodes (one cathode, two grids and two anodes) is rectangle. The center of the cathode was at 0° to the beam line, and the electrodes were perpendicular to the beam line. Two round-shaped $^{147}Sm_2O_3$ samples with aluminum backings were set back to back on the common cathode. Thus, the alpha events were measured almost the entire 4π solid angle.

The abundance of the enriched ^{147}Sm isotope in the sample was 95.3%. The thickness and diameter of each sample were 5.0 mg/cm^2 and 11.0 cm, and the thickness of each aluminum backing was 1.0 mm. The distances from the cathode to grid and from grid to anode of the twin gridded ionization chamber were 7.5 and 2.0 cm, respectively. The distance from the cathode to the center of the gas target was 35.0 cm. The working gas of the gridded ionization chamber was Kr + 2.27% CO_2, and the gas pressure was 2.20 atm. High voltages applied to the cathode, grid and anode were -3400, 0 and +1700 V, respectively.

There were two removable compound alpha sources in the gridded ionization chamber for energy calibration and for adjustment and checking of the electronics system.

Block diagrams of electronics for alpha events measurement is shown in Fig. 2. Forward (0°~90°) and backward (90°~180°) direction alpha events were recorded simultaneously, and the cathode-anode two-dimensional spectra were obtained for forward and backward events, respectively.

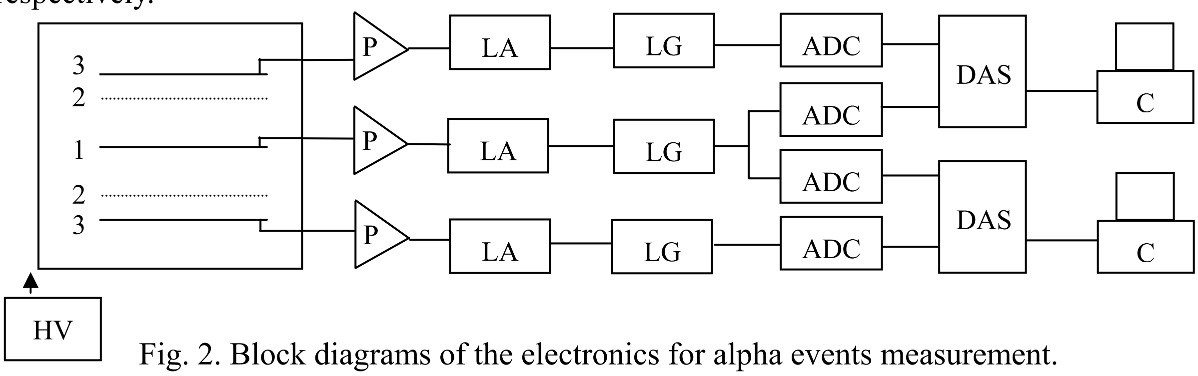

Fig. 2. Block diagrams of the electronics for alpha events measurement.
1-Cathode, 2-Grid, 3-Anode,
HV-High Voltage Divider, PA-Preamplifier, LA-Linear Amplifier, LG-Linear Gate Stretcher, ADC-Analog-to-digital Converter, DAS-Data Acquisition System, C-Computer

The number of forward and backward alpha events can be obtained from the cathode-anode two-dimensional spectra. During experiment, the anode spectra of the ^{238}U fission chamber were also recorded from which the number of the fission fragments can be derived.

The cross section of the ^{147}Sm(n,α)^{144}Nd reaction can be calculated from the following formula:

$$\sigma_\alpha = K\sigma_f \frac{N_\alpha}{N_f}\frac{N_{238U}}{N_{147Sm}} \tag{1}$$

where σ_α denote the cross section to be measured; σ_f is the ^{238}U(n,f) standard cross section at the same neutron energy taken from ENDF/B-VII library; N_α and N_f are numbers of the alpha events from ^{147}Sm(n,α)^{144}Nd reaction and fission fragments from ^{238}U(n,f) reaction, respectively; N_{238U} and N_{147Sm} are the atom numbers of ^{238}U and ^{147}Sm in the samples, respectively; and K is the neutron flux density ratio on ^{238}U and $^{147}Sm_2O_3$ samples which can be calculated by using Monte Carlo method according to the dimensions and positions of the samples and the gas target as well as the angular distribution of the $D(d,n)^3He$ reaction. For E_n = 5.0 and 6.0 MeV, the calculated values of *K* are 94.4 and 92.5 with relative uncertainty 3%, respectively.

The deuteron beam intensity was about 2.5 μA during experiment. For E_n = 5.0 and 6.0 MeV measurement, the beam time were about 28 and 22 h, respectively.

3. Results and discussions

Fig. 3 is the forward direction cathode-anode two-dimensional spectrum for 6.0 MeV measurement.

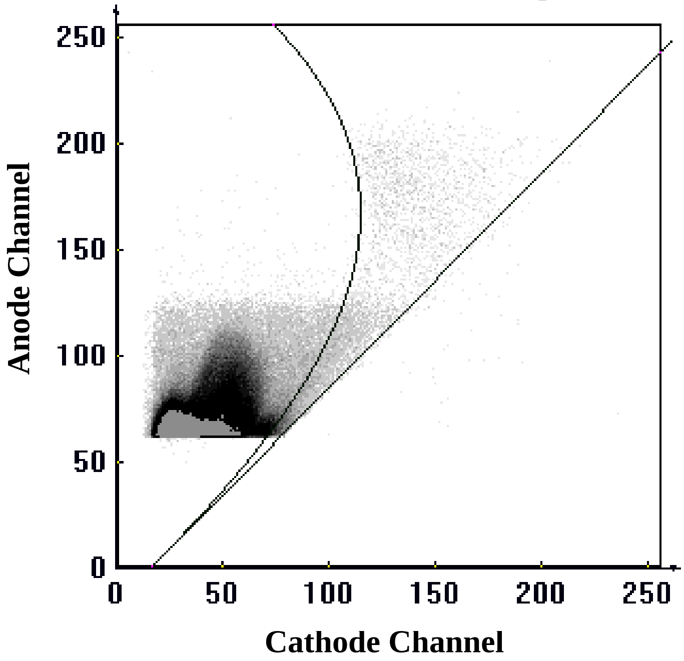

Fig.3. Two-dimensional spectrum of forward events at E_n=6.0 MeV.

One can see from Fig.3 that the counts corresponding to higher anode channels between the 0° line and the 90° line [7] are alpha events from the $^{147}Sm(n,\alpha)^{144}Nd$ reaction. Those for lower anode channels distributed from 90° line to very low cathode channels are alpha events from working gas through (n,α) reaction. Apparently, the number of alpha events from the $^{147}Sm(n,\alpha)^{144}Nd$ reaction is much less than that from the working gas.

From the two-dimensional spectrum, one can get the anode spectrum of the alpha events between the 0° and the 90° lines, as shown in Fig. 4. The counts corresponding to higher anode channels are alpha events from the $^{147}Sm(n,\alpha)^{144}Nd$ reaction. According to the fact that the two-dimensional spectrum of alpha events from the working gas is uniformly distributed along the cathode channel in Fig.3, the background from the working gas between 0° and 90° lines can be estimated by counting the equivalent region at the left side of the 90° line as the dash line shown in Fig.4. Then the number of alpha events with higher channels $N_{\alpha 1}$ (≥130 channel in Fig.4) can be obtained after background subtraction. Because of Coulomb barrier effect, higher energy alpha particles corresponding to the ground state and low energy excited states of ^{144}Nd are dominant, and those corresponding to higher excited states (lower energy alpha particles) should be much less.

In addition to the higher channel part, the anode spectrum of the measured alpha particles should go continuously to lower channels until zero channel due to energy loss inside the sample although the number of low energy alpha particles is not many for the present experiment. Besides, since the $^{147}Sm_2O_3$ sample is 5.0 mg/cm^2 in thickness, some alpha particles can't go out and will be absorbed by the sample.

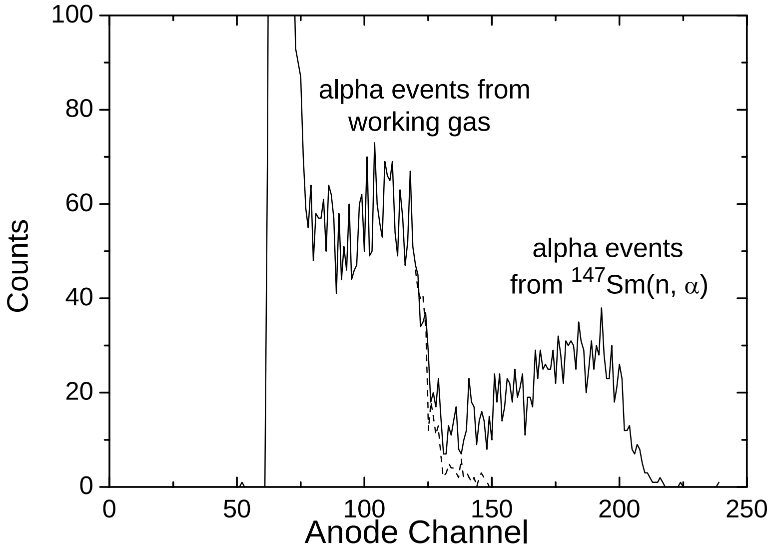

Fig. 4. Anode spectrum of forward events at E_n=6.0 MeV between 0° line and 90° line.

The ratio of the lower channel part together with the self absorption part of alpha particles over total alphas R_1 can be estimated by Monte Carlo method. According to alpha stopping power in the sample, the measured ratio of forward/backward alpha events, and the fact that alpha particles corresponding to the ground state of ^{144}Nd are dominant, the ratios of lower channel part plus the self absorption part over total alphas were calculated. At E_n = 5.0 MeV, the ratios are 6.6% and 9.7% for forward and backward alphas, respectively; and at En = 6.0 MeV, the ratios are 5.3% and 10.6% for forward and backward alphas. Error of the calculated ratio R_1 is about 25%.

Total number of alpha events from the ^{147}Sm(n, α) ^{144}Nd reaction N_α was obtained according to the measured alpha number $N_{\alpha 1}$ and the calculated ratio R_1 :

$$N_\alpha = N_{\alpha 1}/(1-R_1) \tag{2}$$

Error of $N_{\alpha 1}$ comes from statistics (2.5~5%) and uncertainty of background subtraction (3.5~5%). Total error of N_α is 5.5~8.5 %.

The number of fission fragments N_f was derived from the anode spectrum of the ^{238}U fission chamber. Fig. 5 is the anode spectrum of the fission chamber at 5.0 MeV.

Forward and backward cross section data can be calculated from equation (1). In addition, the forward/backward cross section ratio can be calculated. According to equation (1) the forward/backward cross section ratio equals the forward/backward alpha events ratio. Results of cross section data (forward plus backward) and forward/backward ratios in the laboratory reference system for the ^{147}Sm(n,α)^{144}Nd reaction are listed in Table. 1. Error of the cross section comes from the uncertainties of the alpha event N_α (5.5~8.5%), fission count N_f (2.5%), ^{238}U and $^{147}Sm_2O_3$ neutron flux density ratio K (3%), ^{238}U fission cross section (1%), the atom number of ^{147}Sm (1.5%) and ^{238}U (1.3%). Total error is about 10%.

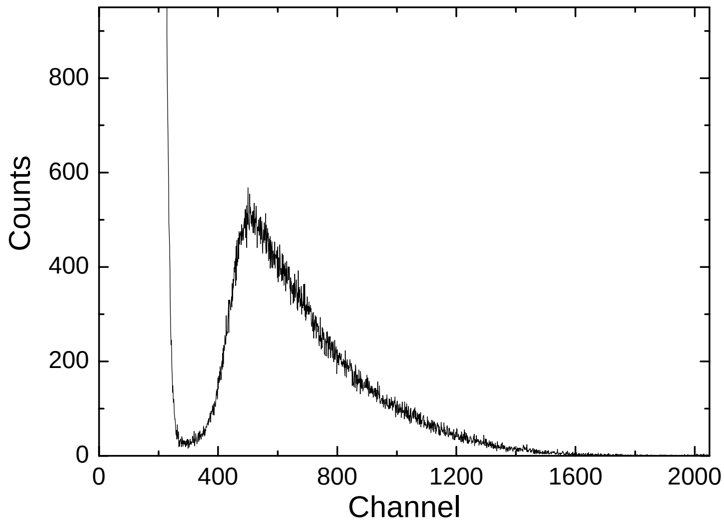

Fig. 5. The anode spectrum of the ^{238}U fission chamber at 5.0 MeV.

During data processing, corrections from the neutron flux attenuation through the 2-mm-thick aluminum wall of the chamber and through the 2-mm-thick aluminum backing of the two samples were carried out. According to the total neutron cross section data of aluminum taken from ENFD/B-VII, the correction factor from attenuation for 5.0 and 6.0 MeV neutrons through 2-mm-thick aluminum are 0.972 and 0.975, respectively.

Table 1: Cross sections of the ^{147}Sm(n,α)^{144}Nd reaction and forward/backward ratios in the laboratory reference system.

E_n / MeV	$\sigma_{n\alpha}$ / mb	forward/backward ratio
5.0 ± 0.16	0.23 (1 ± 10 %)	1.65 (1 ± 10 %)
6.0 ± 0.12	0.28 (1 ± 10 %)	2.54 (1 ± 10 %)

Present results of cross section are compared with existing evaluations and experiments in Fig. 6. Cross section data at 12.1, 14.1 and 18.2 MeV were obtained via integration of differential cross section data of Glowacka et al. [4].

As can be seen from Fig. 6 very large discrepancies exist among different evaluations, especially in the MeV neutron energy region. Our results are in agreement with the evaluation of ENDF/B-VII if the linear-logarithmic interpolation instead of linear-linear is applied from 0.45 to 7.0 MeV. This work is the first one to measure cross section of the ^{147}Sm(n,α)^{144}Nd reaction in the MeV neutron energy region and our results are very useful in determining the threshold behavior of the ^{147}Sm(n,α)^{144}Nd reaction. The forward/backward ratios of the ^{147}Sm(n,α) reaction are as large as 1.65 and 2.54 at 5.0 and 6.0 MeV which is an indication of direct reaction mechanism.

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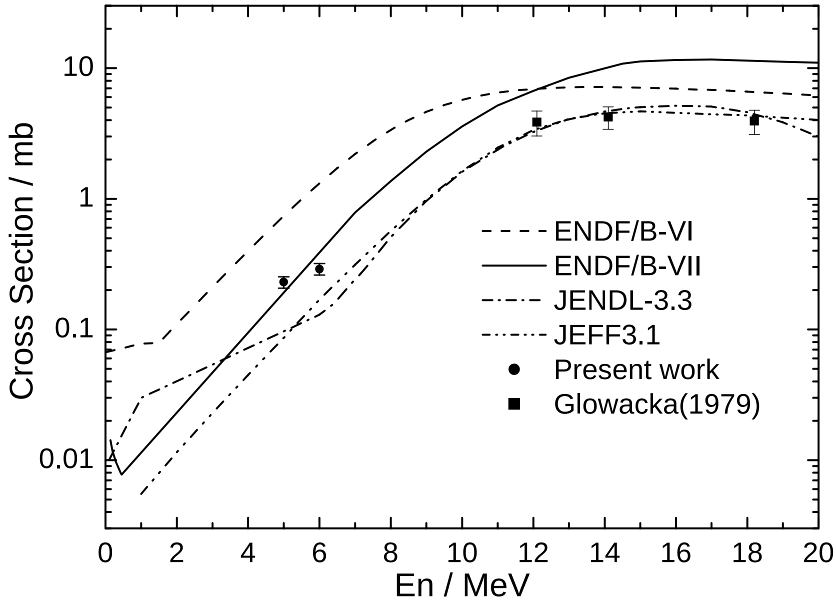

Fig. 6. Present cross sections compared with existing evaluations and experimental data.

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