Cross section measurement for the ^{95}Mo(n, α)^{92}Zr reaction at 4.0, 5.0 and 6.0 MeV

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Abstract: For the ^{95}Mo(n, α)^{92}Zr reaction cross section, there is only one experimental datum in the MeV neutron energy region with large uncertainty. As a result, very large deviations exist in different evaluated nuclear data libraries. This paper report the measurement of cross sections of the ^{95}Mo(n, α)^{92}Zr reaction at En = 4.0, 5.0 and 6.0 MeV. Experiments were performed at the 4.5 MV Van de Graaff of Peking University, China. A twin gridded ionization chamber was used as alpha particle detector and two large area ^{95}Mo samples placed back to back were adopted. Fast neutrons were produced through the D(d, n)^{3}He reaction by using a deuterium gas target. A small ^{238}U fission chamber was adopted for absolute neutron flux determination and a BF_3 long counter was used for neutron flux monitor. Present experimental data are compared with existing evaluations and measurement.

1. Introduction

Cross section data for fast neutron induced charged particle emission reactions are important in the research of nuclear reaction mechanisms and in the determination of parameters of optical model potentials as well as in the application of nuclear engineering. The Q value of the ^{95}Mo(n, α)^{92}Zr reaction is 6.39 MeV. Several works have been performed for this reaction cross section [1,2,6], but almost all measurements exist in the thermal and resonance regions. In the MeV neutron energy region, however, there is only one datum at E_n = 3.0 MeV with large uncertainty [7]. As a result, there are very large deviations among different evaluated nuclear data libraries such as ENDF/B-VII, JEFF3.1, JEFF3.1/A and JENDL3.3 (ENDF, 2008). For example, at E_n = 5.0 MeV, the cross section data of the ^{95}Mo(n, α)^{92}Zr reaction are 0.72, 0.40, 1.0 and 5.7 mb in the above mentioned four data libraries, respectively. To clarify the discrepancies, cross section measurement in the MeV neutron energy region is demanded for this reaction.

In the present work, a twin gridded ionization chamber was used as alpha particle detector. Two large area ^{95}Mo metal samples placed back to back were employed. The detection efficiency and solid angle of the twin gridded ionization chamber are nearly 100% and 4π, respecively. Cross sections for the ^{95}Mo(n, α)^{92}Zr reaction as well as forward/backward ratios for the emitted α particles in the laboratory system were measured at E_n=4.0, 5.0 and 6.0 MeV.

2. Experiment

Experiments were performed at the 4.5 MV Van de Graaff of Peking University, China. The setup of experiment, block diagrams of the electronics, construction of the twin gridded ionization chamber and the details of the arrangement are represented in previous article represented at the ISINN-17 [8].

A mixture of Kr + 2.89% CO_2 was used as working gas for the ionization chamber. A gas pressure of 1.35 atm was used during measurement to ensure α particles from the ^{95}Mo(n, α)^{92}Zr reaction were stopped before reaching the grids. The high voltages for the cathode, grid and anode were -2400, 0 and 1200 V for complete collection of the electrons.

The sample material is metal molybdenum with ^{95}Mo atomic percentage 96.8%. The two samples are back to back attached to the common cathode of the gridded ionization chamber. The thicknesses and diameter for each sample are 5.0 mg/cm^2 and 11.0 cm, respectively. The backings of the samples are aluminum sheets 0.005 inch in thickness.

For background measurement, the molybdenum samples were replaced by an aluminum sheet 0.005 inch in thickness. The position and the condition of the gridded ionization chamber as well as the electronics were the same as for the foreground measurement.

The intensity of the deuteron beam was about 4.0 μA during measurement. For foreground measurement, durations for E_n = 4.0, 5.0 and 6.0 MeV measurement were about 8, 4 and 3 h, respectively; and for background measurement, they were 6, 3 and 2.5 h, respectively.

The following formula is adopted for cross section calculation:

$$\sigma_\alpha = K\sigma_f \frac{N_\alpha}{N_f} \frac{N_{238U}}{N_{95Mo}} \qquad (1)$$

where σ_α is the cross section to be measured; σ_f is the ^{238}U(n, f) cross section taken from ENDF/B-VII library at the same neutron energy point; N_α and N_f are numbers of the alpha events from the ^{95}Mo(n, α)^{92}Zr reaction and the fission fragments from the ^{238}U(n, f) reaction, respectively; N_{238U} and N_{95Mo} are the atom numbers of ^{238}U and ^{95}Mo in the samples, respectively. K is the neutron flux density ratio on ^{238}U and ^{95}Mo samples which can be calculated numerically according to the dimensions and positions of the samples with respect to the gas target as well as the angular distribution of the D(d, n)^{3}He reaction. The expression of K is as follows:

$$K = \frac{\int_{-l/2}^{l/2} \int_0^{tg^{-1}\frac{d_1+x}{r_1}} 2\pi \sin\theta f(\theta) d\theta dx}{\int_{-l/2}^{l/2} \int_0^{tg^{-1}\frac{d_2+x}{r_2}} 2\pi \sin\theta f(\theta) d\theta dx} \cdot \frac{\pi r_2^2}{\pi r_1^2} \qquad (2)$$

where l is the length of the deuterium target gas cell; r_1 and r_2 are the radius of the ^{238}U and ^{95}Mo samples, respectively; d_1 and d_2 are the distances from the center of the deuterium gas cell to the ^{238}U and to the ^{95}Mo samples, respectively; and $f(\theta)$ is the angular distribution of neutrons from the D(d, n)^{3}He reaction. In our experiment, r_1=1.0 cm, r_2= 5.5 cm, d_1=3.45 cm, d_2=35.5 cm. The calculated values of K are 101.8, 96.9 and 92.8 for E_n = 4.0, 5.0 and 6.0 MeV, respectively, with relative uncertainty 3%. This uncertainty is mainly from the relative uncertainty of d_1.

3. Results and discussions

Fig.1 show the forward direction cathode-anode two-dimensional spectrum for the $^{95}Mo(n, \alpha)^{92}Zr$ measurement at E_n=6.0 MeV. The area between 0° and 90° curves [5] with higher anode channels corresponds to the allowed region for α events from the $^{95}Mo(n, \alpha)^{92}Zr$ reaction. At lower anode channels, background from α events in the working gas obscures the signal of interest. According to Fig.1 one can get anode spectrum of alpha events between 0° and 90° lines as shown in Fig. 2. After background subtraction, the measured number of alpha events from the $^{95}Mo(n, \alpha)^{92}Zr$ reaction is obtained, denoted by $N_{\alpha det}$.

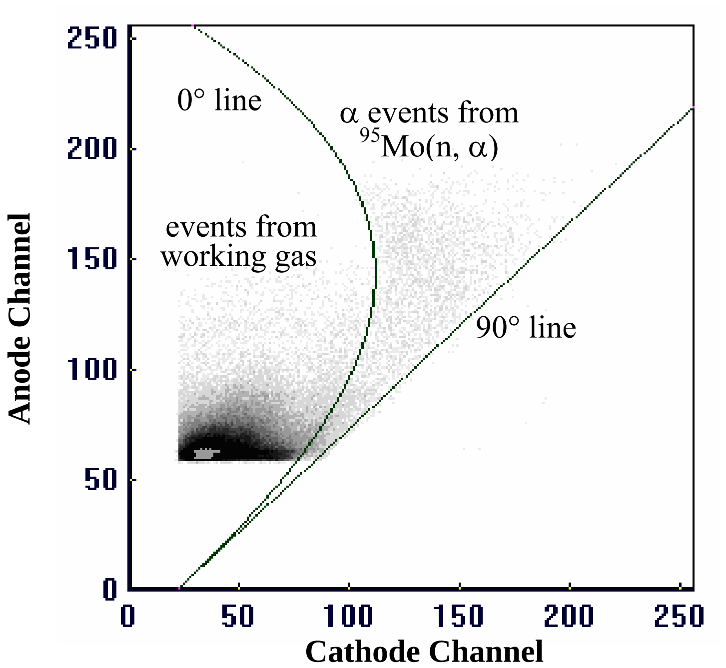

Fig. 1. Cathode-anode two-dimensional spectrum of forward events at E_n = 6.0 MeV.

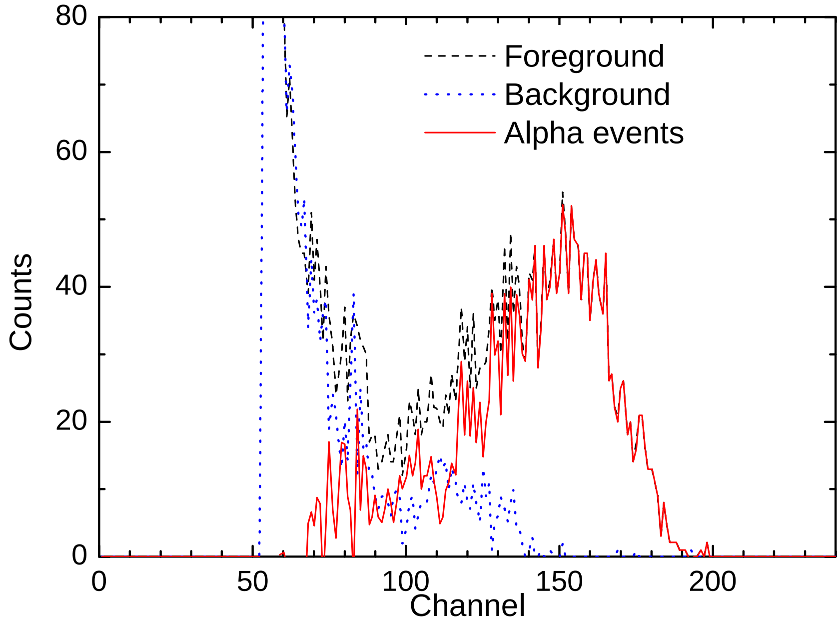

Fig. 2. Anode spectrum of forward events at E_n = 6.0 MeV between 0° line and 90° line.

$N_{\alpha\det}$ is less than N_α in formula (1) because some α events from the ^{95}Mo(n, α)^{92}Zr reaction are below threshold, and in addition a part of α particles absorbed by the investigated sample. The relationship between N_α and $N_{\alpha\det}$ can be expressed as:

$$N_\alpha = \frac{N_{\alpha\det}}{1-R} \quad (3)$$

where R is the ratio of the lower channel alphas plus self absorption alphas from ^{95}Mo(n, α)^{92}Zr reactions over total alpha events. Values of R were estimated by Monte-Carlo simulation of α straggling in the sample. In estimating R, isotropic emission of α particles from ^{95}Mo(n, α)^{92}Zr reaction is assumed and α energies corresponding to emission to the ground state of the residual nucleus ^{92}Zr was used. Because higher energy α particles corresponding to emission to the ground state and low energy excited states of ^{92}Zr are dominate due to Coulomb barrier effect. For our measurement conditions, the estimated R value is around 20%, depending on forward or backward direction, and on the incident neutron energy. The uncertainty of R is about 25%. Sources of uncertainties of $N_{\alpha\det}$ include statistics (2.1–2.8%) and background subtraction (4–5%). Accordingly, relative uncertainty of N_α is (6.5–10%).

Fig. 3 is the anode spectrum of the small fission chamber at 6.0 MeV from which the number of fission counts N_f was obtained.

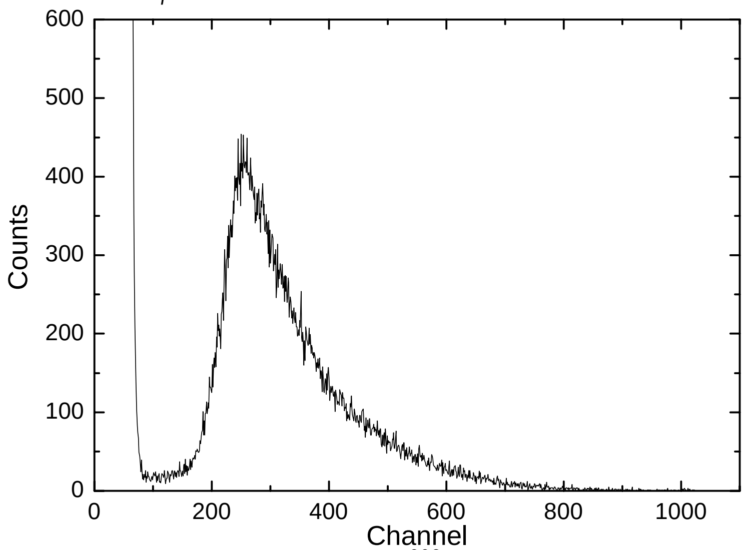

Fig. 3. Anode spectrum of the small ^{238}U fission chamber at E_n = 6.0 MeV.

The forward and backward cross sections were calculated separately using equation (1), and then were added up to obtain total (n, α) cross section. According to equation (1) the forward/backward cross section ratio equals the forward/backward alpha events ratio.

Two corrections are performed during data processing. The correction from the neutron flux attenuation through the 2-mm-thick aluminum wall of the chamber was carried out. According to the total neutron cross section data of aluminum taken from ENFD/B-VII, the correction factor for attenuation of 4.0, 5.0 and 6.0 MeV neutrons through 2-mm-thick aluminum are 0.971, 0.972 and 0.975, respectively. There is small difference for the average neutron energy through the ^{95}Mo samples and through the ^{238}U sample; this is also considered when using the standard ^{238}U(n, f) cross sections from ENDF/B-VII library.

Table 1 shows the results of cross sections and forward/backward ratios in the laboratory reference system for the ^{95}Mo(n, α)^{92}Zr reaction. The main source of uncertainty of the cross sections comes from the uncertainties of the alpha event N_α (6.5–10%) as described above. Other uncertainty sources include fission count N_f (2%), ^{238}U and $^{147}Sm_2O_3$ neutron flux density ratio K (3%), ^{238}U fission cross section (1%), and atom number of ^{95}Mo (1.5%) and ^{238}U (1.3%). Total uncertainty of cross section is about 10%.

Table 1. Cross section data and forward/backward ratios in the laboratory reference system for the ^{95}Mo(n, α)^{92}Zr reaction.

En (MeV)	$\sigma_{n,\alpha}$ (mb)	Forward/backward ratio
4.0 ± 0.23	0.70 ± 0.07	1.10 ± 0.14
5.0 ± 0.16	1.2 ± 0.12	1.24 ± 0.14
6.0 ± 0.12	1.6 ± 0.16	1.37 ± 0.14

In Fig. 6 present cross sections are compared with existing evaluations and measurement. From Fig. 6 one can see very large discrepancies among different evaluations in the MeV neutron energy region. Szarka's value is somewhat lower than the present results. Further measurements near 3.0 MeV and 14 MeV are needed. Our results are consistent with JEFF3.1/A evaluation and they are important in deciding the uptrend and the magnitude of the ^{95}Mo(n, α)^{92}Zr reaction cross sections in the MeV region.

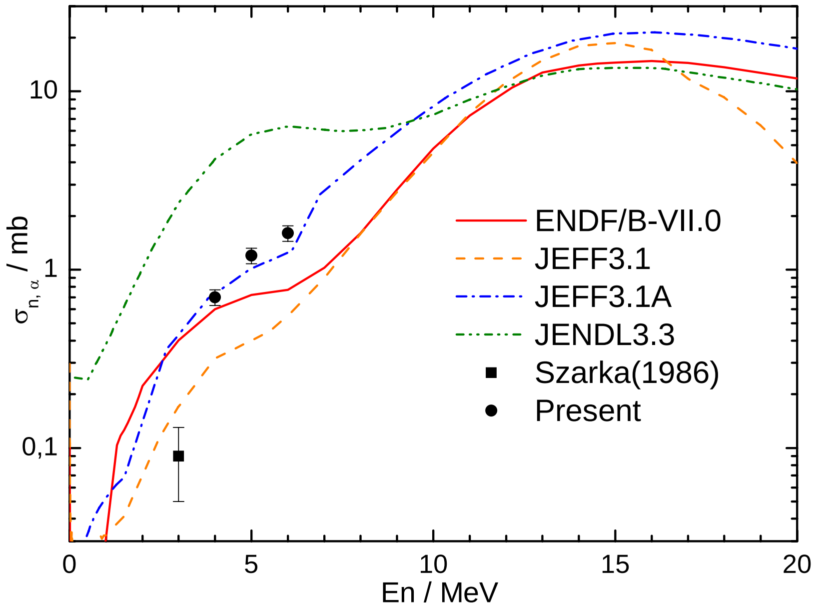

Fig. 6. Present cross sections compared with existing evaluations and measurements.

Acknowledgements

This work is financially supported by the National Natural Science Foundation of China (10875006, 10811120014), China nuclear Data Center and the Russian Foundation for Basic Research (RFBR-NSFC 07-02-92104). Authors are indebted to Prof. Jianyong Wang, Ms. Jianhua Gong and Mr. Xiangjun Yang for their kind help in operating on the 4.5 MV Van de Graaff accelerator of Peking University.

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