MEASUREMENTS OF THE ^{64}Zn AND ^{67}Zn (n,α) REACTIONS CROSS SECTIONS IN THE MeV NEUTRON ENERGY REGION

Y. M. Gledenov[1], M. V. Sedysheva[1], Guohui Zhang[2], Jiaguo Zhang[2], Hao Wu[2], Jiaming Liu[2], Jinxiang Chen[2], G. Khuukhenkhuu[3], P. J. Szalanski[4]

[1] *Frank Laboratory of Neutron Physics, JINR, Dubna, 141980, Russia*
[2] *State Key Laboratory of Nuclear Physics and Technology, Institute of Heavy Ion Physics, Peking University, Beijing 100871, China*
[3] *Nuclear Research Centre, National University of Mongolia, Ulaanbaatar, Mongolia*
[4] *University of Lodz, Institute of Physics, Poland*

1. INTRODUCTION

Nuclear reactions of ^{64}Zn(n,α)^{61}Ni and ^{67}Zn(n,α)^{64}Ni are important because they are gas production reactions and zinc is a reactor constituent element with a significant fraction. The isotopic abundances of the ^{64}Zn and ^{67}Zn isotopes are 48.6% and 4.1%, respectively. But the experimental cross section data of these reactions are very scanty because the residual nuclei ^{61}Ni and ^{64}Ni are stable and the commonly used activation method is not feasible. In the MeV neutron energy region, the measurement is further limited by relatively low neutron source intensity, small cross section and strong background. Consequently, large deviations exist between different nuclear data libraries for these reactions [1]. Therefore, measurements in the MeV neutron energy region are demanded for clarifications.

In the present work, by using a twin gridded ionization chamber as alpha particle detector and back-to-back enriched isotopic samples, differential cross sections and angle-integrated cross sections were measured for the ^{64}Zn(n,α)^{61}Ni reaction at neutron energies of 2.5, 4.0, 5.0, 5.5 and 6.0 MeV and cross sections of the ^{67}Zn(n,α)^{64}Ni reaction were measured at 4.0, 5.0 and 6.0 MeV.

2. EXPERIMENT

Experiments were performed at the 4.5 MV Van de Graaff accelerator of Peking University.

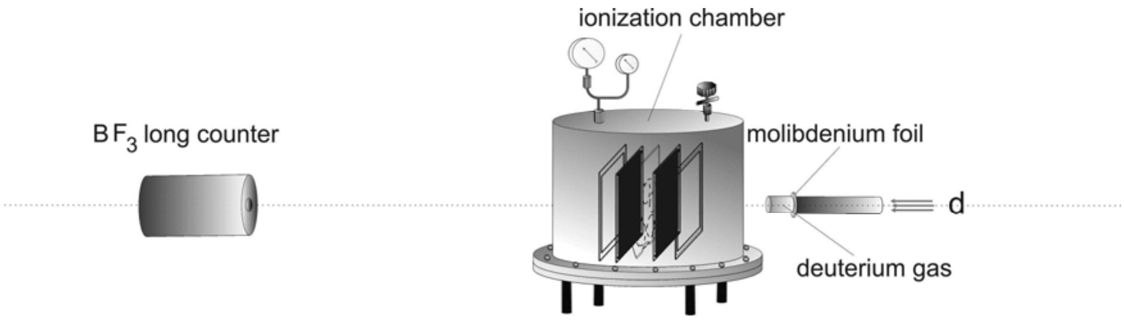

Fig. 1. Setup of the experiment

The setup of the experiment (Fig.1) includes three components, i.e. the neutron source, the neutron flux monitor and the alpha particle detector. Mono-energetic neutrons of 2.5 MeV were produced through the T(p,n)^{3}He reaction with a solid Ti-T target, and those of other energies were produced through the D(d,n)^{3}He reaction with a deuterium gas target. Absolute neutron fluxes were determined through the ^{238}U(n,f) reaction and a BF_3 long counter was used as the neutron flux monitor. The axis of the BF_3 long counter and the normal line of the electrodes of the gridded ionization chamber were at 0° to the beam line.

The alpha particle detector is a twin gridded ionization chamber with symmetric sections. The detected solid angle is nearly 4π and the detection efficiency for charged particle is almost 100%. The shape of the chamber is a vertical cylinder, 28.2 cm in diameter and 27.2 mm in height made of stainless steel. Electrodes of the chamber include one common cathode, double grids, anodes and shields. Working gas of the ionization chamber was mixture of krypton with a few percent of CO_2 to stop the alpha particles emitted from the samples before reaching the grids. High voltages were applied to electrodes for complete collection of the electrons from the ionization.

The mass and the thickness of the ^{64}Zn and ^{67}Zn samples are listed in Table 1.

Table 1. Description of samples

	^{64}Zn		^{67}Zn	
Enrichment of isotope	99.4%		95.4%	
Sample diameter, cm	4.40		4.30	
Sample thickness, μg/cm^2	266.3[a]	266.3[b]	680[a]	470[b]
Backing	Ta sheet		Ta sheet	

[a] Forward sample
[b] Backward sample

Each sample was vacuum evaporated on a tantalum backing 4.8 cm in diameter and 50 μm in thickness. There is a sample changer attached to the common cathode of the ionization chamber with five sample positions (Fig.2). At each sample position, two samples can be back-to-back placed. Double ^{64}Zn and ^{67}Zn samples were placed at the first and second position of the sample changer, respectively. Using back-to-back double samples, forward (0-90°) and backward (90-180°) direction alpha events were measured simultaneously. With the sample changer, it is convenient to change samples without opening the chamber.

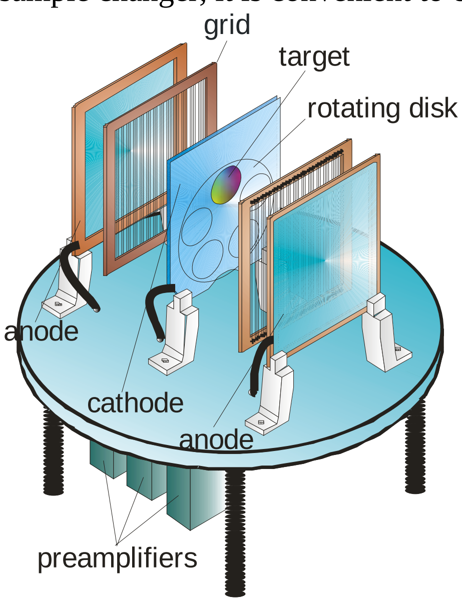

Fig. 2. Inner view of the ionization chamber

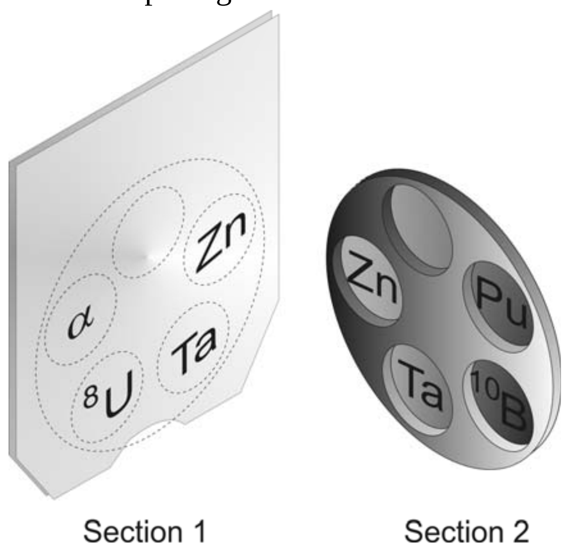

Fig. 3. Schematic view of the cathode

For background measurement (Fig. 3), two tantalum sheets 4.8 cm in diameter and 50 μm in thickness were back-to-back set at the third position of the sample changer. A ^{238}U sample (diameter 4.50 cm, mass 7.85±0.10mg, and ^{238}U enrichment 99.999%) was set at the forward direction of the fourth position for absolute neutron flux measurement. Two compound alpha sources were placed at the last position of the sample changer for energy calibration of electronics system and for the 90° line [2] determination.

At each neutron energy point, the compound alpha sources were measured for energy calibration. Cathode-anode coincident events were recorded for both forward and backward direction. After background subtraction, alpha events with different energies and directions with respect to the normal line of the sample were obtained from the cathode-anode two dimensional spectra of the zinc samples. Also, the number of fission fragments was derived from the anode spectrum of the ^{238}U sample. After normalization via the BF_3 counts, the cross section corresponding to one alpha count from the measured (n,α) reaction can be calculated with the following equation:

$$\sigma_{\alpha 1} = \sigma_f \frac{1}{N_f} \frac{N_{238U}}{N_{Zn}}$$

where $\sigma_{\alpha 1}$ is the cross section corresponding to one alpha count; σ_f is the standard ^{238}U fission cross section taken from the ENDF/B-VII.0 library; N_f is the numbers of the fission fragments from the ^{238}U(n,f) reaction; N_{238U} and N_{Zn} are the atom numbers of the ^{238}U and zinc isotopes in the samples, respectively.

3. RESULTS

3.1 Results of the ^{64}Zn$(n,\alpha)^{61}$Ni reaction

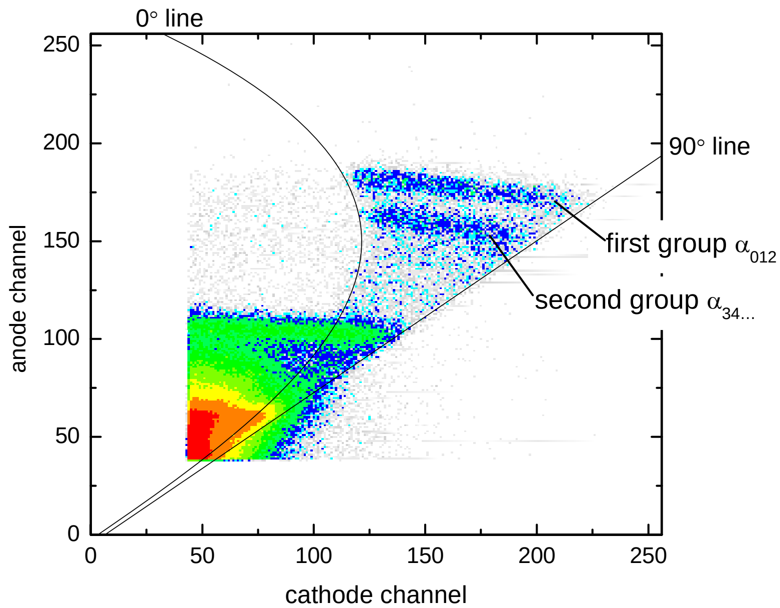

Fig. 4. Two-dimensional spectrum of forward alpha-particles, E_n = 5.50 MeV

Fig.4 is the measured cathode-anode two-dimensional alpha-particle spectrum from the ^{64}Zn$(n,\alpha)^{61}$Ni reaction in the forward direction at E_n = 5.50 MeV. Two major groups of alpha particles can be found. The first group (with higher energy) corresponds to three energy levels of the nucleus ^{61}Ni, i.e., the ground state, the first and second excited states at 67 and 283 keV. The second group corresponds to higher excited states of ^{61}Ni at 656, 909 keV, etc.

The measured differential cross sections of the ^{64}Zn(n,α_{012})^{61}Ni and ^{64}Zn($n,\alpha_{34...}$)^{61}Ni reactions (correspond to the first and the second group of alpha particles) transferred to the center of mass system are plotted in Fig. 5 [3, 4]. At 2.54 MeV, there were too few $\alpha_{34...}$ particles to obtain the differential cross sections of the ^{64}Zn($n,\alpha_{34...}$)^{61}Ni reaction, while the ^{64}Zn($n,\alpha_{34...}$)^{61}Ni reaction cross section was derived from the forward and backward $\alpha_{34...}$ counts.

One can see that the ratio of the two groups changes gradually as the neutron energy increases. Angle-integrated cross sections for each group are listed in Table 2. The uncertainty is mainly from the statistics and background subtraction. In Fig.6, present cross sections of the ^{64}Zn(n,α)^{61}Ni reaction are compared with existing data [1, 5-7].

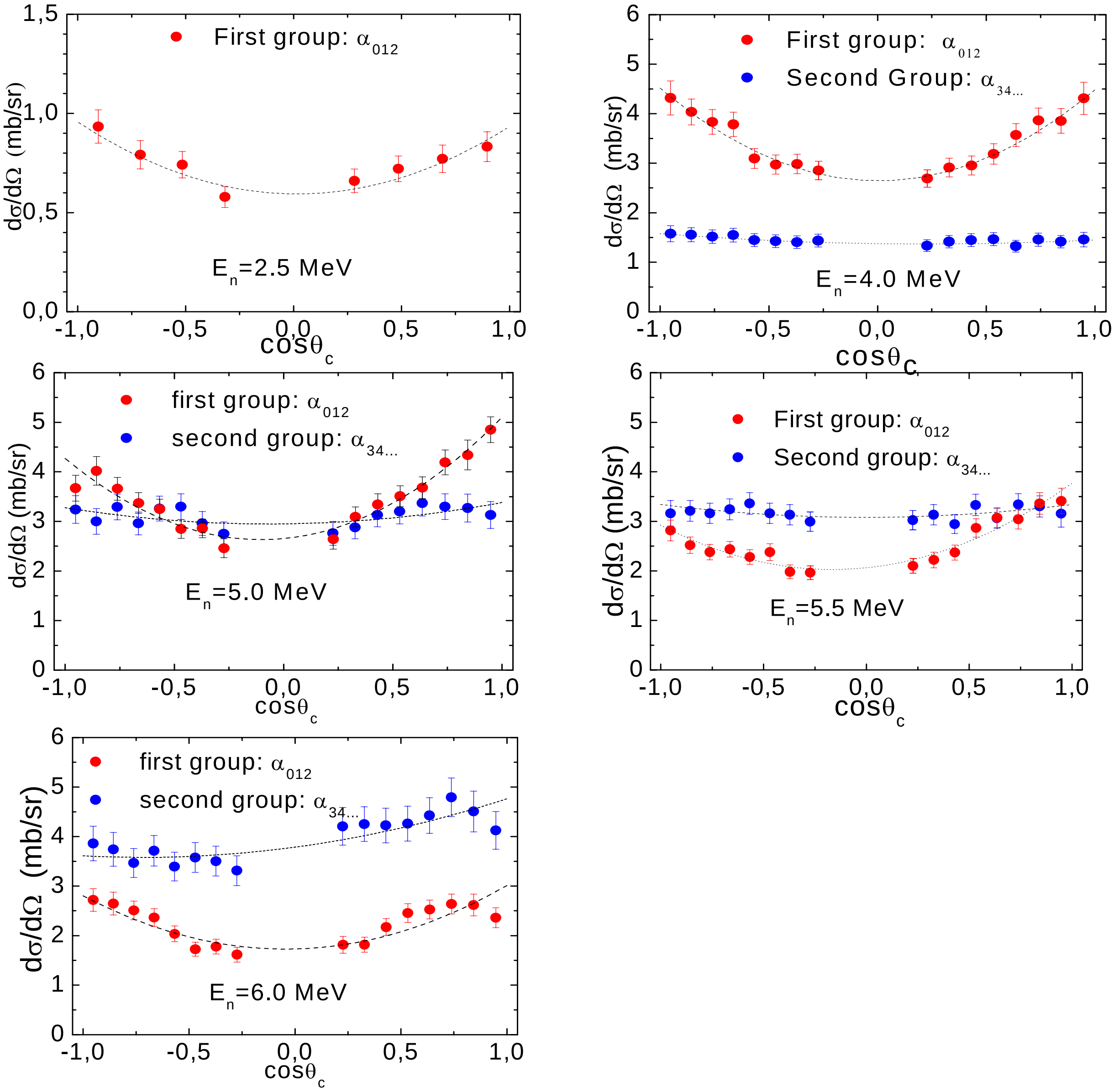

Fig. 5. Differential cross sections of the first and the second group of alpha particles for the ^{64}Zn(n,α)^{61}Ni reaction in the c.m. system

Table 2. Cross sections of the ^{64}Zn(n,α_{012})^{61}Ni, ^{64}Zn(n,$\alpha_{34...}$)^{61}Ni, and ^{64}Zn(n,α)^{61}Ni reactions

E_n (MeV)	σ (mb)		
	First group: ^{64}Zn(n,α_{012})	Second group: ^{64}Zn(n,$\alpha_{34...}$)	Total: ^{64}Zn(n,α)
2.5	9.1 ± 0.9	2.7 ± 1.4	11.8 ± 1.1
4.0	41.5 ± 3.3	18.1 ± 1.4	59.6 ± 3.6
5.0	41.3 ± 2.5	37.8 ± 2.8	79.1 ± 5.3
5.5	31.0 ± 2.5	39.5 ± 3.1	70.5 ± 4.0
6.0	26.5 ± 1.7	49.3 ± 3.8	75.8 ± 5.5

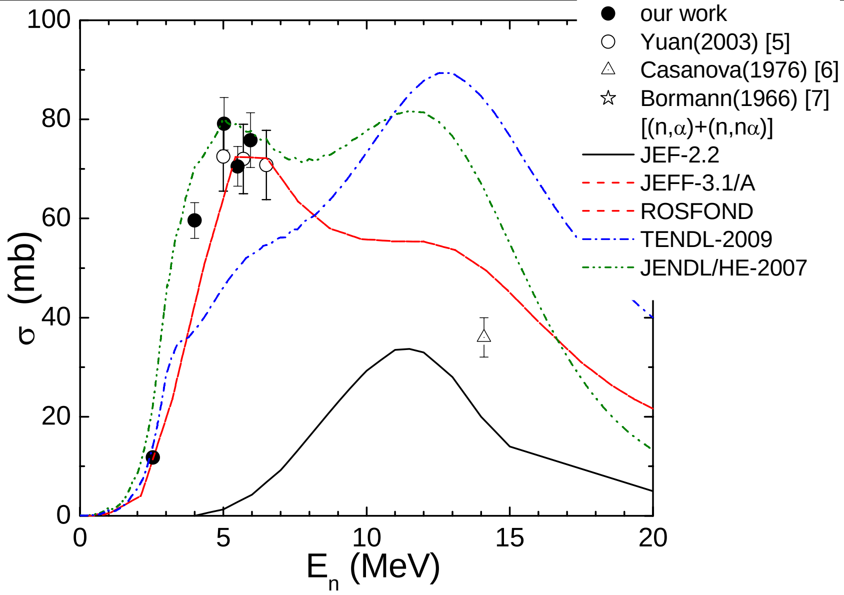

Fig. 6. Present cross sections of the ^{64}Zn(*n, α*)^{61}Ni reaction compared with existing data

3.2 Results of the ^{67}Zn(*n, α*)^{64}Ni reaction

The cathode-anode two-dimensional alpha-particle spectrum from the ^{67}Zn(*n, α*)^{64}Ni reaction is similar to that from the ^{64}Zn(*n, α*)^{61}Ni reaction, but the alpha counts are fewer because of the small reaction cross section. In fact, the alpha counts are too few to get differential cross sections even with longer measurement durations. The cross section data were obtained from alpha counts emitted at forward and backward directions. The anode spectrum of alpha events between the 0° and 90° lines [2] projected from the two-dimensional spectrum is shown in Fig. 7 for forward ^{67}Zn(*n, α*)^{64}Ni reaction measurement at En = 4.0 MeV, from which α_0 counts (corresponding to the ground state of the ^{64}Ni nucleus) are well separated. Total (*n, α*) cross sections and (*n, α_0*) cross sections were measured. Forward and backward cross sections were obtained separately and then added. Cross section data of ^{67}Zn(*n, α_0*)^{64}Ni and ^{67}Zn(*n, α*)^{64}Ni reactions are listed in Table 3. In Fig. 8, present cross sections of the ^{67}Zn(*n, α*)^{64}Ni reaction are compared with previous measurement and evaluations [1, 8]. As shown in Fig. 8, very large deviations exist between different data libraries and the present data agree well with our previous measurement at 6.0 MeV [8].

Comparing Figs.4 and 6 (or Tables 2 and 3), one can find that the cross sections of the ^{67}Zn(*n, α*)^{64}Ni reaction are only about one tenth of the ^{64}Zn(*n, α*)^{61}Ni reaction near 5.0 MeV due to the isotopic effect.

Table 3. Cross sections of the $^{67}Zn(n,\alpha_0)^{64}Ni$ and $^{67}Zn(n,\alpha)^{64}Ni$ reactions

En(MeV)	σ (mb)	
	$^{67}Zn(n,\alpha_0)$	$^{67}Zn(n,\alpha)^{64}Ni$
4.0	2.0 ± 0.2	7.4 ± 0.9
5.0	1.4 ± 0.1	7.6 ± 0.9
6.0	0.81 ± 0.1	8.1 ± 0.9

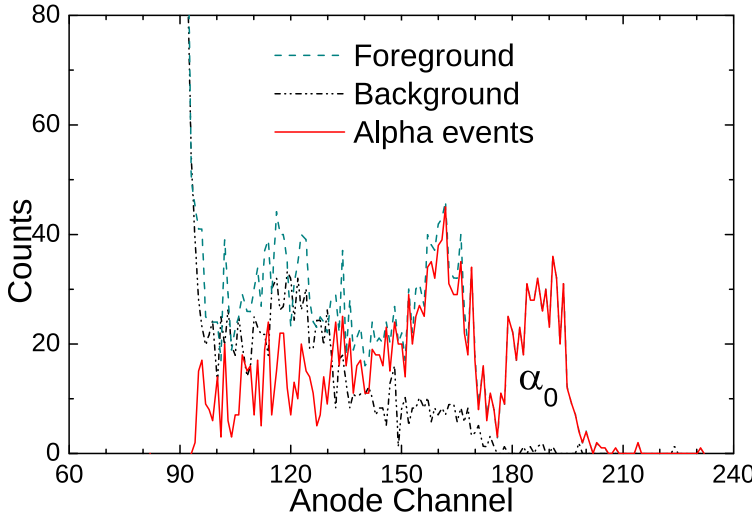

Fig. 7. The anode spectrum for forward $^{67}Zn(n,\alpha)^{64}Ni$ reaction measurement at E_n=4.0 MeV

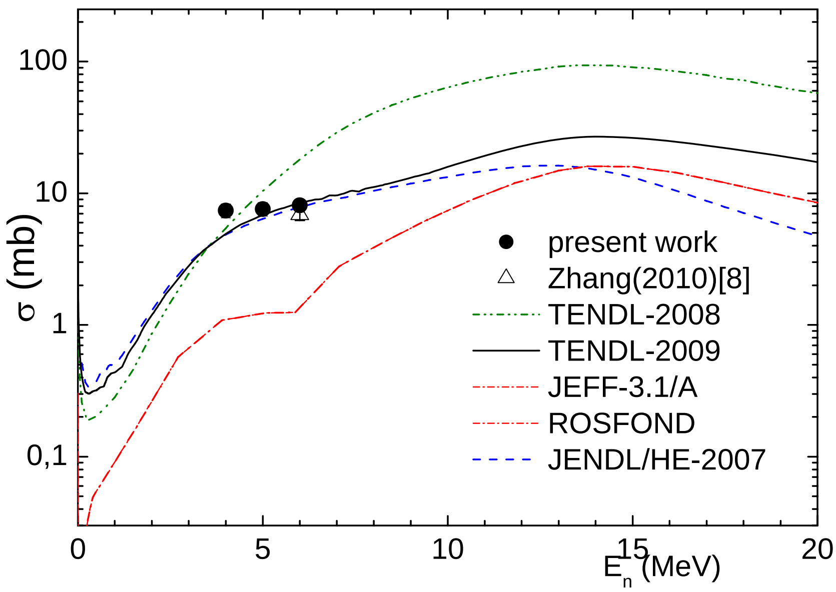

Fig. 8. Present cross sections of the $^{67}Zn(n,\alpha)^{64}Ni$ reaction compared with existing data

4. ACKNOWLEDGMENTS

The authors sincerely thank the operation staff of the 4.5 MV Van de Graaff accelerator of Peking University for kind help. This work was supported by the Russian Foundation for Basic Research (RFBR-NSFC 07-02-92104) and the National Natural Science Foundation of China (10875006), China nuclear Data Center.

5. REFERENCES

1. Evaluated Nuclear Data File (ENDF) Database Version of February 23 2010 http://www-nds.iaea.org/exfor/endf.htm.
2. N. Ito, M. Baba, S. Matsuyama, et al., "Large solid angle spectrometer for the measurements of differential (n,charged-particle) cross sections," *Nucl. Instrum. Methods A*, 337, 474 (1994).
3. G. Zhang, R. Cao, J. Chen, et al., "Differential Cross-Section Measurement for the ^{64}Zn(n,α)^{61}Ni Reaction at 5.03 and 5.95 MeV," *Nucl. Sci. Eng.*, 156, 115 (2007).
4. G. Zhang, J. Zhang, R. Cao, et al., "Measurement of Differential Cross Section for the ^{64}Zn(n,α)^{61}Ni Reaction at 2.54, 4.00 and 5.50 MeV," *Nucl. Sci. Eng.*, 160, 123 (2008).
5. J. Yuan, Z. Chen, G. Tang, et al., "Angular Distribution and Cross-Section Measurements for ^{64}Zn(n,α)^{61}Ni Reaction at 5.0, 5.7 and 6.5 MeV," *Nucl. Sci. Eng.,* 144, 108 (2003).
6. J. L. Casanova and M. L. Sanchez, "Measurement of the (*n,p*), (*n,alpha*), (*n,2n*) Cross Sections of Zn, Ga, Ge, As, and Se For 14.1 MeV Neutrons, and (*n,p*) Cross Sections Analysis," *Anales de Fisica y Quimica*, 72, 186 (1976).
7. M. Bormann, U. Seebeck, W. Voights, G. Woelfer, "Level Densities of some Medium Weight Nuclei from Evaporation Spectra of the Alpha Particles from (*n,alpha*) Reactions," *Zeitschrift fuer Naturforschung, Section A,* 21, 988(1966).
8. Guohui Zhang, Hao Wu, Jiaguo Zhang, Jiaming Liu, Jinxiang Chen, Yu. M. Gledenov, M. V. Sedysheva G. Khuukhenkhuu and P. J. Szalanski, "Cross-section measurement for the ^{67}Zn(n,α)^{64}Ni reaction at 6.0 MeV," *Eur. Phys. J. A*, 43, 1 (2010).