Measurement of keV-Neutron Capture Cross Sections and Capture Gamma-Ray Spectra of Er Isotopes

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Neutron capture cross sections and capture γ-ray spectra of ^{166,167,168}Er were measured in the energy region of 10 to 550 keV. The measurements were performed with a pulsed ^{7}Li(p,n)^{7}Be neutron source and a large anti-Compton NaI(Tl) γ-ray spectrometer. A pulse-height weighting technique and the standard capture cross sections of gold were used to derive the capture cross sections. The errors of the derived cross sections were about 5 %. The present results were compared with other measurements and evaluations. The observed capture γ-ray pulse-height spectra were unfolded to obtain the corresponding γ-ray spectra. An anomalous shoulder was observed around 3 MeV in each of the capture γ-ray spectra.

1. Introduction

The study of keV-neutron capture cross section is important in nuclear engineering, nuclear physics and nuclear astrophysics. Capture γ-ray spectra as well as capture cross sections are necessary for studies on neutron capture reaction mechanisms and nuclear excitation modes.

The element Er is proposed as one of burnable poisons in nuclear reactors, but JENDL-3.2 does not contain Er data. On the other hand, ENDF/B-VI contains data of ^{166,167}Er, but the evaluation was made many years ago[1]. Therefore, the Er data in ENDF/B-VI seem to have a considerable uncertainty. As for the experimental data of Er isotopes, there are a few available data for the keV-neutron capture cross sections and no data for the keV-neutron capture γ-ray spectra.

The aim of the present study is to measure the capture cross sections and capture γ-ray spectra of Er isotopes in the keV-neutron region in order to provide accurate nuclear data and to investigate neutron capture reaction mechanisms and nuclear excitation modes.

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2. Experimental Procedure

A typical experimental set up is shown in Fig.1. The measurement was performed in the neutron energy region of 10-90 keV and at 550 keV. The details of the experimental procedure were described elsewhere[2]. A 1.5-ns pulsed proton beam from the 3-MV Pelletron Accelerator of the Research Laboratory for Nuclear Reactors at the Tokyo Institute of Technology was used to produece keV neutrons by the ^{7}Li(p,n)^{7}Be reaction. The proton energy was set to 1.905 MeV, 24 keV above the threshold energy of the ^{7}Li(p,n)^{7}Be reaction, in the 10-90 keV measurement, and neutrons with energies of 2 to 95 keV were emitted within about 50° with respect to the proton beam direction. In the 550 keV measurement, the proton energy was set to about 2.3 MeV so as to generate neutrons with an average energy of 550 keV. The proton pulse repetition rate was 2 MHz or 4 MHz for the 10-90 keV or 550 keV measurement, respectively. The spectrum of neutrons incident on a capture sample was measured by means of time-of-flight (TOF) method with a ^{6}Li-glass scintillation detector.

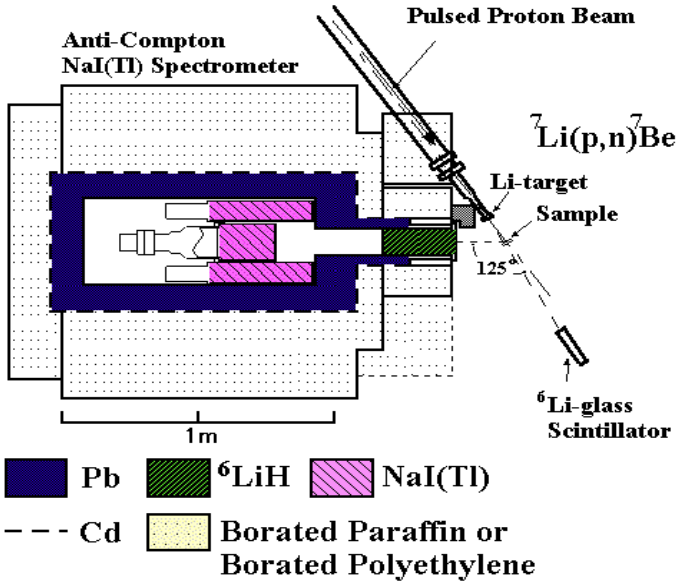

Fig. 1 Experimental setup for the 10-90 keV measurement

Table 1. Characteristics of samples

Sample		^{166}Er	^{167}Er	^{168}Er	^{197}Au
Chemical form		Er_2O_3	Er_2O_3	Er_2O_3	Au
Physical form		Powder	Powder	Powder	metal plate
Weight of powder(g)		1.139	1.140	1.140	—
Chemical purity(%)		> 98.6	> 99.6	> 99.997	99.999
Isotopic composition(%)	^{197}Au	—	—	—	100
	^{162}Er	<0.02	<0.02	<0.002	—
	^{164}Er	0.06	0.06	0.022	—
	^{166}Er	96.31	1.14	0.62	—
	^{167}Er	2.78	95.60	1.21	—
	^{168}Er	0.71	3.08	97.75	—
	^{170}Er	0.15	0.18	0.40	—
Net weight of sample(g)		0.952	0.950	0.974	12.04
Thickness of sample (mm)		3.0	2.2	1.3	2.0
(10^{-3} nuclei/barn)		1.100	1.090	1.138	11.7
Diameter of sample (mm)		20.0	20.0	20.0	20.0
Outer diameter of case (mm)		24.0	24.0	24.0	—
Outer thickness of case (mm)		5.0	4.2	3.3	—

Each of the Er samples was enriched oxide power (Er_2O_3) contained in a graphite case. The net weight of each sample was about 1 g. A gold (Au) sample was used as a standard. The characteristics of the Er and Au samples are shown in Table 1. Each sample was set at a distance of 12 cm or 20 cm from the neutron source for the 10-90 keV or 550 keV measurement, respectively.

The capture γ rays emitted from each sample were measured with a large anti-Compton NaI(Tl) spectrometer, employing a TOF method. The main detector of the γ-ray spectrometer was an NaI(Tl) detector with the diameter of 15.2 cm and the length of 20.3 cm. The main detector was centered in a hollow Compton-suppression NaI(Tl) detector with the outer diameter of 33.0 cm and the length of 35.6 cm. The spectrometer was set in a heavy shield consisting of borated paraffin, borated polyethylene, cadmium and potassium free lead. A ^{6}LiH neutron shield was also interposed between the sample and the main detector. The distance between the capture sample and the front surface of the main detector was 86.0 cm and all the characteristics, such as response functions, weighting function[2], etc., of the spectrometer were defined on this geometrical condition. The capture γ rays were measured at an angle of 125° with respect to the proton beam direction so as to approximately observe the angle-integrated γ-ray spectrum for the dipole transition. The capture events detected by the spectrometer were stored into a workstation as two-dimensional data on TOF and pulse height (PH). The Au, Er and blank runs were made cyclically to average out changes in the experimental conditions.

3. Data Processing

The detail description of the data processing has also been given elsewhere[2]. The incident neutron spectra were obtained from the TOF spectra measured by the ^{6}Li-glass detector. Typical incident neutron spectra are shown in Fig. 2.

Figure 3 shows the TOF spectra observed with the γ-ray spectrometer in the 10-90 keV measurement of ^{167}Er. Several digital gates (DGs) were set in the foreground and background regions in the TOF spectra to obtain foreground and background PH spectra. The net capture γ-ray PH spectra of Er and Au for each DG were obtained by subtracting the background PH spectrum normalized with the ratio of the gate widths from the foreground PH spectra. In the 550 keV measurement, only one DG was set in the foreground region and several ones in the background region. Figure 4 shows the net

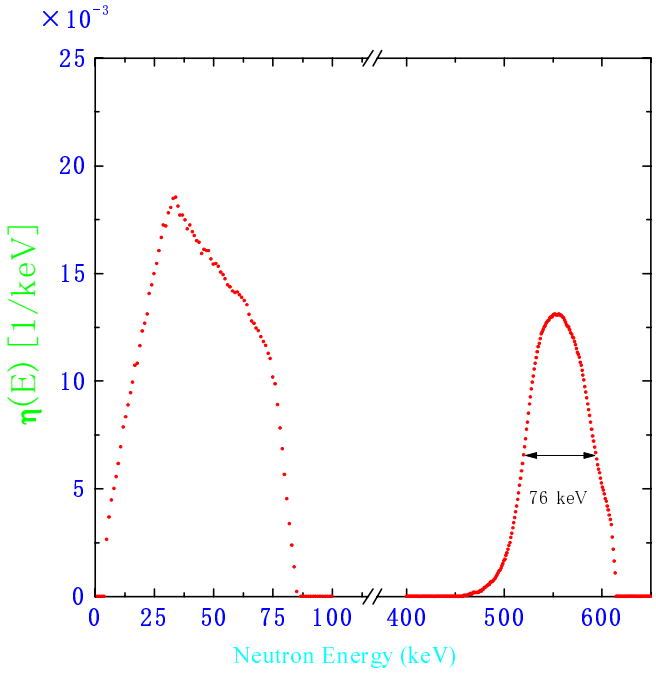

Fig.2. Incident neutron spectra in the ^{166}Er measurements

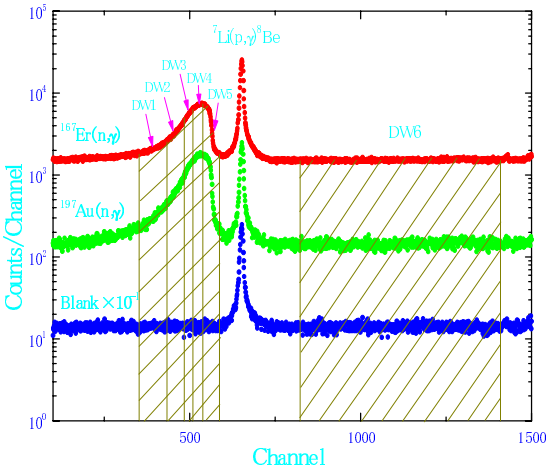

Fig. 3 TOF Spectra observed in the 10–90 keV measurement of ^{167}Er

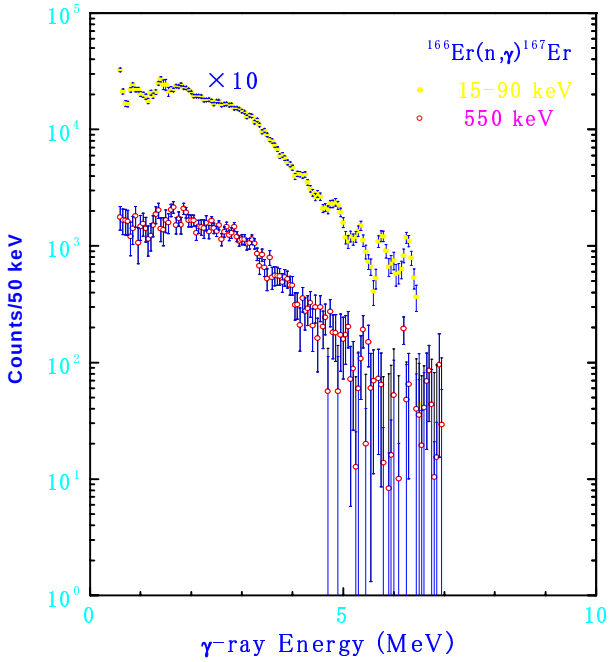

Fig. 4 Net capture γ-ray PH spectra of ^{166}Er

capture γ-ray PH spectra of ^{166}Er in the incident neutron energy region of 15 to about 90 keV and at 550 keV.

A PH weighting technique[3] with the weighting function[2] of the γ-ray spectrometer was applied to each of the net capture γ-ray PH spectra, and the capture yields (the numbers of capture events) of both Er and Au samples for each DG were obtained. The number of incident neutrons for each DG of Au was derived from the corresponding capture yield and an average capture cross section of Au for the DG. The standard capture cross sections of Au were taken from ENDF/B-VI[4]. Then, the number of incident neutrons for the corresponding DG of Er was obtained by using the neutron monitor counts. Finally, the average capture cross section of Er was derived from the corresponding capture yield of Er and the number of incident neutrons.

The capture γ-ray spectrum was obtained by unfolding the net capture γ-ray PH spectrum with a computer code, FERDOR[5], and the response matrix[2] of the γ-ray spectrometer. Then, each γ-ray spectrum was normalized.

Corrections were made for the neutron self-shielding and multiple scattering in the sample, for the γ-ray scattering and absorption in the sample, for chemical and isotopic impurities in the sample, for the dead time, etc.

4. Results and Discussion

(1) Capture Cross Sections

The capture cross sections of ^{166,167,168}Er were derived with errors of about 5 % in the incident neutron energy region of 10 to 90 keV and at 550 keV. The present results are shown in Fig. 5 and compared with previous measurements[6,7] and the ENDF/B-VI evaluations[1].

In the region of 10 to 90 keV, the present results of ^{167,168}Er are in good agreement with those of Shorin

et al.[6] or Kononov et al.[7], but the present results of ^{166}Er are larger than those of Kononov et al. by 5 to 15 %. At 550 keV, there are no available data to be compared.

Shorin et al. and Kononov et al. used a pulsed neutron source by the ^{7}Li(p,n)^{7}Be reaction and the liquid scintillation tank of Institute of Physical and Power Engineering (IPPE). They used the tank of 17*l* filled with C_6F_6 scintillator as a total energy absorption detector.

The ENDF/B-VI evaluation of ^{166,167}Er in the keV region was mainly based on the statistical model calculation with a spherical optical potential. In the calculation, the γ-ray strength function was adjusted so as to reproduce the measured capture cross sections: 0.74 b at 30 keV of Kononov et al. for ^{166}Er and 1.50 b at 30 keV of Shorin et al. for ^{167}Er. Therefore, the evaluations of ^{167}Er are in agreement with the present results in the 10-90 keV region, but those of ^{166}Er in the 10-90 keV region are smaller than the present results by 5-15%. At 550 keV, the evaluation of ^{167}Er is about 10 % larger than the present result, and that of ^{166}Er is about 20 % larger than the present result. It is worth noting that ENDF/B-VI does not contain data of other Er isotopes.

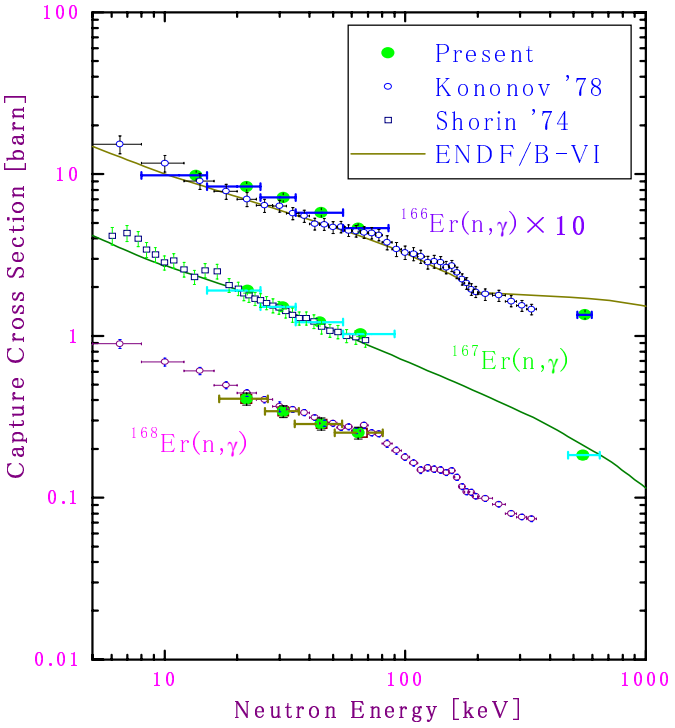

Fig.5. Capture Cross Section of ^{166,167,168}Er

(2) Capture γ-ray Spectrum

The capture γ-ray spectra of ^{166,167,168}Er were derived at the average incident neutron energy of 45 keV (energy region of 15 to about 90 keV) and at 550 keV. The results at 45 keV are shown in Fig. 6. The spectrum at the incident neutron energy of 550 keV was similar to that at 45 keV, especially in the low γ-ray energy region. From the 10-90 keV measurements, the γ-ray spectra corresponding to the individual DGs were also derived, but no difference in the spectral shape was observed.

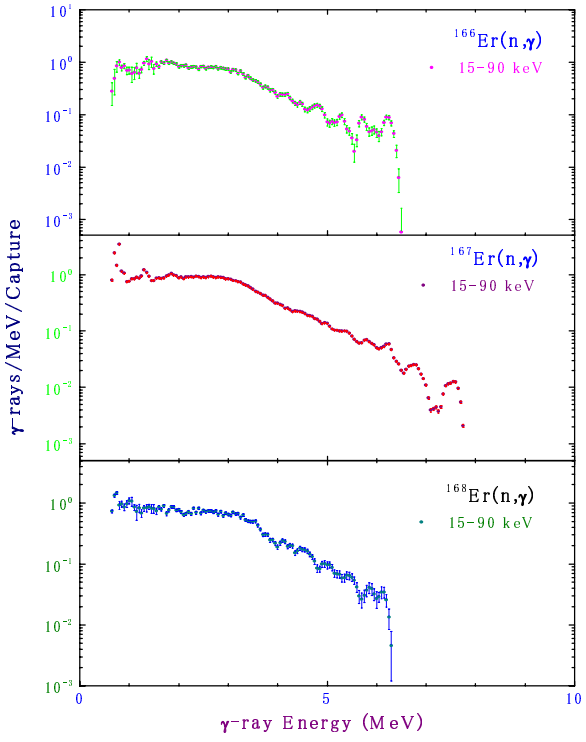

Fig. 6 Unfolded γ-ray spectra of ^{166,167,168}Er

An anomalous shoulder, which was called an anomalous "bump" in our previous work[8], is clearly observed around 3 MeV in the spectra of ^{166,167,168}Er in Fig. 6. The energy position of the shoulder is independent of the incident neutron energy and is consistent with the systematics obtained in our previous work[8]. The anomalous shoulder or bump was ascribed to a resonance structure of the electric-dipole (E1) γ-ray strength function in the previous work, but its origin should be investigated also from different aspects such as the excitation of magnetic-dipole (M1) scissors mode[9].

5. Conclusion

The capture γ rays of ^{166,167,168}Er were measured in the incident neutron energy region of 10 to 90 keV and at 550 keV with an anti-Compton NaI(Tl) γ-ray spectrometer and a 1.5-ns pulsed neutron source. The capture cross sections of ^{166,167,168}Er were derived with errors of about 5 %. In the 10-90 keV region, the present results of ^{167,168}Er were in good agreement with the previous measurements, but the present results of ^{166}Er were larger than the previous ones by 5-15 %. At 550 keV, the present measurements were the first ones. The ENDF/B-VI evaluations of ^{167}Er were in good agreement with the present measurements in the 10-90 keV region but about 10 % larger than the present result at 550 keV. As for ^{166}Er, the evaluations of ENDF/B-VI were larger than the present results by 5-20 %.

The capture γ-ray spectra of ^{166,167,168}Er were derived with good accuracy and good γ-ray energy resolution. An anomalous shoulder was clearly observed around 3 MeV in the spectra of ^{166,167,168}Er. The energy position of the shoulder was independent of the incident neutron energy, and was consistent with the systematics obtained in our previous work. The origin of the anomalous shoulder should be investigated not only from the aspect of the resonance structure of E1 γ-ray strength function but also from different aspects such as the excitation of M1 scissors mode.

Acknowledgements

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