# Measurement of Neutron Total Cross-Sections of Dy and Hf in the Energy Region from 0.002 eV to 100 keV

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The neutron total cross-sections of Dy and Hf have been measured in the energy region from 0.002 eV to 100 keV by the neutron time-of-flight method with a 46 MeV electron linear accelerator (linac) of the Research Reactor Institute, Kyoto University. A $^{6}$Li glass scintillator has been used as a neutron detector and metallic plates of Dy and Hf samples, 0.5 to 5.0 mm thick, have been applied to the neutron transmission measurement. The neutron flight path from the water-cooled Ta target to the $^{6}$Li glass scintillator is 22.1±0.01 m. The background level has been determined by the block-off method and/or by using notch-filters of Co (132 eV), Ag (5.2 and 16.3 eV) and Mn (336 eV) and a Cd sheet. The figures show the present measurements, the previous data and the evaluated data in ENDF/B-VI.

## 1. INTRODUCTION

An electron linear accelerator is a most powerful tool to produce intense pulsed neutrons. Most of the electron linear accelerators were constructed for various fundamental research programs including neutron spectroscopy. They have been used for neutron cross-section measurements by the time-of-flight (TOF) methods covering the energy range from thermal neutron to a few tens of MeV. Pulsed neutrons from an electron linear accelerator (linac) are suited for measuring the energy dependent cross-section with high resolution using the TOF technique.

The neutron total cross-sections of Dy and Hf are of great importance not only for the design and development of nuclear reactors but also for the basic study of neutron interaction with nuclei. Dysprosium (Dy) and hafnium (Hf) are useful absorbing materials for the control rod of thermal reactors because of their large neutron cross-sections in the thermal neutron energy region. Up to now, a few data of their neutron total cross-sections have been reported below 10 eV and a few measurements have been made above a few hundreds keV energy region.

Moore [1] and Okamoto [2] measured the total cross-sections of Dy in the thermal neutron energy region by the transmission method. Sturm *et al.* [3] obtained the cross-sections from 0.08 eV to 20 eV using a heavy water pile and the Bragg reflection method. Brunner *et al.* [4] obtained the total cross-sections in the energy region from 0.015 eV to 2.5 eV with a fast-chopper installed in a thermal reactor. Knorr *et al.* [5] have reported the total cross-sections measured in the energy region below $3.2\times10^{-3}$ eV in a reactor. In the higher energy region, Egelsaff [6] measured the total cross-sections from 144 eV to 36 keV by the TOF method using a fast-chopper.

The total cross-section of Hf has been measured in the thermal neutron energy region by Joki *et al.* [7], Bernstein *et al* [8], Moore [1] , and Schermer [9]. Bollinger et al. [10] obtained the experimental data from 1 eV to 8 keV. Sherwood *et al.* [11] and Divadeenam *et al.* [12] measured the total cross-section of Hf in the energy region from 0.11 keV to 0.15 keV and from 0.12 MeV to 0.64 MeV using a Van-de-Graaff accelerator.

Although these total cross-sections of Dy and Hf have been reported, there exist discrepancies among the data, especially in the resonance energy region. Therefore, the experimental data in the relevant energy range are strongly requested to measure.

In the present work, the total cross-sections of natural Dy and Hf have been measured between 0.002 eV and 100 keV by the neutron TOF method using the 46 MeV electron linear accelerator of the Research Reactor Institute, Kyoto University (KURRI). A $^{6}$Li glass scintillator has been used as we applied in the previous work [13]. The measured results are compared with the previous measurements and the evaluated data in ENDF/B-VI [14].

## 2. EXPERIMENTAL METHOD

The transmission measurements were made by the neutron TOF method with the 46 MeV electron linac at the Research Reactor Institute, Kyoto University (KURRI). Bursts of fast neutrons were produced from a water-cooled photoneutron target, which was made of twelve sheets of Ta plates of 5 cm in diameter and about 3 cm in effective thickness. This target was set at the center of an octagonal water tank, which was 30 cm in diameter and 10 cm thick, to moderate fast neutrons. A shadow bar made of Pb block, 7 cm thick and 20 cm long was placed in the neutron flight path in front of the Ta target to reduce the gamma-flash generated by the electron burst in the target. The neutron collimation system was mainly composed of $B_4C$-hardened epoxy resin, $H_3BO_3$ and Pb collimators, which were symmetrically tapered from 10 cm diameter at both the beginning and the end of the flight tube to 4 cm diameter at the middle position where the transmission sample was located. For the cross-section measurement in the energy range above 0.5 eV, a 0.5-mm-thick Cd sheet was inserted in the TOF beam to suppress overlap of thermal neutrons from the previous pulses due to the high-frequency operation of the linac. During the experiment, the linac was operated in two different modes: One was that the linac operating conditions without a Cd sheet were for the thermal neutron energy region (thermal region) with a repetition rate of 25 Hz, a pulse width of 3 , a peak current of 200 mA, and an electron energy of 30 MeV, and the other with a Cd sheet was for the higher energy region (epi-cadmium region) with a repetition rate of 100 Hz, a pulse width of 22 ns, a peak current of 1 A, and an electron energy of 30 MeV.

In the total cross-section measurements, we have used three kinds of Dy metal samples and four kinds of Hf metal samples. The transmission samples were placed at the midpoint of the flight path and were cycled into the neutron beam by an automatic sample changer with four sample-positions. A set of notch filters of Co, Ag, Mn and a Cd sheet were mounted in front of the sample changer when we made the background measurement.

For the neutron TOF spectrum measurement, a $^{6}$Li glass scintillator of 12.7 cm in diameter and 1.27 cm in thickness was mounted on an EMI-9618/R photomultiplier and used as a neutron detector located at 22.1$\pm$0.01 m distant from the photoneutron target. Neutron signals were amplified, discriminated and sent to the data acquisition system. The neutron intensity during the TOF measurement was monitored with a $BF_3$ proportional counter, which was inserted into the neutron beam. The monitor counts by the $BF_3$ counter were also amplified and led to the computer for storage through a discriminator.

## 2. DATA REDUCTION

### 2.1 . TOF Measurement

For the transmission measurement, three sample-in positions with different samples in thickness and a sample-out (open) position were cycled periodically into the neutron TOF beam for a preset time interval by the automatic sample changer. The cycle time was 8 to 12 min.-period, and the time was allotted to each sample so as to minimize the statistical error in the cross-section measurement.

The TOF signals from the $^6$Li glass scintillator were fed into a time digitizer, which was initiated by the electron burst of the KURRI linac, and the counts versus TOF channel for each sample position were recorded in each section of the data acquisition system linked to a personal computer. The multi-channel time analyzer was operated as four 2048-channel analyzers corresponding to each transmission sample-in or sample-out position. Another four 2048-channel analyzers were used for the TOF measurements using the $BF_3$ monitor system in order to normalize the neutron intensity between the experimental runs.

The channel width of the time analyzer in this experiment was set to be 16 /ch for the thermal neutron energy region and 0.5 /ch for the epi-cadmium energy region. The energy calibration of the TOF neutron beam was performed with the well-known resonance energies of thin Ag, Co, and Mn filters. Total running times for the thermal and the epi-cadmium regions were about 248 hours; 62, 16 and 24 hours for 0.5 mm, 3 mm and 5 mm thick Dy samples and 65, 21, 11 and 49 hours for 0.5 mm, 1.5 mm, 2 mm and 3 mm thick Hf samples, respectively.

### 2.2 . Background Measurement

In order to estimate the background level, we have used two kinds of methods: One was the block-off method using a borated paraffine block of 15 cm in thickness, which was placed in front of the sample to black out the neutron beam. The other was to apply notch-filters of Ag, Co, and Mn and a 0.5-mm-thick Cd sheet. The magnitude of the background level has been interpolated using the fitting function $F(I) = aI^b$, where $a$ and $b$ are constants and $I$ is the channel number of the time analyzer.

## 4. DATA ANALYSIS

The total cross-section is determined by measuring the transmission of neutrons through the sample. The transmission rate of neutrons at energy $E_i$ is defined as a fraction of incident neutrons passing through the sample to the open beam. Thus, the neutron total cross-section is given as follows, using the neutron transmission rate $T(E_i)$:

$$\sigma(E_i) = (1/N) \ln T(E_i) \quad (1)$$

$$T(E_i) = \frac{[I(E_i) - IB(E_i)] / M}{[O(E_i) - OB(E_i)] / MB} \quad (2)$$

where $N$ is the atomic density of the transmission sample, and the bracket ($E_i$) means the total counts in $i$-th energy group corresponding to each TOF channel. $I(E_i)$ and $O(E_i)$ are the foreground counts for sample-in and sample-out, $IB(E_i)$ and $OB(E_i)$ are the background counts for sample-in and sample-out, and $M$ and $MB$ are the monitor counts for the foreground and the background runs, respectively. The monitor counts are obtained by integrating TOF counts in each channel corresponding to the relevant energy region.

## 5. RESULTS AND DISCUSSION

The total cross-sections of natural Dy and Hf have been obtained in the energy range from 0.002 eV to 100 keV by the neutron TOF method. The results obtained have been summed up in every $\delta U$=0.01 lethargy width in order to obtain better statistics. In the data processing, the following corrections have been made: The dead time of the time analyzer used in this experiment was estimated to be less than 0.1 μsec, and the dead time correction could be neglected in the present work. The effect of attenuation of neutron beam due to the thickness of sample was estimated to be less than 0.01 % for the transmission samples. The major impurity elements are Ta (< 0.1 %) and Al (0.05%). The effect due to the impurities on the transmission measurement is estimated to be < 0.1% considering their total cross-section values. The total uncertainties in the present experiment are estimated to be less than 3% as follows. Main sources of the uncertainties are due to the statistical errors (0.65~1.53 % for Dy, 0.36~1.25 % for Hf), the detection efficiencies (1.85~1.98 %), the geometric factor for the samples (< 0.1 %), and the systematic errors (0.5~1.0 %) including some other corrections.

For the Dy cross-section, generally, good agreement can be seen between the existing measured and evaluated data and the present measurement, as shown in **Fig. 1**, although the data by Moore [1] and Sailor et al. [15] and the ENDF/B-VI data show a tendency to be lower a little than the present result at energies between 0.01 eV and 1.5 eV. In **Fig. 1** (a), the data from 0.26 meV to 3.21 meV measured by Knorr et al. [5] are a little bit higher and the data from 0.015 eV to 2.512 eV by Brunner et al. [4], and from 0.63 meV to 0.02 eV by Okamoto [2] are in good agreement with the present measurement. The data by Moore [1] seem to have a structure around 0.2 eV. The data from 0.1 eV to 1 eV measured by Sturm et al. [3] are markedly discrepant from the previous measurements and the evaluated data in ENDF/B-VI. In the **Fig. 1** (b) for the total cross-section of Dy, the data from 2.41 eV to 43 eV measured by Carter [16] are in good agreement with the present measurement and the evaluated ones. But, the data from 144 eV to 10 keV measured by Egelstaff [6] show extremely low values compared to the present measurements. The evaluated data in ENDF/B-VI are rather close to the measurements, although they are higher in the energy range from 500 eV to 2 keV.

For the Hf cross-section, previous data measured by Bernstein et al. [4], Bollinger et al. [10], Okazaki et al. [17], Moore [1], Joki et al. [7], and Schermer [9], are in good agreement with the present measurement. The evaluated data in ENDF/B-VI are also in general agreement except for the resonance region or above 300 eV, as shown in **Fig. 2**. In the resonance energy region, the resonance parameters for Dy and Hf have to be investigated in the future by analyzing the measured data with a computer code in the future.

## 6. CONCLUSIONS

The neutron total cross-sections of natural Dy and Hf have been measured in the energy region from 0.002 eV to 100 keV by using the neutron TOF method and the $^{6}$Li glass scintillator as a neutron detector. For the total cross-section of Dy, it has been found that the previous measurements and the evaluated data in ENDF/B-VI are in good agreement with the present measurement except for the data from 0.1 eV to 1.0 eV by Sturm et al. and from 144 eV to 10 keV by Egelstaff. The evaluated values in ENDF/B-VI are higher than the present measurement in the energy range from 500 eV to 2 keV. The evaluated cross-section of Hf in ENDF/B-VI are higher than the measured cross-section in the energy region above 300 eV, although the evaluation and most of the previous measurements are close to the present data in general. The data measured in the resonance energy region should be analyzed in the future to get the resonance parameters.

## ACKNOLEDGEMENT

The authors would like to express their sincere thanks to the staff of the Research Reactor Institute, Kyoto University (KURRI) for the excellent linac operation. One of the authors (H. J. Cho) is grateful to the Korea Science and Engineering Foundation (KOSEF) for the 1999 Post-Doc. Program.

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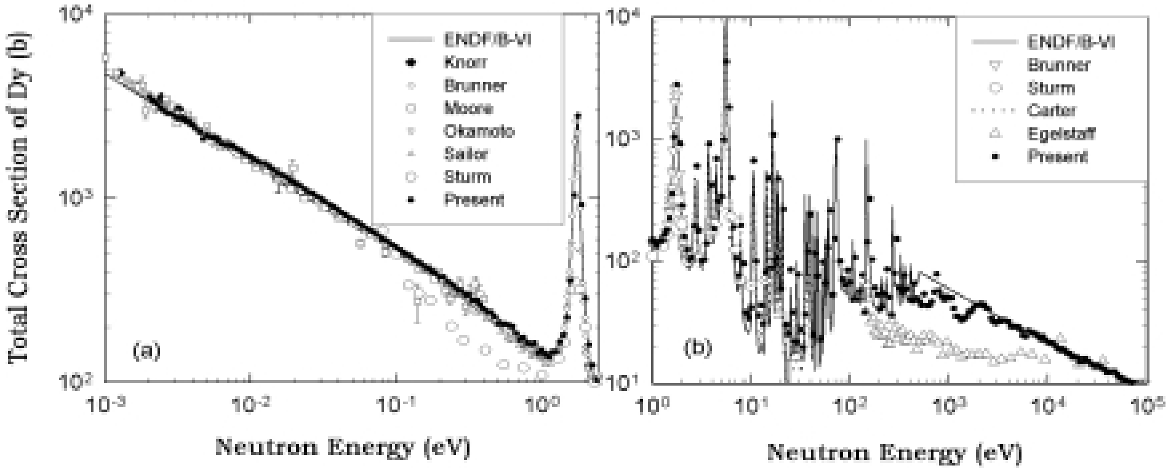


Fig. 1. Comparison of the neutron total cross-section of Dy with the experimental data and the evaluated : (a) in the lower energy region below 3 eV and (b) in the higher energy region between 1 eV and 100 keV.

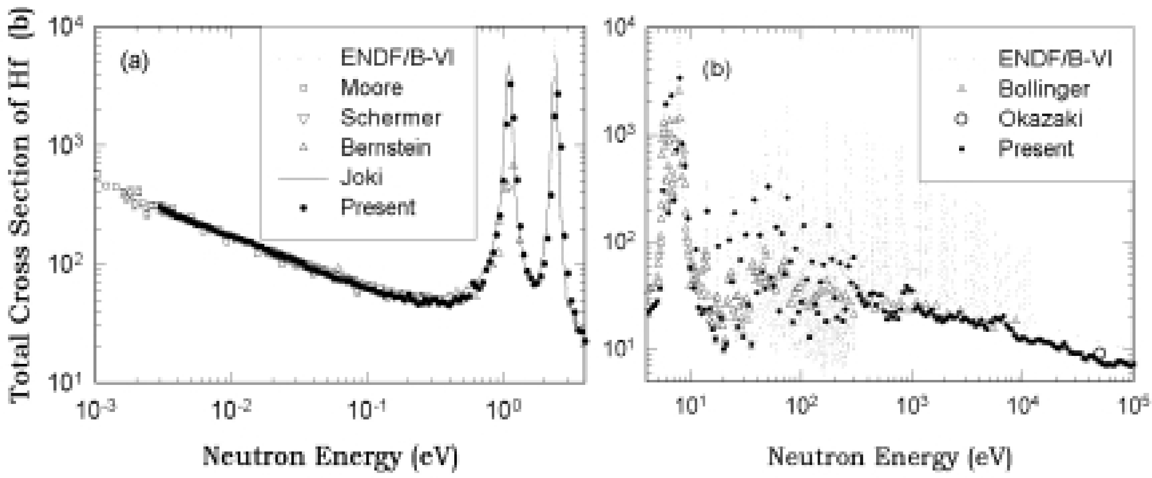


Fig. 2. Comparison of the neutron total cross-section of Hf with the experimental data and the evaluated data : (a) in the lower energy region below 4 eV and (b) in the higher energy region between 4 eV and 100 keV.