Journal of the Korean Physical Society, Vol. 59, No. 2, August 2011, pp. 1745∼1748

Molybdenum and Zirconium Neutron Total Cross Section Measurements in the Energy Range of 0.5 to 20 MeV

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(Received 26 April 2010)

Neutron transmission measurements were made on natural molybdenum and zirconium samples using the time of flight method at the Rensselaer Polytechnic Institute Gaerttner Linac Laboratory. These measurements utilize a 100 meter flight path, fast detector response and electronics and a narrow neutron pulse width to provide high accuracy data. Neutron total cross sections have been determined in the energy range of 0.5 to 20 MeV and are compared to commonly used nuclear data evaluations. Molybdenum shows good agreement with the evaluations, while zirconium shows improvement is required with the most recent evaluations in the range of 0.5 to 15 MeV.

PACS numbers: 25.40.-h
Keywords: ND2010, Nuclear data, Transmission, Cross section, Molybdenum, Zirconium
DOI: 10.3938/jkps.59.1745

I. INTRODUCTION

This paper introduces new measurements performed on natural samples of molybdenum and zirconium. Both materials are used in nuclear reactor applications and so accurate knowledge of the neutron total cross section of these materials is of interest.

A review of the evaluated total neutron cross section for zirconium in the energy range 0.5 to 20 MeV shows a significant change was made to the ENDF values between ENDF/B-VI.8 and ENDF/B-VII.0 [1] (see Fig. 1). Looking at the existing experimental data retrieved from EXFOR [2] shows that much of the data agrees with the ENDF/B-VI.8 evaluation, while the other evaluations follow the data from Nereson *et al.* [3]. Molybdenum shows little disagreement between the evaluations and the prior experimental data and is therefore not shown.

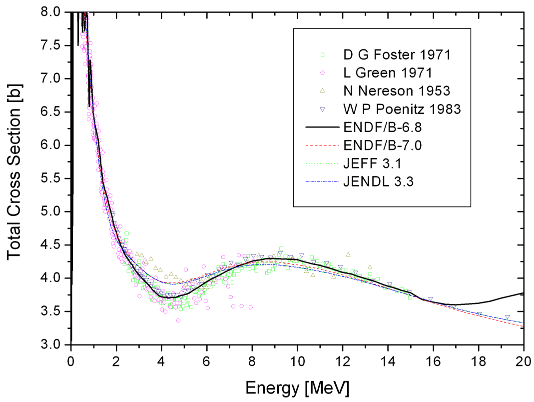

Fig. 1. (Color online) Total neutron cross section evaluations for zirconium plotted with previously measured data from EXFOR. The JEFF 3.1 and JENDL 3.3 evaluations lie on top of one another, the same data (JENDL 3.3) is used in both.

II. EXPERIMENTAL CONDITIONS

Neutrons are produced at the Rensselaer Polytechnic Institute (RPI) Gaerttner Linac Laboratory via a pulsed electron beam from the linear accelerator striking the water cooled tantalum plates in the neutron producing target [4]. The high energy electrons from the linear accelerator generate bremsstrahlung X-rays within the target which interact with the tantalum to produce photoneutrons. The RPI target was placed on-axis with the flight tube and used without a moderator to enhance neutron production in the energy range of interest. The repetition rate was 400 pulses per second with a pulse width of approximately 8 nsec. The average electron current on the target was about 5 μA with energy of 58 MeV.

The neutrons produced in the target pass through a

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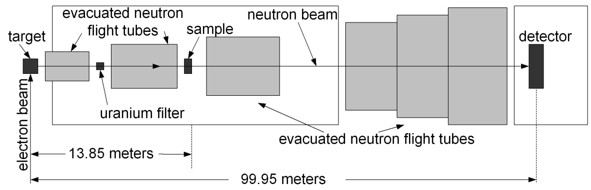

Fig. 2. Experimental setup showing the general layout of the neutron producing target, filter, sample and detector (not to scale).

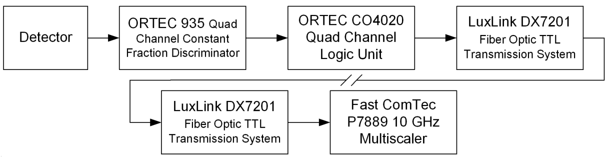

Fig. 3. Block diagram of electronics used for data collection.

12.7 cm depleted uranium filter to prevent paralyzing the neutron detector with the intense pulse of high energy bremsstrahlung X-rays. The neutron beam is collimated to a diameter of 4.76 cm before passing through the sample material located at 13.85 m and continuing on to the neutron detector located at 99.95 m. The distance from target to detector was determined using the resonance structure in carbon. An overview showing the layout of the experimental setup can be seen in Fig. 2.

The neutron detector system consists of two Eljen Technology Model 510-50X70X138/301 EJ-301 liquid scintillator modules [5]. Each module has an inner volume dimension of 17.78 cm high, 35.05 cm long and 12.7 cm thick. Two Photonis XP4572B photomultiplier tubes are mounted on each module to optimize light collection throughout the detector volume. Two modules are stacked on top of each other to give a total detection area of 35.56 cm high by 35.05 cm wide.

Figure 3 shows the electronics and signal path used in the experiments. Events detected in each module are fed to an ORTEC 935 constant fraction discriminator for optimizing time resolution over the wide range of pulse amplitudes and then summed in an ORTEC CO4020 logic unit. This output is then converted to an optical signal for transport to the data acquisition computer using a LuxLink DX7201 Fiber Optic TTL Transmission System. The data acquisition computer houses a FAST ComTec P7889 Time of Flight Multiscaler board with which collects the data in 1.6 nanosecond bins with no dead time between channels. The dead time of the system is set by the electronics to be 100 nanoseconds and verified by experiment. To ensure that dead time correction error is minimal the neutron beam intensity was set such that the dead time correction factor had a maximum value of five percent.

Additional neutron detectors (Reuter-Stokes RS-P6-2403-121 and Amperex B300D fission chambers) are in place at the LINAC facility on a separate flight path located approximately 9 meters from the target. These detectors collect data at the same time as the sample measurements and are used to monitor the variation in the neutron beam intensity during the experiment.

Table 1. Impurities in the molybdenum sample.

Impurity	ppm	Impurity	ppm
Al	<5	Mn	<5
Ca	<5	Ni	<5
Cr	<5	Pb	<5
Cu	<5	Si	<5
Fe	<5	Sn	<5
Mg	<5	Ti	<5

Table 2. Impurities in the zirconium sample.

Impurity	ppm	Impurity	ppm
Al	58	Mg	<10
B	<0.25	Mn	<25
C	70	Mo	<10
Cd	<0.25	N	<20
Co	<10	Ni	<35
Cr	60	Si	11
Cu	<25	Sn	<35
Fe	470	Ti	<25
H	4	U	<1
Hf	50	W	<30

III. DATA COLLECTION

The materials used for these experiments were 99.99% natural molybdenum and 99.9% natural zirconium. Impurities for each material can be seen in Tables 1 and 2 respectively.

Two independent experiments were run, one for molybdenum and one for zirconium, each lasting a total of approximately 100 hours.

Two 7.62 cm diameter samples were used for each experiment; 3 cm and 8 cm thick for molybdenum and 6 cm and 10 cm thick for zirconium.

A third sample, 13 cm carbon (graphite), was run during both experiments. Carbon is used as the standard in these experiments since it is well measured in transmission and all evaluations are in excellent agreement.

The division of experimental time between the samples was chosen to optimize statistical accuracy in accordance with Ref. 6. The transmission through the samples was measured using the time-of-flight method, allowing for time-to-energy conversion.

IV. DATA ANALYSIS

The energy dependent total cross section can be determined from the transmission measurement for each time bin, i, using Eq. 1:

$$\sigma_t\left(E_i\right) = -\frac{1}{N}\ln\left(T_i\right), \tag{1}$$

where;

$\sigma_t(E_i)$ is the total cross section in barns in the TOF channel i,

T_i is the transmission in the TOF channel i,

N is the atomic number density of the sample in atoms/barn.

The transmission for each sample is determined using the ratio of the normalized open beam and sample measurements:

$$T_i = \left[\frac{C_i^S - B_i^S}{C_i^O - B_i^O}\right]\frac{mon^O}{mon^S}, \tag{2}$$

where;

$C_i^S$is the dead time corrected counts in the sample measurement for TOF channel i,

$B_i^S$is the background counts in the sample measurement for TOF channel i,

$C_i^O$is the dead time corrected counts in the open beam for TOF channel i,

$B_i^O$is the background counts in the open beam measurement for TOF channel i,

$mon^O$is the monitor counts for the open beam measurement for TOF channel i,

mon^S is the monitor counts for the sample measurement for TOF channel i.

Two components contribute to the background counting rates shown in Eq. 2. The first is the room background, which is time independent. The second component is associated with the production and transport of the pulsed neutron beam and varies with time. The room background can be easily measured by collecting data with the Linac off. The time dependent background can only be obtained during operation and is therefore masked by the neutron spectrum. A method has been developed and employed which uses a combination of Monte Carlo calculation and experimental data to determine this component [7].

V. RESULTS

The graphite measurement for both experiments showed excellent agreement with the cross section evaluations as seen in Fig. 4. This gives confidence to the molybdenum and zirconium measurements.

Molybdenum results agree with the evaluations over the energy range 0.5 to 20 MeV (see Fig. 5). In the lower region of this energy range cross section structure can be seen that is not included in the evaluations.

The zirconium data shows good agreement with the ENDF/B-VI.8 evaluation over the energy range 0.5 to 15 MeV as shown in Fig. 6. Most of the experimental data, including the current, do not support the ENDF/B-VII.0 higher cross-section near 4 MeV. Above 15 MeV the ENDF/B-VI.8 data deviates from the RPI data and the other evaluations are in better agreement. As with the molybdenum data, resonance structure is seen in the energy range of 0.5 to ∼ 2 MeV that is not present in the evaluations.

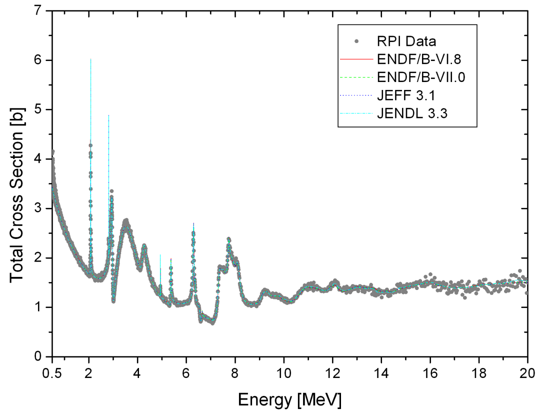

Fig. 4. (Color online) Graphite measurement showing agreement between RPI data and evaluations.

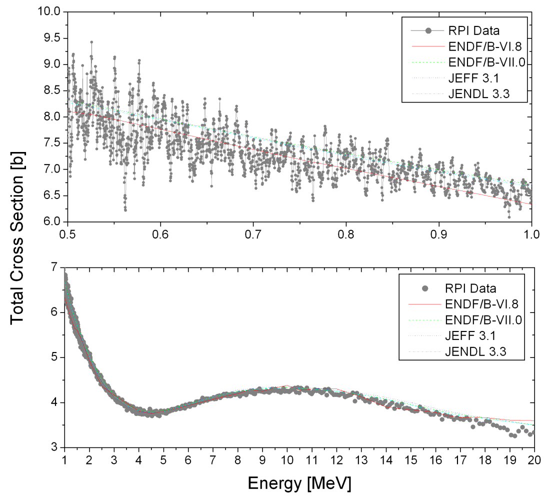

Fig. 5. (Color online) Molybdenum cross section showing good agreement of RPI data with the evaluations. The low energy region (upper plot) shows cross section structure that is not present in the evaluations.

VI. CONCLUSIONS

New neutron total cross section measurements of molybdenum and zirconium have been made at the RPI Gaerttner Linac facility in the energy range of 0.5 to 20 MeV. The resulting data has been presented and compared to the commonly used cross section evaluations.

The molybdenum data collected shows good agreement with the ENDF/B-VI.8, ENDF/B-VII.0, JEFF

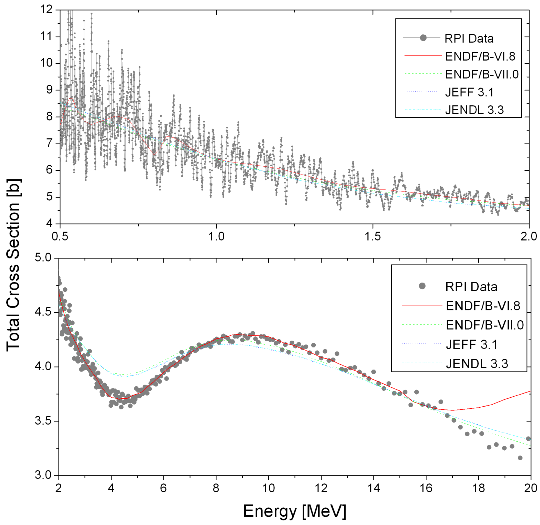

Fig. 6. (Color online) Zirconium cross section showing good agreement of ENDF/B-VI.8 with RPI data between 0.5 and 15 MeV. The RPI measurement shows unresolved cross section structure in zirconium that is not shown in the evaluations (upper plot). The JEFF 3.1 and JENDL 3.3 evaluations lie on top of one another in the above plots, the same data (JENDL 3.3) is used in both.

3.1 and JENDL 3.3 cross section evaluations, while zirconium shows that improvement in the evaluation is required. Zirconium shows good agreement with the ENDF/B-VI.8 evaluation up to ∼ 15 MeV and good agreement with ENDF/B-VII.0 from ∼ 15 to 20 MeV. Both of the measurements show cross section structure in the energy range of 0.5 to ∼ 2 − 3 MeV that is not represented in the evaluations.

These new measurements can help to resolve the issues with the zirconium evaluations and give high resolution, high accuracy data showing the low MeV cross section structure in both molybdenum and zirconium. The quality of this unresolved resonance structure makes it viable for inclusion in future evaluations.

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