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Neutron total cross-sections and resonance parameters of Mo and Ta

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Abstract. Experimental results of transmissions for the samples of natural molybdenum with thickness 0.0192 atoms/barn and for the four samples of natural tantalum with thickness 0.0222, 0.0111, 0.0055 and 0.0025 atoms/barn are presented in this work. Measurements were carried out at the Pohang Neutron Facility which consists of a 100 MeV Linac, water-cooled tantalum target, and 12 m flight path length. Effective total cross-sections were extracted from the transmission data, and resonance parameters were obtained by using the code SAMMY. The present measurements were compared with other measurements and with the evaluated nuclear data file ENDF/B-VI.8.

Keywords. Linear accelerator; total cross-sections; resonance parameters; SAMMY code.

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1. Introduction

The neutron total cross-section provides clues to the problem of nuclear structure and offers the testing ground for ideas about nuclear forces. So cross-section is used to obtain information about the internal structure of atomic nuclei and their constituents. Accurate knowledge of the cross-sections in neutron-induced reactions at energy levels where resonance occur is crucial to design the nuclear reactors. In this work, the total cross-section of natural Mo and Ta has been measured between 0.01 and 100 eV by the n_TOF method at the Pohang Neutron Facility (PNF). The measured result has been compared with other measurements and the evaluated data in ENDF/B-VI.8. The resonance parameters were determined from the fitting of transmissions as well as total cross-sections data by using the multilevel R-matrix code SAMMY and compared with the data of other measurements.

2. Experimental procedure

The PNF consists of a 100 MeV electron linac, water-cooled Ta target and a 12 m long evacuated flight tube. The e-linac consists of a thermionic RF-gun, an alpha magnet, four quadruple magnets, two SLAC-type accelerating sections, a quadruple triplet and a beam-analyzing magnet. As a photo-neutron target, it is necessary to use heavy mass materials in order to produce intense neutrons by way of bremsstrahlung under high-power electron beams. We used Ta as the target material, which has high density (16.6 g-cm^{-3}), high melting point (3017°C) and high resistance against the corrosion by cooling water. The TOF tubes were made of stainless steel with two different radii of 7.5 and 10 cm. The neutron beam line was equipped with a four-position sample changer that can allow the simultaneous transmissions measurement for four samples. For details, please see ref. [1].

2.1 *Pulsed neutron source*

Pulsed neutrons were produced from a water-cooled Ta target in a water tank as a neutron moderator. The target is composed of 10 Ta plates with a radius of 2.45 cm and an effective thickness of 7.4 cm. There is a 0.15 cm water gap between Ta plates for cooling the target effectively. The housing of the target is made of titanium. The calculated neutron yield per kW of beam power at the Ta target was 1.9×10^{12} n/s [2]. The neutron energy distributions with and without water moderator of the PNF were shown in ref. [2]. The electron beam produced from the linear accelerator hit the Ta target, located in the center of the cylindrical water moderator contained in an aluminum cylinder with a thickness of 0.5 cm, a radius of 15 cm and a height of 30 cm and the target is aligned vertically with the center of the TOF tube. Water moderator slowed down the generated neutrons and water was 3 cm above the target surface. The neutron collimation system was composed of H_3BO_3, Pb, and Fe collimators. During the transmission measurement of Mo and Ta samples, the linac was operated with the beam energy of 65 MeV, repetition rate of 10 Hz, and pulse width of 1 μs.

2.2 *Data acquisition system*

The configuration of the data acquisition system along with neutron guide tube of Pohang Neutron Facility can be seen in refs [3,4]. To measure neutron TOF spectra, there are three different data acquisition systems, which are NIM-, CAMAC-, and VME-based systems. Generally, NIM-based system is used to separate neutron gamma and also we may accumulate the neutron TOF spectra. We can select different channel widths for each crate so that we may cover all the expected incident neutron energy range. And finally we can add all the energy ranges by considering better energy resolutions for the channel widths of the data saving systems. The detailed explanations of the data acquisitions are given in refs [1,3,4].

2.3 *Samples and data taking*

In the measurement period the exposition times for Mo and Ta samples were 15 min (9000 pulses of PNF linac); for empty position, it was also 15 min. Thus, the duration for the sample was the same as those for the total open beam measurements. The interleaving sequence of free position of the sample changer was chosen to minimize the influence of slow and (/or) small variation of the neutron beam intensity. If the beam intensity variation or its drift was fast and (/or) large, then these partial measurements were excluded from the total statistics. The total data taking times for Mo and Ta were 48 and 61.25 h.

3. Total cross-sections measurements

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

$$\sigma(E_i) = -\frac{1}{\sum_j N_j} \ln T(E_i), \tag{1}$$

$$T(E_i) = \frac{[I(E_i) - IB(E_i)]/M_I}{[O(E_i) - OB(E_i)]/M_O}, \tag{2}$$

where N_j is the atomic density per cm^2 of the jth isotope in the sample. $I(E_i)$ and $O(E_i)$ are the foreground counts for the sample in and out, $IB(E_i)$ and $OB(E_i)$ are the background counts for sample- in and -out, and M_I and M_O are monitor counts for the sample-in and the open beam, respectively. We estimated the background level by using the resonance energies of the neutron TOF spectra of notch-filters of Co, In, and Cd. The magnitude of the background level was interpolated between the black resonances by using the fitting function $y = A_1 \exp(-x/t_1) + y_0$, where A_1, t_1 and y_0 are constants and x is the channel number of the time digitizer.

The neutron energy E in eV corresponding to each channel I in the TOF spectrum is derived from the following relation:

$$E = \left\{ \frac{72.3 \times L}{I \times W - \tau_0} \right\}^2, \tag{3}$$

where L is the neutron flight path in meters, W is the channel width in microseconds, and τ_0 is the time difference between the start time from the RF trigger and the real time zero when the neutron burst was produced. The flight path length L and τ_0 are determined by fitting channel numbers corresponding to the well-known resonance energy of the samples by using eq. (3). In this experiment, we used $W = 0.5$ μs and found $L = (12.06 \pm 0.02)$ m and $\tau_0 = (7.15 \pm 0.01)$ μs from the fitting. Then the energy resolution can be written by the expression as

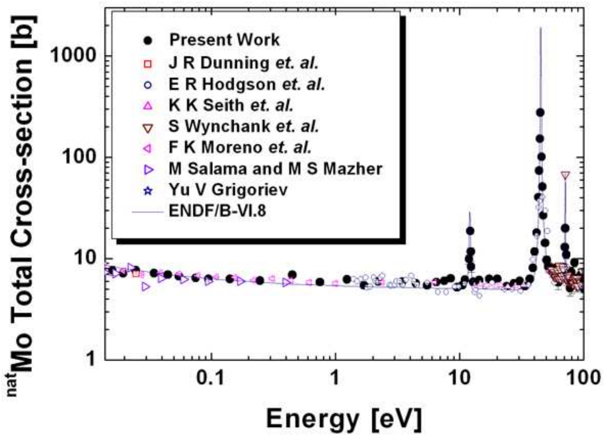

Figure 1. Total cross-sections of $^{\mathrm{nat}}$Mo.

$$\frac{\Delta E}{E} = 2\frac{\Delta t}{t}, \tag{4}$$

where the uncertainty (Δt) of the neutron TOF (t) is composed of uncertainties due to the flight path (2 cm), the moderator thickness (3 cm), the pulse width of the electron beam (1 μs), the channel width of the time encoder (0.5 μs), and the time jitter (negligibly small) from the neutron detector. The energy resolutions for the neutron energy of 0.01, 0.1, 1, 10 and 100 eV are 0.59%, 0.60%, 0.65%, 1.01% and 2.63%, respectively.

The neutron total cross-sections of natural Mo and Ta were obtained by taking the weighted average values of all samples in the energy range from 0.01 to 100 eV by using eqs (1) and (2). Then, we have calculated the effective total cross-sections for the same energy interval as follows:

$$\sigma_{\mathrm{eff}}(E) = \frac{\int_{E_i}^{E_f} \sigma(E) \cdot E \cdot \mathrm{d}E}{\int_{E_i}^{E_f} E \cdot \mathrm{d}E}. \tag{5}$$

The total cross-sections by this analysis with other reported values [5–19] are given in figures 1 and 2.

4. Evaluations of resonance parameters

To determine the resonance parameters of each resonance's peak, we fitted all the transmissions as well as total cross-sections data of Ta with the SAMMY code [20]. The neutron total cross-sections were evaluated from the multilevel R-matrix theory [21] in the Reich–Moore approximation [22] as follows:

$$\sigma_{\mathrm{T}} = \frac{2\pi}{k^2} g \left\{ 1 - \cos 2\phi \left(1 - \frac{\Gamma_1 \Gamma}{2d} \right) - \sin 2\phi \frac{\Gamma_1 (E_\lambda - E)}{d} \right\}. \tag{6}$$

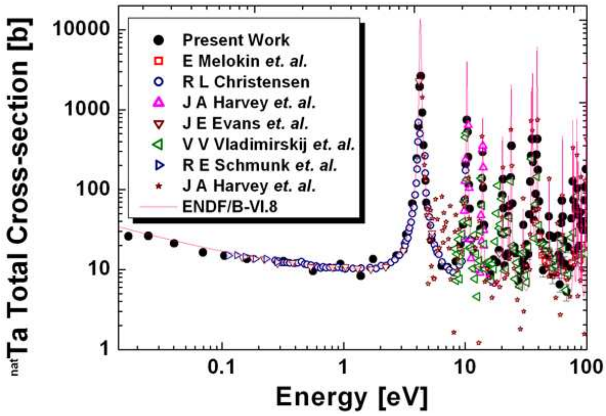

Figure 2. Total cross-section of $^{\mathrm{nat}}$Ta.

Here k is the wave number associated with the incident channel, ϕ is the potential scattering phase shift, g is the spin statistical factor, E is the neutron energy, and E_λ is the resonance energy. Γ and Γ_1 are the sum of partial widths and a partial width of the decay channel 1, respectively. d can be defined as

$$d = \left\{ (E_\lambda - E)^2 + \left(\frac{\Gamma}{2}\right)^2 \right\}. \tag{7}$$

In the SAMMY code, the Bayes' theorem (generalized least squares) is used to fit the experimental data to get the resonance parameters. For the Doppler broadening and resolution analysis, the MULTI method [23] is applied: the free gas model is applied to the Doppler broadening and the convolution of Gaussian and exponential function to the resolution. Resolution function $R(E, E')$ used in this calculation is the convolution of Gaussian and exponential function and its mathematical expression is as follows:

$$R_{\mathrm{GE}}(E, E') = \frac{1}{\Delta_{\mathrm{E}} \Delta_{\mathrm{G}} \sqrt{\pi}} \int_{E-\Delta E_{\mathrm{S}}}^{\infty} \mathrm{d}E^0 \exp\left\{ -\frac{(E^0 - (E - \Delta E_{\mathrm{S}}))}{\Delta_{\mathrm{E}}} \right\} \times \exp\left\{ -\frac{(E' - E^0)^2}{\Delta_{\mathrm{G}}^2} \right\}, \tag{8}$$

where the width of Gaussian resolution function Δ_{G} is given by

$$\Delta_{\mathrm{G}} = E[aE + b]^{1/2} \tag{9}$$

and the width of exponential resolution function Δ_{E} is given by

$$\Delta_{\mathrm{E}} = cE^{3/2}. \tag{10}$$

The energy shift ΔE_{S}, which is automatically determined in the SAMMY, is introduced in order to locate the maximum of the broadening function at $E' = E$. The

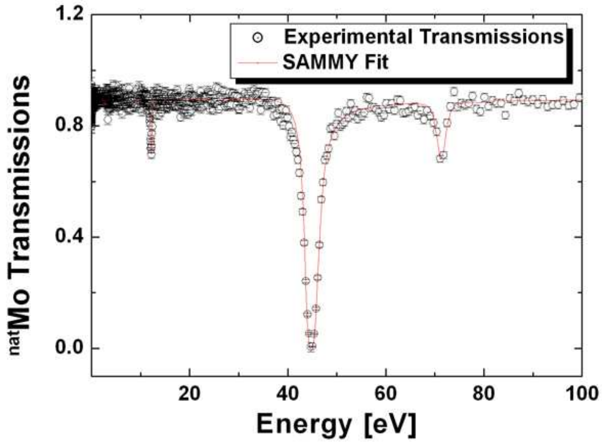

Figure 3. Experimental transmissions of Mo and SAMMY fit.

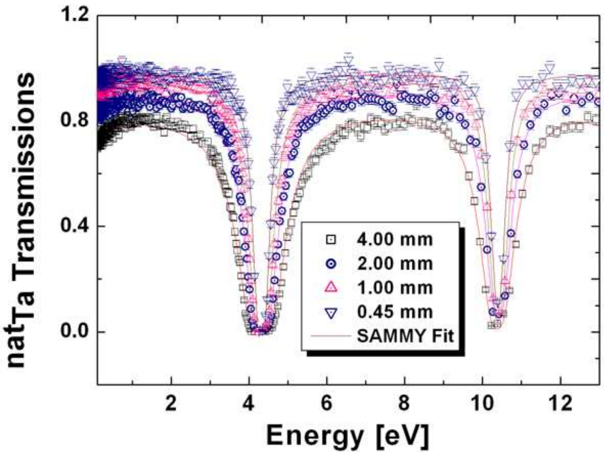

Figure 4. Experimental transmissions of Ta and SAMMY fit.

constant values of a, b, and c are 1.09 $\times 10^{-6}$ eV^{-1}, 7.33 $\times$ 10^{-6}, and 5.37 $\times$ 10^{-4} eV$^{-1/2}$, respectively.

The evaluated resonance parameters are given in table 1. The transmissions and SAMMY fitting curves are shown in figures 3 and 4.

5. Conclusions

The Pohang Neutron Facility (PNF) in Korea, which consists of a 100 MeV linac, with a Ta target surrounded by the water moderator, and 12.06 m flight path has been used for the measurement of total cross-sections of natural molybdenum and tantalum. These neutron total cross-sections were determined from sample-in and sample-out transmission measurements for neutron energies from 0.01 to 100 eV.

Table 1. Resonance parameters of Ta-181 isotope obtained by this evaluation with Christensen [13], Harvey *et al* [14] and Mughabghab [24]. The symbols E_λ, Γ_γ, and Γ_n are resonance energy, gamma width and neutron width, respectively.

J		E_λ (eV)	Γ_γ (meV)	Γ_n (meV)
	Present	4.3107 ± 0.0002	156.870 ± 0.405	1.414 ± 0.002
4	Christensen	4.29 ± 0.02	–	1.9
	Mughabghab	4.28 ± 0.02	53 ± 4	3.200 ± 0.142
	Present	10.3991 ± 0.0011	199.790 ± 3.047	2.202 ± 0.005
3	Christensen	10.36 ± 0.05	–	2.5
	Harvey *et al*	10.38 ± 0.10	50 ± 10	4.5 ± 0.5
	Mughabghab	10.36 ± 0.05	65 ± 6	4.00 ± 2.06
	Present	13.9260 ± 0.0032	154.930 ± 9.631	0.748 ± 0.007
4	Christensen	13.9 ± 0.1	–	1.3
	Harvey *et al*	13.95 ± 0.12	50 ± 10	1.04 ± 0.08
	Mughabghab	13.95 ± 0.05	54 ± 4	1.013 ± 0.026
	Present	20.4207 ± 0.0056	198.380 ± 4.238	0.858 ± 0.006
3	Christensen	20.7	–	1.1
	Mughabghab	20.29 ± 0.10	52 ± 5	1.097 ± 0.046
	Present	22.9468 ± 0.0015	262.700 ± 8.104	0.436 ± 0.067
3	Harvey *et al*	22.8 ± 0.3	50 ± 10	0.25 ± 0.04
	Mughabghab	22.72 ± 0.10	60 ± 10	0.240 ± 0.023
	Present	24.0586 ± 0.0081	248.670 ± 4.277	2.624 ± 0.019
4	Christensen	24.2 ± 0.2	–	5
	Harvey *et al*	24.0 ± 0.3	50 ± 10	6.1 ± 0.7
	Mughabghab	23.92 ± 0.10	62 ± 6	5.155 ± 0.178
	Present	30.1994 ± 0.016	38.142 ± 3.614	0.279 ± 0.082
3	Harvey *et al*	30.1 ± 0.3	50 ± 10	0.23 ± 0.05
	Mughabghab	30.02 ± 0.05	55 ± 11	0.320 ± 0.034
4	Present	34.4811 ± 0.0076	411.910 ± 2.878	1.463 ± 0.121
	Mughabghab	34.19 ± 0.05	60 ± 10	0.169 ± 0.018
	Present	35.2921 ± 0.0144	200.180 ± 3.631	7.840 ± 0.096
3	Harvey *et al*	35.4 ± 0.4	50 ± 10	17 ± 2
	Mughabghab	35.14 ± 0.05	69 ± 6	18.286 ± 1.143
	Present	36.0222 ± 0.0156	238.810 ± 3.597	5.055 ± 0.102
4	Christensen	36.7 ± 0.3	–	11.7
	Harvey *et al*	36.1 ± 0.4	50 ± 10	18 ± 2
	Mughabghab	35.90 ± 0.05	65 ± 7	14.222 ± 0.098
	Present	39.2171 ± 0.0062	539.160 ± 0.138	10.687 ± 0.672
4	Christensen	39.4 ± 0.5	–	8.6
	Harvey *et al*	39.3 ± 0.5	50 ± 10	51 ± 5
	Mughabghab	39.12 ± 0.06	60 ± 7	44.467 ± 0.800
	Present	49.1841 ± 0.0001	38.381 ± 0.145	1.118 ± 0.001
3	Harvey *et al*	49.4 ± 0.6	50 ± 10	1.1 ± 0.3
	Mughabghab	49.13 ± 0.08	54 ± 6	1.20 ± 0.11

Table 1. *Contd...*

J		E_λ (eV)	Γ_γ (meV)	Γ_n (meV)
	Present	56.9497 ± 0.0004	56.877 ± 1.008	0.031 ± 0.002
4	Harvey *et al*	57.5 ± 0.7	50 ± 10	0.5 ± 0.2
	Mughabghab	57.53 ± 0.08	⟨55⟩	0.249 ± 0.027
	Present	58.3752 ± 0.0060	51.645 ± 1.735	0.573 ± 0.006
	Mughabghab	59.05 ± 0.08	⟨55⟩	0.116 ± 0.027
	Present	62.979 ± 0.006	226.51 ± 14.33	3.443 ± 0.037
4	Harvey *et al*	62.9 ± 0.8	50 ± 10	10 ± 2
	Mughabghab	63.11 ± 0.08	64 ± 7	4.800 ± 0.533
	Present	75.5107 ± 0.0022	27.121 ± 5.442	3.516 ± 0.046
4	Mughabghab	76.85 ± 0.08	49 ± 15	10.667 ± 0.889
	Present	76.9689 ± 0.0009	49.239 ± 2.802	10.880 ± 0.021
4	Harvey *et al*	77.2 ± 1.3	50 ± 10	10 ± 2
	Mughabghab	77.61 ± 0.10	56 ± 15	4.444 ± 0.444
3	Present	78.4618 ± 0.2520	25.994 ± 5.753	4.418 ± 0.003
	Mughabghab	78.95 ± 0.04	⟨55⟩	1.943 ± 0.229

To observe the effect of thickness we carried out transmission experiments for four different tantalum metallic sheets with thicknesses 4.00, 2.00, 1.00, and 0.45 mm. The thicker the sample, the more sensitive is the data observed to the cross-section structure. These are more sensible to the total cross-section between resonances and especially to the resonance wings.

Resonance parameters of Mo and Ta were determined by a consistent analysis in which corrections for Doppler broadening, resolution broadening, and other experimental effects were incorporated to the Bayesian SAMMY code.

PNF transmission data sets were analyzed sequentially so that each fit was connected to the previous set by the SAMMY parameter covariance matrix, thereby obtaining energies and widths. In this analysis negative-energy resonances were also included to account for bound levels and several additional energy resonances were considered to account for the effect of resonances above the SAMMY fitting range. Fits were obtained for all sets of transmission data. The experimental transmission data and SAMMY fits were good with possibly minimum Chi-sq/N values.

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