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DETERMINATION OF THE RESONANCE CHARACTERISTICS OF NIOBIUM-93 AND NATURAL TUNGSTEN

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ABSTRACT

The mean resonance parameters for niobium-93 and natural tungsten were evaluated using the resolved resonance data in the ENDF/B files and the results of transmission measurements performed on the 1000 m time base of the IBR-30 over the 0.465-200 keV range. The scope for and problems of assigning mean resonance parameters to isotope mixtures are discussed.

Introduction

Improving the accuracy of nuclear data on structural materials for reactors is important in order to improve the reliability of nuclear power generation facilities. The issue is particularly pressing for such materials as niobium and tungsten which are used in nuclear transport facilities and nuclear reactors. At present, the accuracy of the nuclear physics constants for these materials is poor, particularly in the unresolved resonance region. The aim of this article is to re-evaluate the mean resonance parameters for niobium and tungsten using the available resonance parameter library files, and the experimental transmission and cross-section values obtained in Ref. [1]. In addition, an optimum set of mean parameters is introduced to describe the resonance structure of the natural tungsten isotope mix.

Methodology for the correction of the experimental data

The resonance structure in neutron cross-sections causes resonance blocking and, consequently, the experimental transmission functions differ from the values calculated from the mean group total cross-sections. The logarithm of their ratios can be used to characterize this blocking quantitatively. These ratios were obtained from the transmission value T_{calc} and the total cross-section $\sigma_{t\,calc}$ which were calculated using the ENDF/B files. These values were used to convert the experimental results:

$$\sigma_{t\,exp} = (\sigma_{t\,calc}\, n + \ln T_{calc} - \ln T_{exp})/n \qquad (1)$$

where n is the filter sample thickness.

The expected averaged total cross-section value is determined using the formula:

$$\sigma_{t\,exp} = \sum_i w_i^{-2} \sigma_{t\,exp} \sum_i w_i^{-2} \qquad (2)$$

where $w_i = \Delta T^i_{exp} / T^i_{exp}\, n_i$, and ΔT is the experimental transmission error level for a filter of thickness n_i.

The error level of the total cross-section was determined using the following formula:

$$\Delta\sigma_{t\,exp} = \sqrt{\sum_i w_i^2 / N^3} \qquad (3)$$

where N is the number of filter samples.

The resonance blocking effect can be corrected by recalculating using formula (1) in the unresolved resonance region.

Determination of the strength functions

The neutron strength functions may be obtained from the experimental total cross-sections using the method of least squares and Hauser-Feshbach formalism, as is recommended in the procedures of the ENDF/B library [2]. It should be noted that the cross-sections calculated using Hauser-Feshbach formalism are averaged mean group cross-sections which fluctuate owing to the finite number of resonances in the group. The statistical error levels z_j for the cross-section in the j-th group may be estimated using random resonance series, as is shown in Ref. [3]. To minimize the function, an expression of the following type was used:

$$L_t = \sum_{j=1}^{g} (\sigma_{jt\ exp} - \sigma_{jt\ HF})^2 / (\Delta\sigma_{jt\ exp}^2 + z_{jt}^2) \qquad (4)$$

where $\sigma_{j\ HF}$ is the cross-section calculated using Hauser-Feshbach formalism. The radiative capture widths Γ_γ were changed as well as the neutron strength functions. This was done by fitting the data to the mean group cross-sections σ_γ obtained from the ENDF/B data using the following expression:

$$L_\gamma = \sum_{j=1}^{g} (\sigma_{j\gamma} - \sigma_{j\gamma\ HF})^2 / z_{j\gamma}^2 \qquad (5)$$

where $z_{j\gamma}$ is the estimated fluctuation for the mean group cross-section $\sigma_{j\gamma}$.

Mean resonance parameters of niobium-93

To determine the mean resonance parameters of niobium-93, the experimental transmission values and cross-sections from Ref. [1] were used and the data from the

ENDF/B-4 library which were derived from the measurements in Ref. [4] and the analysis in Ref. [5]. The resolved resonance region here extends to 7.5 keV. The mean resonance parameters in ENDF/B are given for l = 0;1. Table 1 gives the ENDF/B-4 parameters which were obtained from resolved resonance statistics (columns 1 and 2). The results of our analysis are given in column 3.

The method recommended in Ref. [6] was used for the statistical analysis. The recommendations of Ref. [7] were followed to obtain resonance parameters with different values of J, and the dependence of the mean density on J was determined using a formula derived from the Fermi gas model [6]:

$$\rho_J = K[e^{-J^2/2\sigma^2}] - e^{-(J+1)^2/2\sigma^2}] \quad (6)$$

where K is a constant and σ = 3.3 for niobium [8].

For low values of J, the density is represented more simply as $\rho = (2J+I)\rho_0$. For niobium-93, the value of J is not low since the spin of the nucleus I = 4.5. Consequently, the distance between levels D_J rises as J increases contrary to what is given in ENDF/B-4.

The mean resonance parameters shown in Table 1 (column 3) were obtained by fitting the data using the ENDF/B-4 evaluated data (column 2). The s and p neutron strengthen functions were fitted. As may be seen, the s strength function only changed by 14%, whereas the p strength function almost doubled. These changes in the strength functions are due to the fact that the p-resonances have been less accurately determined than the s-resonances.

Mean resonance parameters for natural tungsten

In order to reduce the number of neutron parameters for the isotope mixture of natural tungsten in particular, we attempted to introduce certain formal parameters. It is assumed that natural tungsten consists of four isotopes: ^{182}W(26.4%), ^{183}W(14.4%), ^{184}W(30.6%), ^{186}W(28.4%); we ignore ^{185}W owing to the small quantities involved. The ENDF/B-4 files only give resolved resonance parameters for the wave l = 0. From these, the mean resonance parameters can be derived and they are given in Table 2.

For the p-resonances, the data were taken from Ref. [9] where the p strength functions have the following values: ^{182}W (S_1 = 7.2E-5), ^{183}W (S_1 = 7.2E-5), ^{184}W (S_1 = 5.8E-5), ^{186}W (S_1 = 3.7E-5). They were used to obtain the initial value S_0 for natural tungsten.

Natural tungsten consists of the nuclei of four isotopes of approximately identical weight and size, which simplifies the task of introducing generalized mean resonance parameters. In addition, Breit-Wigner single-level resonance formalism is applied in this case. The main formulae for determining the generalized mean parameters from the components of the resonance parameters for the individual isotopes are given below. Working from simple physical principles it follows that the mean distances between resonances for the spins J and l must be determined using the formula:

$$D^{J,l}=1/\sum_i 1/D_i^{J,l} \qquad (7)$$

Since the cross-sections at infinite dilution are proportional to the strength functions, the generalized strength function for the isotope mixture must be represented by the expression:

$$= \sum_i \rho_i S_i \qquad (8)$$

where ρ_i is the content of the i-th isotope in the mixture.

The mean generalized resonance widths are obtained by multiplying the mean distances by the strength functions; the statistical characteristics of the widths do not change if they are identical for all components of the various isotopes.

The spin of the nucleus in the ground state l in the formulae is required only for the calculation of the statistical weight g_J, and therefore the unique spin I can be introduced for the mixture (in this case I = 0) while selecting J in such a way that g_J does not change. For natural tungsten, unusual spins of J = -0.25; 0.25 are obtained owing to the isotope ^{183}W, i.e. the spin J loses its physical sense for the isotope mixture and becomes a formal resonance parameter.

The parameters given in Table 2 were used as the source data when fitting the S - strength functions. The resonance parameters from Ref. [10] were used to fit the p - strength functions.

The data on the resonance series of the compound nucleus were obtained assuming that the strength functions S(l-l;J) were not dependent on J and may be determined according to the rule set forth in Ref. [7]:

$$(l,J) = (2l+1)S; / \sum_J g_J \qquad (9)$$

When determining the mean distances, it was assumed that the level density was not dependent on parity [7] and in this way the mean distances and initial strength functions were obtained for the p-resonances. The mean radiation widths Γ_γ were obtained by fitting the data to the mean group cross-sections $<\sigma_\gamma>$ calculated from the ENDF/B files which yielded the negligibly small p - strength functions $S_1 < 10^{-9}$.

Table 3 gives the initial and final mean resonance parameters for natural tungsten.

The mean group cross-sections were calculated using the final mean resonance parameters for niobium-93 and natural tungsten. The calculated cross-sections obtained agree with the experimental values within the limits of error.

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Table 1

Mean resonance parameters of niobium-93

Parameter	l = 0			l = 1		
	1	2	3	1	2	3
S(l)	1,55E-5	4.41E-5	5.00E-5	7,42E-5	2,04E-4	3.98E-4
D(l)	69,795	64,86	64,86	61,19	57,67	57,67
Γ_n(J=3)				1,144E-2	5,37E-2	1,05E-1
D(J=3)				349,6	176,4	176.4
Γ_n(J=4)	1,934E-3	5,08E-3	5,75E-3	1,471E-2	3,01E-2	5,90E-2
D(J=4)	155,1	115,1	115,1	271,9	197,5	197,5
Γ_n(J=5)	2,364E-3	6,55E-3	7,42E-3	1,798E-2	3,88E-2	7,61E-2
D(J=5)	126,9	148,6	148,6	222,5	254,9	254,9
Γ_n(J=6)				2,124E-2	1,14E-1	2,22E-1
D(J=6)				188,3	372,6	372,6
S(J=3)				3,27E-5	3,05E-4	5,96E-4
S(J=4)	1,25E-5	4,41E-5	5,00E-5	5,41E-5	1,52E-4	2,98E-4
S(J=5)	1,86E-5	4,41E-5	5,00E-5	8,08E-4	1,52E-4	2,98E-4
S(J=6)				1,13E-4	3,05E-4	5,96E-4
Γ_γ	2,00E-1	1,92E-1	1,12E-1	2,40E-1	2,07E-1	2,10E-1

The mean widths and distances between resonances are given in eV in the tables. The error levels are 8.6% for the s-resonances and 8.3% for the p-resonances.

Table 2

Mean resonance parameters of the tungsten isotopes

Isotope	Parameter					
	I	J	D	Γ_n	S_0	Γ_γ
W-182	0	0,5	68,30	1,91E-2	2,81E-4	6,29E-2
W-183	0,5	0	51,71	1,18E-2	2,28E-4	6,75E-2
W-183	0,5	1	18,88	4,29E-3	2,27E-4	6,75E-2
W-184	0	0,5	69,28	1,98E-2	2,86E-4	6,87E-2
W-186	0	0,5	79,10	1,84E-2	2,33E-4	6,45E-2

Table 3

Mean resonance parameters for natural tungsten

Parameter	L							
	0				1			
J	-0,25	0,25	0,5	-0,25	0,25	0,5	0.75	1,5
D	51,71	18,88	23,97	54,00	18.00	23,97	10,80	12.00
Initial generalized resonance parameters								
$S_n 10^5$	3,27	3,27	24,2	1,38	1,38	4,75	1,38	4,75
$\Gamma_n 10^4$	17,0	6,14	58,0	7,45	2,48	11,4	1,49	5,70
$\Gamma_\gamma 10^3$	12	12	12	8,8	8,8	8,8	8,8	8,8
S_0=2,75E-4					S_1=7,84E-5			
Final generalized resonance parameters after fitting								
$S_n 10^5$	2,46	2,46	18,1					
$\Gamma_n 10^4$	12,7	4,62	4,34					
$\Gamma_\gamma 10^3$	23,3	23,3	23,3					
$S\ 10^4$ = 2,06 ± 0,12, Statistical error level - 5.5%								

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