Total neutron cross sections and average parameters of the resonances of the ^{115}In nucleus in the energy range $E=2$–614 keV

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Average total neutron cross sections have been measured. Effects of a resonance self-screening of the nucleus ^{115}In in the energy range 2–614 keV are studied. The average parameters of the resonances for *s* and *p* waves are found through an analysis of the data.

1. The cross sections for the radiative capture of neutrons by ^{155}In and that for inelastic scattering involving the excitation of the first (isomer) level of this nucleus are used as standards in measuring the neutron cross sections of other nuclei. They are also used in applied research. When reliable experimental data are available on the neutron cross sections of a nucleus, the average parameters of the resonances of the nucleus can generally be determined very accurately. The information currently available on the average parameters of the ^{115}In resonances is extremely limited and even contradictory. For example, the value reported in Ref. 1 for the *p*-neutron strength function, $S^1=(2.5\pm0.5)\times10^{-4}$, differs by a factor of nearly 2 from the estimate in Ref. 2, $S^1=(4.35\pm0.65)\times10^{-4}$. There are no data on the *p*-wave potential-scattering parameter R_1^∞

The reliability with which the average parameters of resonances are determined for the partial neutron waves with $l>0$ can be improved by including in the analysis some additional experimental information on neutron cross sections found in the region of unresolved resonances. Accordingly, total neutron cross sections averaged over resonances have been measured at the VVR-M nuclear reactor of the Institute of Nuclear Research of the Ukrainian Academy of Sciences. A set of neutron filters was used. We studied the effects of a resonance self-screening for ^{115}In in the energy range $E_n=2$–614 keV. Analysis of the results yields average parameters of the resonances of this nucleus for *s*- and *p*-neutron waves.

2. The total neutron cross sections were measured in neutron-transmission experiments. Beams of quasimonoenergetic neutrons were formed by sending the neutrons with the reactor spectrum through interference filters based on materials enriched in the stable isotopes ^{52}Cr, ^{54,56}Fe, and ^{58,60}Ni (Refs. 3 and 4). This approach made it possible to distinguish neutrons with average energies $E_n=3.5$ keV [the half-width at half-maximum (HWHM) of this neutron line is 2.5 keV], 12.0 keV (the HWHM is 0.7 keV), 24 keV (2 keV), 144 keV (25 keV), and 610 keV (7 keV). Neutrons transmitted through the sample and neutrons of the direct beam were detected by gas-filled proportional counters (an SNM-52 ^{3}He counter for energies $E_n\leqslant12$ keV and an SNM-38 hydrogen counter for $E_n > 12$ keV). The measurement procedure and the procedure for analyzing the raw experimental data are described in detail in Ref. 4. As test samples we used a set of metal plates of natural indium. The plates were 15 mm in diameter and had thicknesses ranging from 0.0044 to 0.042 nuclei/b (nuclei per barn).

The transmission averaged over the neutron spectrum was found as the ratio of the total number (N) of counts in the detector from neutrons which passed through the sample (on the one hand) to the number (N_0) of counts due to neutrons of the direct beam (on the other):

$$\langle T\rangle = N/N_0. \tag{1}$$

The total neutron cross section observed for a given sample thickness n is found as

$$\tilde{\sigma}_t = -\frac{1}{n}\ln\langle T\rangle. \tag{2}$$

Figure 1 shows the results on the cross sections $\tilde{\sigma}_t$ as a function of the thickness n (this is the so-called resonance self-screening effect).

3. The average transmission in (1) can be written in the form

$$\langle T\rangle = \frac{\int \varphi(E)\exp[-n\sigma_t(E)]dE}{\int \varphi(E)dE}, \tag{3}$$

where $\varphi(E)$ is the neutron energy distribution function in the beam, and $\sigma_t(E)$ is the total neutron cross section.

Since the quantities $\langle T\rangle$ and $\tilde{\sigma}_t$ are sensitive to the structural details of the cross sections, we parametrized them through a Monte Carlo simulation of the resonance structure in $\sigma_t(E)$. The method used for this simulation is described in Ref. 5. Using this method, we generated random values of the parameters of the resonances over the energy range corresponding to each filter. Working from these parameter values, we then directly calculated the cross sections $\sigma_t(E)$ and their functionals (3) and (2). To calculate the cross sections we used the R-matrix approximation of isolated resonances, taking the Doppler effect into account.

In generating the resonance structure with the help of random numbers, we adopted a Wigner distribution for the distances between levels, and a Porter–Thomas distribution for the neutron widths. The radiation widths Γ_γ were assumed to have no fluctuations. The resonance parameters of each system of levels with a given angular momentum J and a given parity π were generated independently. The value of the average distance ($\bar{D}_J$) between levels used in this process can be related to the distance ($\bar{D}^0$) observed between s-wave resonances in the low-energy region,[5] and the average neutron partial width $\bar{\Gamma}^{sl}_{nJ}$ can be related to the strength function:

$$S^l \equiv \frac{\rho\bar{\Gamma}^{sl}_{nJ}d_l}{\sqrt{E}p_l\bar{D}_J}, \tag{4}$$

where l and s are the orbital angular momentum and spin of the channel, p_l is the penetrability factor, $\rho = k_a$, k is the wave number, a is the radius of the nucleus

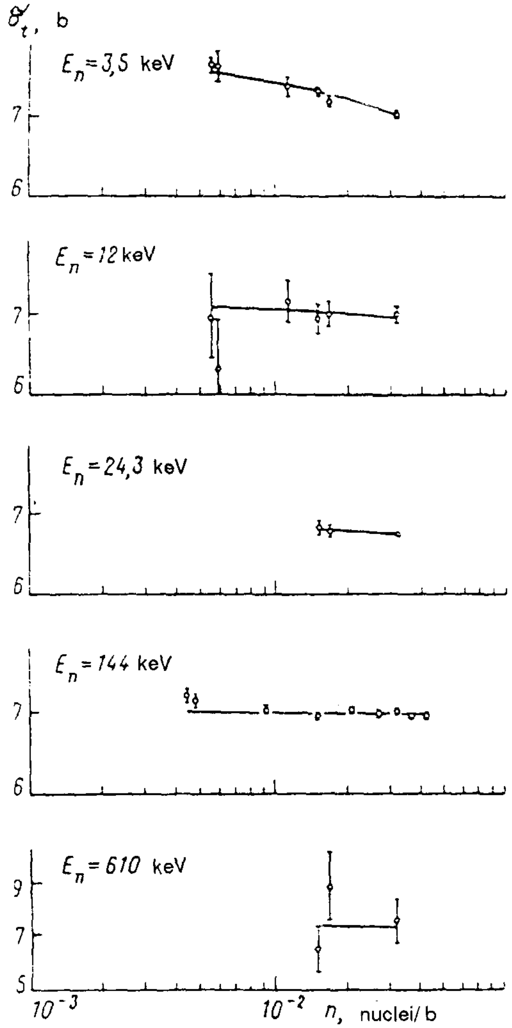

FIG. 1. Observed total neutron cross sections $\tilde{\sigma}_t$ of the ^{115}In nucleus versus the sample thickness n. The solid curves are a description of the data by the Monte Carlo method.

($a=1.35\cdot A^{1/3}$ fm), and d_l is a renormalization coefficient.[6] The potential-scattering phase shifts φ_l were parametrized through the nonresonance components R_l^∞ which were singled out in the R matrix. These components reflect the contribution of remote levels:

$$\varphi_l=\phi_l-\arctan\frac{p_lR_l^\infty}{1-s_l^0R_l^\infty}, \tag{5}$$

where ϕ_l is the phase shift in scattering by an impenetrable sphere, $s_l^0\equiv s_l-B_l$, s_l is the shift factor, and B_l is a parameter of the boundary condition, specifically, $B_l=-l$.

To generate the resonance structure at random, we thus need the following set of average parameters: $\bar{D}^0$, S^l, R_l^∞, and $\tilde{\Gamma}_\gamma$. Since $\tilde{\sigma}_t$ exhibits a slight sensitivity to the

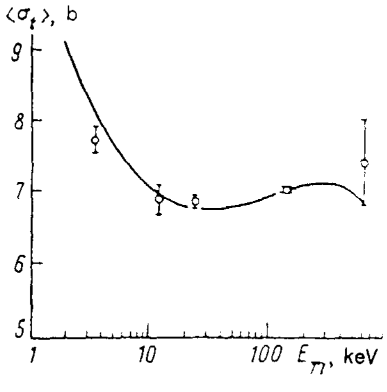

FIG. 2. Average total neutron cross sections of ^{115}In. The indicated errors include, in addition to the experimental errors, fluctuation errors corresponding to the energy interval of the averaging.

average radiative width, we did not vary the value of the latter; we took it to be[1] $\tilde{\Gamma}_\gamma = 0.0887$ eV. The optimum values of the other parameters were found by a variation procedure, by the least-squares method in a parametrization of the experimentally observed cross sections $\tilde{\sigma}_t$.

4. A separate analysis of the data obtained for each of the filters made it possible to determine the average total cross sections $\langle\sigma_t\rangle$ corresponding to the energy intervals of these filters (Fig. 2). For the curves in Fig. 1, they correspond to an extrapolation of the observed cross sections to zero thickness. We see some increase in $\langle\sigma_t\rangle$ in Fig. 2 at $E_n \sim (30\text{–}300)$ keV. It is due to a substantial increase in the p-wave contribution in this region, which is in turn attributed to a substantial value of the p-neutron strength function of the ^{115}In nucleus in the region of a $3p$ resonance.

The average parameters of the resonances of ^{115}In were found through a joint analysis of all the measurements. In a first cycle of calculations we studied the sensitivity of the observed cross sections to the average distances between resonances ($\bar{D}^0$) and to the potential-scattering parameter for the p-neutron wave, R_1^∞. For this purpose we used the least-squares method to vary the set of all parameters to which the cross sections $\tilde{\sigma}_t$ are sensitive: $\bar{D}^0$, S^0, R_0^∞, S^1, and R_1^∞ As a result, we found the values $\bar{D}^0 = 10.7 \pm 5.2$ eV and $R_1^\infty = -0.42 \pm 0.24$. Within the errors, these values agree with data in the literature, $\bar{D}^0 = 10.7 \pm 0.6$ eV (this is an estimate[1] over the region of resolved resonances) and $R_1^\infty = -0.2$ (an estimate for ^{115}In on the basis of the systematics[7] of neighboring nuclei). However, all the parameter values found in this cycle have large errors ($\geqslant 50\%$), and they correlate with each other strongly (the correlation coefficients are $\rho = 0.8\text{–}0.9$). It is thus not possible to refine the existing data.

In a second cycle of calculations, the quantities $\bar{D}^0$ and R_1^∞ to which the cross sections $\tilde{\sigma}_t$ are least sensitive, were not varied. Their values were specified in accordance with Refs. 1 and 7: $\bar{D}^0 = 10.7$ eV and $R_1^\infty = -0.2$. This approach substantially reduced the errors in the other parameters. The values found for the average parameters of the ^{115}In resonances are $S^0 = (0.48 \pm 0.06) \times 10^{-4}$, $R_0^\infty = 0.11 \pm 0.03$, and $S^1 = (3.7 \pm 0.3) \times 10^{-4}$.

In the literature, one often finds the scattering radius $R'=a(1-R_0^\infty)$ used in place of the parameter R_l^∞ for $l=0$. For the value found for R_0^∞ this radius is $R'=5.8\pm0.1$ fm. This value, like the value found for S^1, agrees better with the systematics for neighboring nuclei[7] than do the corresponding estimates in Refs. 1 and 2. The accuracy in the determination of the other average parameters of the resonances for $l\geqslant 1$ may possibly be improved by including in the analysis some additional experimental data, e.g., data on the cross sections for radiative capture.

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