Inelastic scattering of neutrons and energy dependence of the *p*-neutron strength function

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Analysis of data in the literature on the cross section for the inelastic scattering of neutrons accompanied by the excitation of the 2^+, 45-keV level of uranium-238 yields local values of the p-neutron strength function S_{n1} for the neutron-energy interval $E_n = 82$–275 keV. At energies $E_n \leqslant 275$ keV, no energy dependence of S_{n1} outside the experimental errors ($\sim 15\%$) is found.

The neutron strength functions S_{nl} of heavy nuclei in a limited energy interval $E_n \leqslant 0.5$ MeV corresponding to the region of isolated resonances are generally assumed[1] to be independent of the neutron energy E_n. This assumption is based on the optical–statistical model, which gives a satisfactory parametrization of the neutron cross sections averaged over the resonances under the assumption of a fragmentation of the strength of the one-particle states among compound resonances.[2]

Contemporary semimicroscopic and microscopic models predict an intermediate structure in the distribution of the one-particle neutron strength not only at low nuclear excitation energies, but also at excitation energies above the neutron binding energy (Ref. 3, for example). If intermediate structure were to be observed on the energy dependence of S_{nl}, we would be forced to reexamine several results of model-dependent calculations, e.g., the calculations of the cross sections for the radiative capture of neutrons by nuclei in an excited state. These cross sections are required for astrophysical estimates of the s-process of stellar nucleosynthesis.[4]

Only the neutron strength functions for the s and p partial neutron waves, i.e., S_{n0} and S_{n1}, can be determined comparatively reliably through an analysis of neutron cross sections at energies $E_n \leqslant 0.5$ MeV (Ref. 1). However, even these strength functions are difficult to determine over the entire interval of isolated resonances, because the cross sections are highly sensitive to other parameters. The cross section for the inelastic scattering of neutrons, σ_{inel}, accompanied by the excitation of the 2^+ first level of even–even nuclei is an exceptional case. Because of the difference between the spins of the ground level and the excited level, the cross section σ_{inel} is dominated by the p-neutron wave over the entire energy range from the reaction threshold up to $E_n \sim 0.5$ MeV. It was shown in Ref. 5 for the particular examples of ^{232}Th and ^{238}U that analyzing σ_{inel} for even–even nuclei is one of the most reliable methods for determining the neutron strength function S_{n1} in the region of unresolved isolated resonances.

The average resonance parameters of this nucleus (the neutron strength functions S_{n0}, S_{n1}, and S_{n2} and the average radiation widths of the s and p resonances), optimized over a broad energy range, were determined in Ref. 6 through a joint analysis of $\sigma_{\rm inel}$ and the cross section (σ_γ) for the radiative capture of neutrons of ^{238}U over the energy range E_n=0–275 keV. In this paper, we take the approach of Refs. 5 and 6: Analyzing data[5-11] on $\sigma_{\rm inel}$ of ^{238}U, we find local values of the p-neutron strength function S_{n1} within an error ~15% over the energy interval E_n= 82–275 keV. By supplementing the results with data[1] from the region of resolved resonances we can analyze the energy dependence of S_{n1} over the broad energy range E_n=0–275 keV, corresponding to the region of well-isolated resonances.

The formalism for parametrizing $\sigma_{\rm inel}$ is described in detail in Ref. 6. In this parametrization one uses an expression of the type

$$\sigma_{\rm inel}=\frac{2\pi^2}{k^2}\sum_{J\pi l}\frac{g(J)}{D_j}\frac{\Gamma_n^{jl}}{\Gamma_j}\sum_{l'}\Gamma_{n'}^{jl'}F, \tag{1}$$

where $g(J)$ is a statistical factor; D_j is the average distance between resonances with spin J; Γ_j, Γ_n^{jl}, and $\Gamma_{n'}^{jl'}$ are, respectively, the average values of the total width of the resonance and of the partial widths for the elastic and inelastic scattering of neutrons with orbital angular momenta l and l'; and F is a fluctuation factor, which reflects the difference between the product of the average values of the widths and the average value of their product.

The partial widths for the channels of elastic scattering (Γ_n^{jl}) and inelastic scattering ($\Gamma_{n'}^{jl}$) are parametrized by means of the neutron strength functions S_{nl}, in the form

$$\Gamma_{n(n')}^{jl}=\frac{S_{nl}}{d_l(E_{n(n')})}D_j\nu_{n(n')}^{jl}\,v_l(E_{n(n')})E_{n(n')}^{1/2}, \tag{2}$$

where $E_{n(n')}$ is the energy of the neutrons in the elastic (inelastic) scattering channel, v_l is the normalized optical penetrability,[12] $\nu_{n(n')}^{jl}$ is the degree of degeneracy of the total angular momentum J of the composite system for the channel of elastic (inelastic) scattering (i.e., the number of degrees of freedom in the channel), and d_l is a renormalization factor.[6]

The first excited level of ^{238}U is collective, so there cannot be any nonstatistical strengthening of the inelastic-scattering channel by virtue of pre-equilibrium states of the ("two particles plus a hole" type). Such a strengthening was observed in Ref. 13 for ^{187}Os, and a similar strengthening is expected at low energies for several other nuclei with low-lying levels which are clearly of a one-particle (or one-quasiparticle) nature.[14] Another type of nonstatistical strengthening, which arises because of a coupling of the entrance channel with collective phonon excitations, becomes discernible only in the region of partially overlapping resonances (Ref. 15, for example). The fluctuation factor F in (1) was calculated in the approximation that there is no correlation (coupling) of the channels of elastic and inelastic scattering. The procedure for calculating F is described in detail in Ref. 6.

The experimental data of Refs. 5–11 on the cross section for inelastic neutron scattering, $\sigma_{\rm inel}$, accompanied by the excitation of the first level of uranium-238

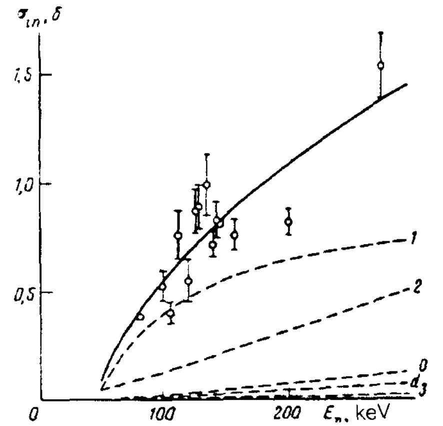

FIG. 1. Cross section for inelastic neutron scattering accompanied by the excitation of the 2^+, 45-keV first level of uranium-238. The points are experimental data.[5-11] Dashed curves 0, 1, 2, 3, and d—The contributions to the cross section from, respectively, the s, p, d, and f partial neutron waves in the entrance channel and direct processes; solid curve—sum of the partial cross sections.

($I_1^\pi = 2^+$, $E_1 = 45$ keV) are shown in Fig. 1. Also shown here are partial contributions to σ_{inel} from various neutron waves in the entrance channel and the contribution of direct processes.[16]

Local values of the p-neutron strength function S_{n1} were calculated by a method of successive approximations, from

$$S_{n1}^{i+1} = S_{n1}^{i} + (\sigma_{\text{inel}}^{\text{exp}} - \sigma_{\text{inel}}^{i}) \left(\frac{\partial \sigma_{\text{inel}}}{\partial S_{n1}} \right)^{-1}, \tag{3}$$

where S_{n1}^{i} is the value of the parameter from the ith iteration, and σ_{inel}^{i} is the corresponding calculated value of the cross section. The errors in the local values, ΔS_{n1}, are calculated as

$$\Delta S_{n1} = \left(\frac{\partial \sigma_{\text{inel}}}{\partial S_{n1}} \right)^{-1} \left[(\Delta \sigma_{\text{inel}}^{\text{exp}})^2 + \sum_i \left(\frac{\partial \sigma_{\text{inel}}}{\partial x_i} \Delta x_i \right)^2 \right]^{1/2}, \tag{4}$$

where the summation incorporates the contributions from all other parameters to which the quantity σ_{inel} exhibits a sensitivity. Their values were taken from Refs. 1 and 6.

Figure 2 shows the local values of S_{n1} found for uranium-238 in the energy interval $E_n = 82$–275 keV. Also shown here is the value of S_{n1} from the region of resolved resonances,[1] $E_n \leqslant 5$ keV. On the average, the errors in determining the local values of S_{n1} are $\sim 15\%$. We see from this figure that the values found here do not exhibit any intermediate structure outside the errors:

$$S_{n1} \approx \text{const}(E_n) \quad (\pm 15\%). \tag{5}$$

The value of the p-neutron strength function of ^{238}U is determined primarily by the $4p$ one-particle state, which lies near the neutron binding energy B_n (Ref. 2). The results found indicate that there is no intermediate structure in the distribution of the strength of the state among compound resonances; this conclusion agrees well with the predictions of the optical model. According to that model, the neutron strength functions at low energies are parametrized in the form[2]

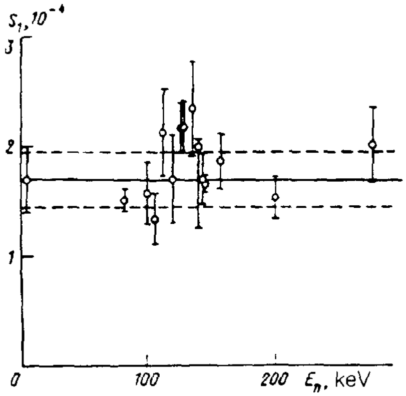

FIG. 2. Local values of the p-neutron strength function of uranium-238. The dashed lines show the 15% error corridor.

$$S_{nl}=\frac{1}{2\pi}\sum_{m,j}\frac{\Gamma_m^{lj}\uparrow\,\Gamma_m^{lj}\downarrow}{[E_m^{lj}-(E_n+B_n)]^2+(\Gamma_m^{lj}\downarrow/2)^2},\tag{6}$$

where E_m^{lj} is the energy of the mth single-particle state, with orbital angular momentum l and channel spin j, $\Gamma_m^{lj}\downarrow$ is the fragmentation width of this state corresponding to transitions to compound states, and $\Gamma_m^{lj}\uparrow$ is the partial width corresponding to decay into the continuum. The fragmentation width $\Gamma_m^{lj}\downarrow$ is determined by the average value of the imaginary part of the optical potential. Near the single-particle maxima it has a value on the order of a few MeV. Using the estimate[2]

$$\Gamma_m^{lj}\downarrow\,(E_m^{lj}\sim B_n)\approx 4\ \text{MeV},\tag{7}$$

we find from (6) the maximum possible change in S_{nl} in the vicinity of a single-particle state:

$$|E_m^{lj}-B_n|\ll\Gamma_m^{lj}\downarrow\ .\tag{8}$$

According to (6)–(8), as we go from $E_n\sim 0$ to $E_n\sim 300$ keV, this change is

$$\delta S_{nl}=\frac{|S_{nl}(0)-S_{nl}(300\ \text{keV})|}{S_{nl}}\times 100\%\leqslant 8\%.\tag{9}$$

Estimate (9) is consistent with the results found in the present study, (5).

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