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ANALYSIS OF THE ENERGY SPECTRUM OF PHOTONEUTRONS FOR THE (γ, xn) REACTION WITHIN THE FORMALISM OF STATISTICAL MULTISTEP COMPOUND PROCESSES

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The energy spectra of photoneutrons generated in the (γ, xn) reaction on medium and heavy nuclei in the region of dipole giant resonance were analyzed. The analysis was carried out within the framework of the generalized model of multipole giant resonance decay using the formalism of statistical multistep compound processes and allowing for the yield multiplicity. The nucleons were explicitly separated into two types (neutrons and protons). The emission of two neutrons was correctly taken into account. The results of calculations of photoneutron spectra for the nuclei ^{115}In ($E_\gamma^{\max} = 28$ MeV), ^{181}Ta ($E_\gamma^{\max} = 19$ MeV), and ^{209}Bi ($E_\gamma^{\max} = 20$ MeV) are presented and compared with experiment.

The generalized model of the decay of multipole giant resonances (MGR) takes into account the direct, pre-equilibrium, and equilibrium mechanisms of particle emission [1–4]. In the microscopic formulation, the MGR is described within the framework of the shell model of nucleus. The initial MGR wavefunctions ψ_{in} for the closed or nearly closed shells can be obtained through diagonalization and a residual interaction in the $1p1h$ basis set, or in an extended basis set taking into account the "dangerous" $2p2h$ configurations. The wavefunctions $\psi_{\text{in}}(\varepsilon_\gamma, J, \pi)$ describe the initial stage of the $1p1h$ pair production (in the general case, the fragmentation to more complicated "dangerous" configurations must be taken into consideration). For simplicity, in what follows we will assume that the ψ_{in} function represents a collective $1p1h$ state.

Within the formalism of statistical multistep compound processes (SMCP) [5, 6], the differential cross section of the $A(\gamma, xn)B$ reaction has the form

$$d\sigma_{\gamma,n}^{(\text{SMCP})}(\mathcal{E}_\gamma, \mathcal{E}_n)/d\mathcal{E}_n = \sigma_{\text{abs}}^{(E1)}(\mathcal{E}_\gamma)\Big\{\Gamma_{\text{in},n}^{\uparrow}(\mathcal{E}_\gamma, \mathcal{E}_n)/\Gamma_{\text{in}}(\mathcal{E}_\gamma)$$
$$+ \sum_{N=2}^{\overline{N}} (\Gamma_{\text{in}}^{\downarrow}(\mathcal{E}_\gamma)/\Gamma_{\text{in}}(\mathcal{E}_\gamma)) \left[\prod_{k=4}^{N-2} \Gamma_k^{\downarrow}(\mathcal{E}_\gamma)/\Gamma_k(\mathcal{E}_\gamma)\right] (\Gamma_{N,n}^{\uparrow}(\mathcal{E}_n)/\Gamma_N(\mathcal{E}_\gamma))\Big\},$$

where

$$\Gamma_{\text{in},b}^{\uparrow}(\mathcal{E}_\gamma, \mathcal{E}_b) = 2\pi\overline{V}_{\text{in}}^2 \left[\rho_{2,b}^{f+}(U_B) + \rho_{2,b}^{f0}(U_B)\right] \rho(\mathcal{E}_b)(2s_b + 1)\mathcal{P}_b(\mathcal{E}_b),$$
$$\mathcal{P}_b(\mathcal{E}_b) = \delta_{b,n} + (\sigma_p(\mathcal{E}_b)/\sigma_n(\mathcal{E}_b))\delta_{b,n},$$
$$\Gamma_{\text{in}}^{\uparrow}(\mathcal{E}_\gamma) = \sum_{b=p,n} \int d\mathcal{E}_b \Gamma_{\text{in},b}^{\uparrow}(\mathcal{E}_\gamma, \mathcal{E}_b),$$
$$\Gamma_{\text{in}}^{\downarrow}(\mathcal{E}_\gamma) = 2\pi\overline{V}_{\text{in}}^2 \rho_2^{+}(\mathcal{E}_\gamma),$$
$$\Gamma_{N,b}^{\uparrow}(\mathcal{E}_\gamma) = 2\pi\overline{V}_{bb}^2 \left[\rho_{N,b}^{f+}(U_B) + \rho_{N,b}^{f0}(U_B) + \rho_{N,b}^{f-}(U_B)\right] \rho(\mathcal{E}_b)(2s_b + 1)\mathcal{P}_b(\mathcal{E}_b),$$
$$\Gamma_N^{\downarrow}(\mathcal{E}_\gamma) = 2\pi\overline{V}_{bb}^2(\mathcal{E}_\gamma)\rho_N^{+}(\mathcal{E}_\gamma),$$
$$\sigma_{\text{abs}}^{(E1)}(\mathcal{E}_\gamma) = \sigma_{\gamma,p}(\mathcal{E}_\gamma) + \sigma_{\gamma,n}(\mathcal{E}_\gamma) + \rho_{\gamma,2n}(\mathcal{E}_\gamma) = \sigma_\gamma^{(\text{SMCP})}(\mathcal{E}_\gamma)$$
$$= \sigma_{\gamma,n}^{(\text{SMCP})}(\mathcal{E}_\gamma) + \sigma_{\gamma,p}^{(\text{SMCP})}(\mathcal{E}_\gamma) = \sum_{b=p,n} \int d\mathcal{E}_b \, d\sigma_{\gamma,b}^{(\text{SMCP})}(\mathcal{E}_\gamma, \mathcal{E}_b)/d\mathcal{E}_b.$$

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The mean square matrix element $\overline{V}^2_{\rm in}$ was obtained from the data on the width of the dipole giant resonance (DGR) in particular nuclei [7]. The value obtained in this way for nuclei with $A \gtrsim 100$ was $\overline{V}^2_{\rm in} \simeq 55\,A^{-3}$ MeV^2, and the $\overline{V}^2_{bb}$ value was determined by analyzing the nucleon reactions within the formalism of statistical multistep compound and direct processes [6]: $\overline{V}^2_{bb} \simeq 400\,A^{-8/3}$ MeV^2 ($A \gtrsim 100$). The densities of the permissible final states, $\rho^{f(\Delta n)}_{n,b}(U_B)$, were calculated by formulas from [6]. The total photoneutron cross section $\sigma^{(E1)}_{\gamma(n)}(\mathcal{E}_\gamma) = \sigma^{(\rm SMCP)}_{\gamma,n}(\mathcal{E}_\gamma)$ was described by resonance Lorentz curves with the parameters $\{E_{mi}, \sigma_{mi}, \Gamma_i\}$ taken from [8]:

$$\sigma^{(E1)}_{\gamma(n)}(\mathcal{E}_\gamma) = \sum_i \sigma_{mi}/\{1 + [(\mathcal{E}^2_\gamma - E^2_{mi})/\mathcal{E}^2_\gamma\Gamma^2_i]\},$$

where $i = 1$ for spherical nuclei; $i = 1, 2$ for deformed nuclei.

For the differential cross section $d\sigma^{(\rm SMCP)}_{\gamma,2n}(\mathcal{E}_\gamma, \mathcal{E}_n)/d\mathcal{E}_n$ we have

$$\begin{aligned} d\sigma^{(\rm SMCP)}_{\gamma,2n}(\mathcal{E}_\gamma, \mathcal{E}_n)/d\mathcal{E}_n = \sigma^{(E1)}_{\rm abs}(\mathcal{E}_\gamma)\Big\{ &[\Gamma^{\downarrow}_{\rm in}(\mathcal{E}_\gamma)/\Gamma_{\rm in}(\mathcal{E}_\gamma)] \\ &\times \sum_{N=4}^{\overline{N}} \Big[\prod_{k=4}^{N-2} \Gamma^{\downarrow}_k(\mathcal{E}_\gamma)/\Gamma_k(\mathcal{E}_\gamma)\Big] \int_0^{\mathcal{E}_\gamma - B_n} d\mathcal{E}_{n'} \sum_{\Delta N} (\Gamma^{\uparrow(\Delta N)}_{N,n'}(\mathcal{E}_{n'})/\Gamma_N(\mathcal{E}_\gamma)) \Big\} \\ &\times \Big\{ \sum_{N'=N+\Delta N-1}^{\overline{N'}} \Big[\prod_{k'=N+\Delta N-1}^{N'-2} \Gamma^{\downarrow}_{k'}(\mathcal{E}_\gamma - B_n - \mathcal{E}_{n'})/\Gamma_{k'}(\mathcal{E}_\gamma - B_n - \mathcal{E}_{n'})\Big] \\ &\times \Gamma^{\uparrow}_{N',n}(\mathcal{E}_n)/\Gamma_{N'}(\mathcal{E}_\gamma - B_n - \mathcal{E}_{n'})\Big\}, \end{aligned}$$

$$\Gamma^{\uparrow(\Delta N)}_{N,n'}(\mathcal{E}_{n'}) = 2\pi \overline{V}^2_{bb}\rho^{f(\Delta N)}_{N,n'}(U_{B'} = \mathcal{E}_\gamma - B_n - \mathcal{E}_{n'})\rho(\mathcal{E}_{n'})(2s_{n'} + 1),$$

where the limiting numbers of excitons, $\overline{N}$ and $\overline{N'}$, are determined from the relations

$$\Gamma_{\overline{N}}(\mathcal{E}_\gamma) = \Gamma^{\dagger}_{\overline{N}}(\mathcal{E}_\gamma); \quad \Gamma_{\overline{N'}}(\mathcal{E}_\gamma - B_n - \mathcal{E}_{n'}) = \Gamma^{\dagger}_{\overline{N'}}(\mathcal{E}_\gamma - B_n - \mathcal{E}_{n'}).$$

For intranuclear transitions with $\Delta N = 2, 0$, the differential cross sections $d\sigma^{(\rm SMCP)}_{\gamma,n}/d\mathcal{E}_n$ and $d\sigma^{(\rm SMCP)}_{\gamma,2n}/d\mathcal{E}_n$ are given by the formulas

$$d\sigma^{(\rm SMCP)}_{\gamma,n}(\mathcal{E}_\gamma, \mathcal{E}_n)/d\mathcal{E}_n = \sigma^{(E1)}_{\rm abs}(\mathcal{E}_\gamma) \sum_{N=2}^{\overline{N}} \tau_N(\mathcal{E}_\gamma)\Gamma^{\uparrow}_{N,n}(\mathcal{E}_n),$$

$$\begin{aligned} d\sigma^{(\rm SMCP)}_{\gamma,2n}(\mathcal{E}_\gamma, \mathcal{E}_n)/d\mathcal{E}_n = \sigma^{(E1)}_{\rm abs}(\mathcal{E}_\gamma) &\sum_{N=2}^{\overline{N}} \tau_N(\mathcal{E}_\gamma) \sum_{\Delta N} \int_0^{\mathcal{E}_\gamma - B_n} d\mathcal{E}_{n'} \Gamma^{\uparrow(\Delta N)}_{N',n'}(\mathcal{E}_{n'}) \\ &\times \sum \tau'_{N'}(\mathcal{E}_\gamma - B_n - \mathcal{E}_{n'})\Gamma^{\uparrow}_{N',n}(\mathcal{E}_n). \end{aligned}$$

The quantities $\tau_N(\mathcal{E}_\gamma)$ and $\tau'_{N'}(\mathcal{E}_\gamma - B_n - \mathcal{E}_{n'})$ are obtained upon solving a system of equations

$$-\delta_{N,2} = \Gamma^{+}_{N-2}(\mathcal{E}_\gamma)\tau_{N-2}(\mathcal{E}_\gamma) + \Gamma^{-}_{N+2}(\mathcal{E}_\gamma)\tau_{N+2}(\mathcal{E}_\gamma) - \Gamma_N(\mathcal{E}_\gamma)\tau_N(\mathcal{E}_\gamma), \quad N = 2, \ldots, \overline{N},$$

where

$$\begin{aligned} &\Gamma^{-}_2(\mathcal{E}_\gamma) = \Gamma^{+}_{\overline{N}}(\mathcal{E}_\gamma) = \Gamma^{-}_{\overline{N}+2}(\mathcal{E}_\gamma) = 0, \\ &\Gamma_N(\mathcal{E}_\gamma) = \Gamma^{+}_N(\mathcal{E}_\gamma) + \Gamma^{-}_N(\mathcal{E}_\gamma) + \Gamma^{\uparrow}_N(\mathcal{E}_\gamma), \\ &\Gamma^{\uparrow}_N(\mathcal{E}_\gamma) = \Gamma^{\uparrow}_{N,n}(\mathcal{E}_\gamma) + \Gamma^{\uparrow}_{N,p}(\mathcal{E}_\gamma), \\ &\Gamma^{+}_N(\mathcal{E}_\gamma) = 2\pi\overline{V}^2_{bb}(\mathcal{E}_\gamma)\rho^{+}_N(\mathcal{E}_\gamma), \quad N > 2, \\ &\Gamma^{-}_N(\mathcal{E}_\gamma) = 2\pi\overline{V}^2_{bb}(\mathcal{E}_\gamma)\rho^{-}_N(\mathcal{E}_\gamma), \quad N > 2, \\ &\Gamma_2(\mathcal{E}_\gamma) = \Gamma_{\rm in}(\mathcal{E}_\gamma), \quad \Gamma^{+}_2(\mathcal{E}_\gamma) = \Gamma^{\downarrow}_{\rm in}(\mathcal{E}_\gamma); \end{aligned}$$

and from another system

$$-\delta_{N',N'_0} = \Gamma^{+}_{N'-2}(U)\tau'_{N'-2}(U) + \Gamma^{-}_{N'+2}(U)\tau'_{N'+2}(U) - \Gamma_{N'}(U)\tau'_{N'}(U),$$
$$N' = N'_0, \dots, \overline{N'}, \qquad N'_0 = N + \Delta N - 1,$$

where

$$\Gamma^{-}_{N'_0}(U) = \Gamma^{+}_{N'_0-2}(U) = \Gamma^{+}_{\overline{N'}}(U) = \Gamma^{-}_{\overline{N'}+2}(U) = 0,$$
$$U = \mathcal{E}_\gamma - B_n - \mathcal{E}_{n'}.$$

The experimentally measured value is

$$d\sigma_{\gamma,xn}(\mathcal{E}_\gamma, \mathcal{E}_n)/d\mathcal{E}_n = d\sigma^{(\mathrm{SMCP})}_{\gamma,n}(\mathcal{E}_\gamma, \mathcal{E}_n)/d\mathcal{E}_n + d\sigma^{(\mathrm{SMCP})}_{\gamma,2n}(\mathcal{E}_\gamma, \mathcal{E}_n)$$
$$= d\sigma_{\gamma,n}(\mathcal{E}_\gamma, \mathcal{E}_n)/d\mathcal{E}_n + 2d\sigma_{\gamma,2n}(\mathcal{E}_\gamma, \mathcal{E}_n)/d\mathcal{E}_n.$$

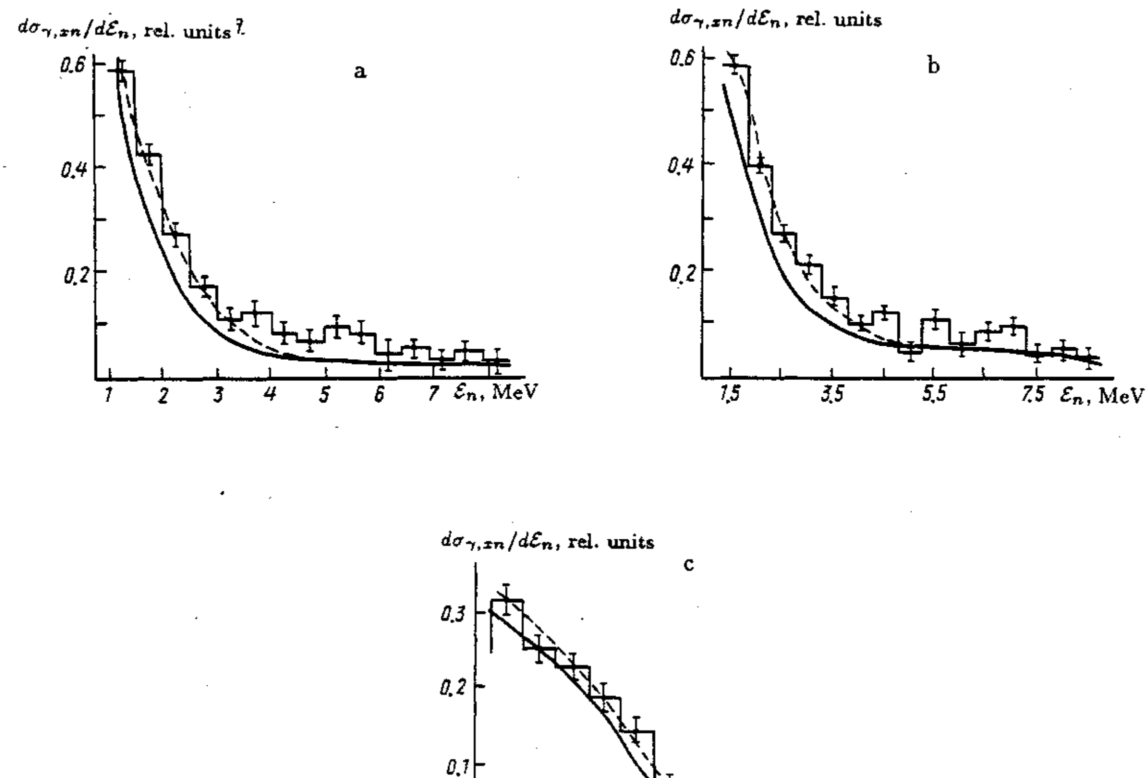

Fig. 1

Spectrum of photoneutrons emitted from a ^{115}In nucleus for the bremsstrahlung energy $E^{\max}_\gamma = 28$ MeV (a), from ^{181}Ta for $E^{\max}_\gamma = 19$ MeV (b), and from ^{209}Bi for $E^{\max}_\gamma = 20$ MeV (c). Solid curves: spectra calculated for the (γ, n) reaction; dashed curves: spectra corrected for the $(\gamma, 2n)$ contribution; hystogram: experimental data.

Within the framework of a quantum DGR decay model, we have calculated the energy spectra of photoneutrons for the nuclei ^{115}In, ^{181}Ta, and ^{209}Bi and the energy of γ-quanta in the DGR region ($\mathcal{E}_\gamma \lesssim 30$ MeV; bremsstrahlung γ-spectrum). The choice of the DGR region was related to the fact that the proton emission for heavy nuclei in this region is considerably suppressed by the Coulomb barrier. The mean square matrix elements $\overline{V}_{\text{in}}^2$ and $\overline{V}_{bb}$ were obtained from the experimental data. The densities of permissible final states were calculated in the equidistant approximation, because the role of the shell effect in heavy nuclei is small. The spectra of photoneutrons were averaged by integrating over the weighing function $\varphi(\mathcal{E}_\gamma, E_\gamma^{\max})$ which takes account of the shape of the bremsstrahlung spectrum of γ-quanta. The shape of this spectrum was chosen to be a triangle, and the integration was performed from E_{th} to $E_\gamma^{\max}$. The differential cross section $\sigma_{\text{abs}}^{(E1)}(\mathcal{E}_\gamma)$ was approximated by resonance Lorentz curves with the parameters $\{E_{mi}, \sigma_{mi}, \Gamma_i\}$ [8] selected so as to provide the best fit to experiment. In calculating the energy spectra of photoneutrons, we have separately evaluated individual contributions due to equilibrium emission, SMCP, and direct escape of neutrons.

Figure 1 a shows the calculation results for the ^{115}In nucleus. A comparison with experiment [9] suggests that the proposed quantum model of DGR decay in the SMCP formalism satisfactorily describes the shape of the energy spectrum. The model is further confirmed by a similar calculation and comparison with experiment for ^{181}Ta and ^{209}Bi [10, 11] (Fig. 1 b and c).

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