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The Possibility of Reconstructing the Low-Energy Part of the Neutron Spectrum of a Photoneutron Source via Neutron Activation Analysis

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Abstract—Ways of reconstructing the form of the energy spectrum of the W–Be photoneutron source at the Russian Academy of Sciences' Institute for Nuclear Research are considered, along with contributions to the spectrum of thermal and epithermal neutrons. A comparative analysis of neutron capture cross sections for various nuclei is performed, accompanied by convolutions of these cross sections with different energy regions of the model neutron spectrum. A number of elements are selected as samples for irradiation by source neutrons and subsequent neutron activation analysis. Only thermal and epithermal neutrons or combinations of them make an appreciable contribution to the measured activities of these elements. The samples are irradiated and the activation spectra are measured using a low-background gamma spectrometer. The shape of the source neutron spectrum in the low-energy part of the spectrum is reconstructed. The values of the neutron flux density for these regions of the spectrum are estimated.

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INTRODUCTION

To construct new installations for nuclear physics, ways and means are needed for ensuring accurate and reliable measurements of their characteristics. The main characteristics of photoneutron sources are those of the neutron field that forms during their operation. These characteristics are specific to every source and depend on its structural features [1, 2]. Apart from the need to measure the neutron flux densities inside and outside a source, we must also be able to measure the energy distributions (spectra) of neutrons inside it and at the output of the neutron measuring channels. It is especially important to know the energy distributions of the neutron flux density in studies involving neutron activation analysis.

PHOTONEUTRON SOURCE AT THE RUSSIAN ACADEMY OF SCIENCES' INSTITUTE FOR NUCLEAR RESEARCH

The IN-LUE activation measuring complex [3] created at the Russian Academy of Sciences' Institute for Nuclear Research includes a W–Be photoneutron source of neutrons [4] based on a linear accelerator of electrons and a low-background gamma spectrometer [5].

The LUE-8-5 industrial low-energy accelerator of electrons is used as the source of electrons. The energy of the electron beam can be altered in the range of 4.5–9 MeV. Electrons accelerated to, e.g., and energy of 7 MeV strike a tungsten converter and produce in it a beam of bremsstrahlung gamma quanta with a maximum energy of 7 MeV. The bremsstrahlung gamma quanta striking the beryllium photoneutron target (a material with a low threshold of photoneutron generation) generate fast neutrons with energies of up to 5 MeV. The photoneutron target is positioned in a block of polyethylene block-moderator. Fast neutrons in this block are slowed to an energy close to that of thermal neutrons. Inside the moderator block is a working chamber into which the samples to be irradiated are placed. The chamber's dimensions are $10 \times 10 \times 10$ cm. An external layer of protective borated polyethylene slows the fast neutrons exiting the moderator and absorbs slow and thermal neutrons. The source also has channels for the output of neutrons.

The measuring part of the complex includes a low-background chamber with passive protection, a gamma spectrometer based on an ORTEC detector made of high-purity germanium, and a system for the registration, collection, and processing of information from the detector [5]. This protective scheme ensures a background count rate of no fewer than 3 pulses per second in the 100–2500 keV range of gamma-quanta registration energies.

The density of the thermal neutron flux inside and outside the source is measured by means of neutron activation analysis (NAA) [6] using the known cross sections of (n, γ) reactions. ^{63}Cu, ^{55}Mn, ^{115}In, and ^{45}Sc

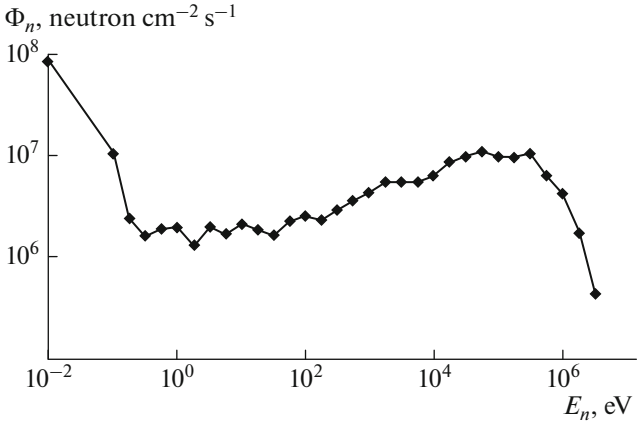

Fig. 1. Simulated energy spectrum (flux density Φ_n) of neutrons in the photoneutron source's working chamber upon irradiating a Be target with electrons at an energy of 7 MeV and a current of 40 μA [4].

samples, irradiated with neutrons in the source's working chamber, are used to monitor the neutron flux density in these measurements. The activation spectra are measured with a gamma spectrometer inside a low-background chamber. The experimentally measured density of the thermal neutron flux in the region of sample irradiation varies in range of ~10^6–10^8 neutron cm^{-2} s^{-1} [3], depending on the electron beam current.

Simulations of the photoneutron source's characteristics show that the spectrum of neutrons from the source is of a complicated nature. In addition to the main contribution from thermal neutrons, it contains ones from epithermal and fast neutrons. In Fig. 1, the solid curve with points shows the results from simulating the spectrum of neutrons in the working chamber of the photoneutron source upon irradiating a Be target with electrons at an energy of 7 MeV and a current of 40 μA [4].

RECONSTRUCTING THE NEUTRON SPECTRUM OF THE PHOTONEUTRON SOURCE

NAA with the use of neutron activation detectors (samples with known activation cross sections) is employed to reconstruct the neutron spectrum. NAA includes neutron irradiation of the detectors, subsequent measurement and analysis of the corresponding activation gamma spectra, and determination of the activity induced by neutrons in the detector material. In NAA, the measured area of the peak of the i-th radionuclide in the gamma spectrum of an activated detector is presented in the form

$$S_i = \frac{m_i g_i N_A p_i \varepsilon}{A_i \lambda_i} K_i J_i, \quad (1)$$

where S_i is the number of counts in the analytical peak of the i-th element's isotope (without background); m_i is the mass of the i-th element in the detector; g_i is the content of the analytical isotope of the ith element in the natural mixture of isotopes; N_A is the Avogadro constant; p_i is the yield of gamma quanta per one decomposition of the formed radioactive isotope; ε is the efficiency of registering the radiation of the induced activity; A_i is the atomic weight of the ith element; and λ_i is the radioactive decay constant of the i-th element's analytical isotope.

Here, J_i is the reaction rate

$$J_i = \int_0^\infty \sigma_i(E)\varphi(E)\,dE, \quad (2)$$

where $\sigma_i(E)$ is the cross section of the activating nuclear reaction as a function of neutron energy E; and $\varphi(E)$ is the spectral density of the neutron flux,

$$K_i = (1 - e^{-\lambda_i t_a}) e^{-\lambda_i t_d} (1 - e^{-\lambda_i t_m}), \quad (3)$$

where t_a is the time required for activation; t_d is the decay time after irradiation; and t_m is the time needed for measuring.

Formula (2) can serve as the basis for reconstructing either the reaction cross section or the neutron spectrum, depending on which parameters are known. From this formula, we can see the activation approach is an integral one and cannot provide detailed information on the characteristics of the neutron field. Using detectors with selective sensitivity to neutrons of different energies, however, we can determine fairly accurately the fluxes of neutrons with different energies incident on the detector.

To do so, we present convolution integrals (2) in the form of sum m of the products of cross sections $\sigma_i(E_j)$ and neutron flux density $\Phi(E_j)$ averaged over m elementary energy regions E_j of width ΔE_j. We assume that the spectral density of the neutron flux in region ΔE_j is $\varphi(E_j) = \Phi(E_j)/\Delta E_j$. For the set of k detectors, we then obtain a system of equations for the unknown densities of neutron flux $\Phi(E_j)$:

$$\begin{cases} \int_0^\infty \sigma_1(E)\varphi(E)\,dE = J_1 \\ \cdots \\ \int_0^\infty \sigma_k(E)\varphi(E)\,dE = J_k \end{cases} \Rightarrow \begin{cases} \sum_{j=0}^{m} \sigma_1(E_j)\Phi(E_j) = J_1 \\ \cdots \\ \sum_{j=0}^{m} \sigma_k(E_j)\Phi(E_j) = J_k \end{cases}. \quad (4)$$

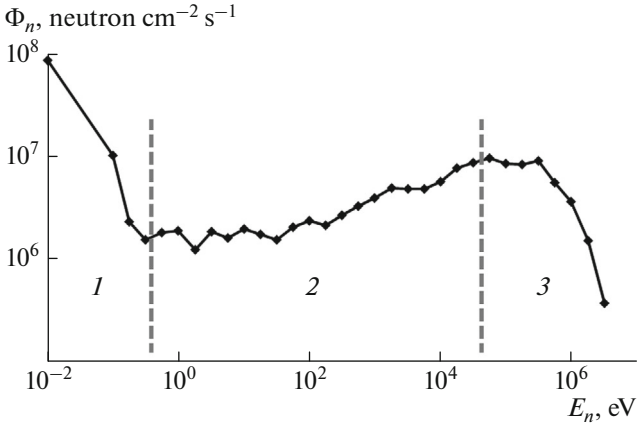

Fig. 2. Breakdown of the neutron energy spectrum of Fig. 1 into three regions: (*1*) thermal, (*2*) intermediate, and (*3*) fast neutrons.

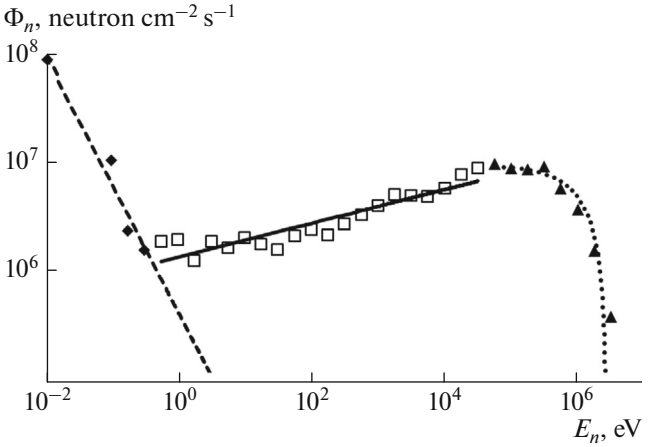

Fig. 3. Approximation of the energy spectrum in Fig. 2 with functions for the thermal region (dashed line), for intermediate neutrons (solid line), and for the region of fast neutrons (dotted curve). Symbols show the portions of the spectrum in the regions of (◆) thermal, (□) intermediate, and (▲) fast neutrons.

The solution to system (4) can be sought using different ways of solving the inverse problem. However, an easier method can also be used: reducing the number of unknowns in system (4) and parametrization of the spectrum of $\Phi(E_j)$ using a set of elementary functions.

In Fig. 2, we see the spectrum can be provisionally divided into three nominal regions: thermal, intermediate, and fast neutrons. In addition, low-energy spectral regions (numbers *1* and *2*) can be approximated using linear functions in log–log coordinates (Fig. 3) or with exponent functions of the form $\Phi_j = AE_j^B$ in ordinary coordinates. In the region of fast neutrons, the spectrum can be approximated with a polynomial function.

Using detectors with selective sensitivity to neutrons in spectral regions *1* and *2* (Fig. 2), we can reduce the dimensionality of the spectrum being reconstructed. The regions in this case can be analyzed individually, approximated with separate functions, and then stitched into a complete spectrum. For reconstruction, we must therefore solve a system of four equations with two unknown quantities for each spectral region, or three equations with three unknown quantities with allowance for the stitching of the spectral regions. The number of experimentally determined quantities should correspondingly also be three or four; i.e., it is sufficient to irradiate and then perform a neutron activation analysis of the data for three or four activation detectors.

One criterion of activation detector sensitivity is the ratio of resonance integral I_{res} to the cross section of a reaction with thermal neutrons σ_{therm}, the values of which were given in [7] for isotopes with different half-decay periods that form in (n, γ)-reactions.

In our case, however, other criteria can also be used. Figure 4 shows the energy dependences of the cross sections of capture reactions (n, γ) for ^{50}Ti and ^{75}As nuclei, and of product $\sigma_i(E_j)\Phi(E_j)$ of these cross sections and the simulated energy spectrum of Fig. 1. We can see that both cross sections and convolutions have characteristic features in different regions of the energy dependence.

Figure 5 shows for the same reactions the sums of the cross sections and convolutions for regions *1–3* of the spectrum in Fig. 2. In the case of ^{50}Ti, we can see

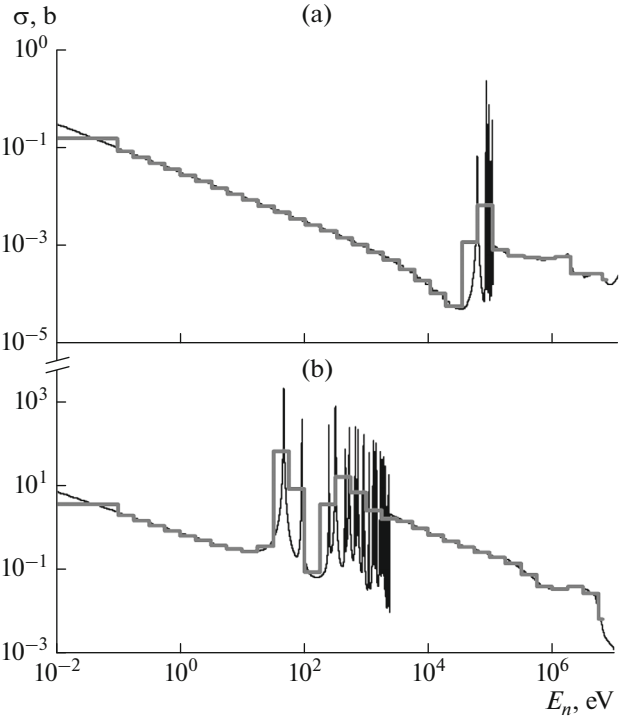

Fig. 4. Energy dependence of the cross sections (fine lines) and products $\sigma_i(E_j)\Phi(E_j)$ of the cross section and simulated energy spectrum of Fig. 1 (heavy lines) of capture reactions (a) ^{50}Ti $(n, \gamma)^{51}$Ti and (b) ^{75}As $(n, \gamma)^{76}$As.

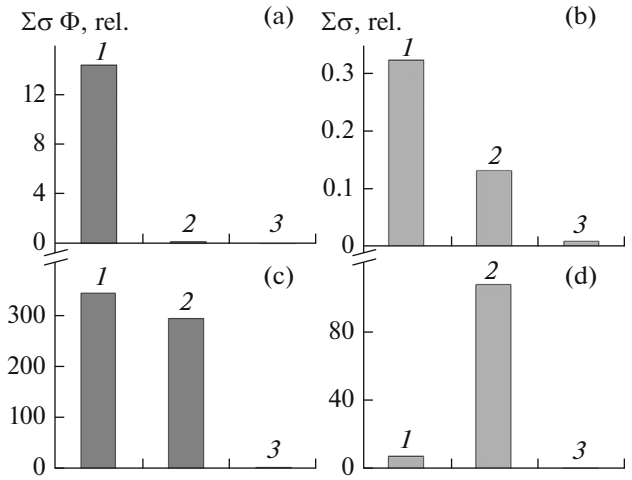

Fig. 5. Convolution and cross section sums of Fig. 4 for regions *1–3* of the spectrum in Fig. 2 for capture reactions (a, b) ^{50}Ti $(n, \gamma)^{51}$Ti and (c, d) ^{75}As $(n, \gamma)^{76}$As.

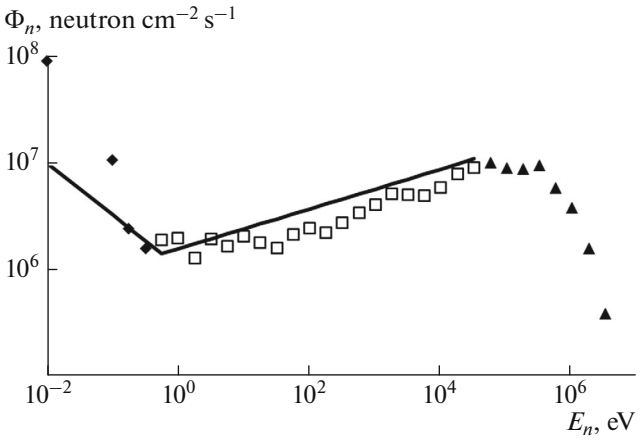

Fig. 6. Results from reconstructing the low-energy portion of our photoneutron source spectrum with functions $\Phi_j = AE_j^B$ for thermal and intermediate spectral regions (solid line). Other denotations are as in Fig. 3.

that although the contributions to the cross sections of the thermal and intermediate parts of the spectrum are substantial, only the thermal region contributes to the sum of convolutions. For ^{75}As, the main contribution to the sum of convolutions conversely comes from the thermal and intermediate parts of the spectrum; only the intermediate region contributes to the cross section. We can also see that the contribution from the fast part of the spectrum to the sum of convolution and cross section is minor. A similar analysis of capture reactions for other nuclei showed we can choose a set of elements for use as activation detectors that will be sensitive mainly to neutrons from the thermal region (e.g., ^{23}Na, ^{26}Mg, ^{27}Al, ^{37}Cl, ^{50}Ti, ^{55}Mn, and ^{63}Cu) either from the intermediate region (e.g., ^{116}Sn, ^{114}Cd, and ^{116}Cd) [8]. Also possible is the general case in which a detector can be sensitive to all neutrons from low-energy spectral regions (e.g., ^{127}I, ^{175}Lu, ^{79}Br, ^{81}Br, and ^{197}Au). At the same time, practically no examples are known in which the contribution from fast neutrons to sums of convolution is notable. Only ^{106}Cd, ^{114}Cd, and ^{116}Cd are (to different degrees) sensitive in all spectral regions.

Samples of ^{26}Mg, ^{50}Ti, ^{71}Ga, and ^{75}As were used as activation detectors to demonstrate the possibility of reconstructing the spectrum of neutrons from a photoneutron source in the thermal and intermediate parts of the spectrum. Both cross sections and convolutions of the pairs of nuclei ^{26}Mg, ^{50}Ti and ^{71}Ga, ^{75}As have characteristic features in the same areas of the energy dependences and are similar to the corresponding dependences shown in Figs. 4 and 5.

Mg, Ti, and GaAs samples weighing 0.19, 0.32, and 0.66 g, respectively, were activated for 30 min with a flux of thermal neutrons. Spectrum acquisition times were 1000, 500, and 1000 s, respectively. Using Eqs. (1) and (2), the areas of analytical peaks S_i and reaction rates J_i were calculated for the analytical lines corresponding to ^{26}Mg, ^{50}Ti, ^{71}Ga, and ^{75}As: 844, 320, 834, and 559 keV, respectively. In system (4), the sums of convolution in the first two equations for ^{26}Mg and ^{50}Ti contain only the terms that correspond to neutrons in the thermal region of the spectrum; for ^{71}Ga and ^{75}As, they contain only the terms corresponding to neutrons in the thermal and intermediate spectral regions. For ^{26}Mg, ^{50}Ti, ^{71}Ga, and ^{75}As, there are practically no contributions to system (4) from neutrons of the fast part of spectrum. System (4) of four equations with three unknowns was solved according to the χ^2 technique with the condition of stitching according to the endpoints of function $\Phi_j = AE_j^B$ for the thermal and intermediate regions of the spectrum. The results are presented in Fig. 6. It was found that contribution to the spectrum of thermal neutrons was lower than in our simulation results. To verify this, the neutron flux density in the thermal spectral region was estimated using measurements of the activation gamma spectra from (n, γ) reactions for ^{45}Sc nuclei (lines at 889 and 1120 keV), ^{55}Mn (847 keV), and ^{68}Zn (439 keV). The obtained thermal neutron flux density values (~10^6–10^7 neutrons cm^{-2} s^{-1}) agree with the results of reconstruction in the thermal region (Fig. 6).

CONCLUSIONS

We considered the possibility of reconstructing thermal and epithermal neutron spectra of a photoneutron source using data from neutron activation analysis. The relationships between the sums of convolution and cross sections of the capture reactions for

different spectral regions were used as criteria for selecting the elements of the activation detectors. The use of fairly simple functions with few parameters was also considered as an alternative means of reconstruction. Each of these functions describes its own portion of the source energy spectrum. We obtained data describing the behavior of the neutron spectrum in the of low-energy region. Experimentally measured thermal neutron flux densities agreed with reconstruction results for this energy region. This approach can be used for rapid analysis of a photoneutron source's neutron spectrum.

REFERENCES

1. Auditore, L., Barna, R.C., De Pasquale, D., et al., *Nucl. Instrum. Methods Phys. Res., Sect. B*, 2005, vol. 229, p. 137.
2. Patil, B.J., Chavan, S.T., Petheat, S.N., et al., *Appl. Radiat. Isot.*, 2012, vol. 70, p. 149.
3. Andreev, A.V., Burmistrov, Yu.M., Zuyev, S.V., Konobeevski, E.S., Mordovskoy, M.V., and Nedorezov, V.G., *Bull. Russ. Acad. Sci.: Phys.*, 2017, vol. 81, p. 748.
4. Andreev, A., Burmistrov, Yu., Gromov, A., et al., *Proc. 5th Int. Conf. on Nuclear Fragmentation*, Kemer, 2015. https://fias.uni-frankfurt.de/historical/nufra2015/talks/Sobolevsky_nufra2015.pdf.
5. Andreev, A.V., Burmistrov, Yu.M., Zuyev, S.V., et al., *Yad. Fiz. Inzh.*, 2013, vol. 4, p. 879.
6. Gut'ko, V.I., *Aktivatsionnyi analiz* (Activation Analysis), Minsk: MGEU, 2008.
7. Frontasyeva, M.V., *Phys. Part. Nucl.*, 2011, vol. 42, no. 2, p. 332.
8. Atlas of Neutron Capture Cross Sections. https://www-nds.iaea.org/ngatlas2/.

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