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NUCLEI
Experiment

Nuclear-Level Densities in the ^{49}V and ^{57}Co Nuclei on the Basis of Evaporated-Neutron Spectra in (p, n) and (d, n) Reactions

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Abstract—The spectra of neutrons from the reactions ^{49}Ti$(p, n)^{49}$V and ^{57}Fe $(p, n)^{57}$Co were measured in the range of proton energies between 8 and 11 MeV along with their counterparts from the reactions ^{48}Ti$(d, n)^{49}$V and ^{56}Fe $(d, n)^{57}$Co at the deuteron energies of 2.7 and 3.8 MeV. These measurements were conducted with the aid of a time-of-flight fast-neutron spectrometer on the basis of the EGP-15 pulsed tandem accelerator of the Institute for Physics and Power Engineering (IPPE, Obninsk). An analysis of measured data was performed within the statistical equilibrium and preequilibrium models of nuclear reactions. The respective calculations based on the Hauser—Feshbach formalism of statistical theory were carried out with nuclear-level densities given by the generalized superfluid model of the nucleus, the back-shifted Fermi-gas model, and the Gilbert—Cameron composite formula. The nuclear-level densities of ^{49}V and ^{57}Co and their energy dependences were determined. The results were discussed together with available experimental data and data recommended by model systematics.

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INTRODUCTION

The nuclear-level density is a fundamental statistical feature of excited nuclei. Knowledge of the absolute values of nuclear-level densities and special features of their behavior is of paramount importance both for developing a consistent theoretical description of the properties of excited nuclei and for calculating cross sections for nuclear reactions within the statistic model. The spectra of particles emitted in nuclear reactions provide information about the nuclear-level density in the energy range between discrete states and the neutron binding energy to a precision commensurate with the precision of resonance data. The present article reports on measuring the spectra of neutrons from the reactions ^{49}Ti$(p,\ n)$49V and ^{57}Fe$(p,\ n)$57Co in the proton-energy range from 8 to 11 MeV and from the reactions ^{48}Ti$(d, n)^{49}$V and ^{56}Fe$(d, n)^{57}$Co at the deuteron energies of 2.7 and 3.8 MeV. The results were analyzed within the equilibrium and preequilibrium statistical models of nuclear reactions. The nuclear-level densities in the ^{49}V and ^{57}Co nuclei and their energy dependence were determined. Such studies make it possible to compare the results obtained on the basis of these reactions for the same nucleus over a broad range of excitation energies.

EXPERIMENTAL PROCEDURE

We measured the spectra of neutrons from the $(p,\ n)$ reactions on ^{49}Ti and ^{57}Fe nuclei at proton energies between 8.1 and 11.2 MeV in the angular range of 20°—140° and from the (d, n) reactions on ^{48}Ti and ^{56}Fe nuclei at the deuteron energies of 2.7 and 3.8 MeV at an angle of 105°. The measurements of these spectra were performed by the time-of-flight fast-neutron spectrometer on the basis of the pulsed tandem accelerator EPG-15 of the Institute for Physics and Power Engineering (IPPE, Obninsk). As targets, we employed self-supporting metal foils 0.88, 1.96, 2.17, and 1.49 mg cm^{-2} thick enriched to 97.8, 60.7, 99.9, and 88.6% in ^{48}Ti, ^{49}Ti, ^{56}Fe, and ^{57}Fe, respectively. Neutrons were detected by a scintillation detector involving a stilbene crystal ($d = 40$ mm, $h = 40$ mm) and a photomultiplier tube (PMT-143). In order to reduce the background, the detector was placed within a massive shielding. In addition, use was made of the electronic discrimination of gamma rays. The detector efficiency was determined as follows. First, the spectrum of prompt neutrons originating from ^{252}Cf spontaneous fission was measured by the time-of-flight method, a fast ionization fission chamber specially designed in the same geometry of the experiment being used as a source. After that, the detector efficiency was found by comparing the measured spectrum and its counterpart adopted as reference one [1]. In order to

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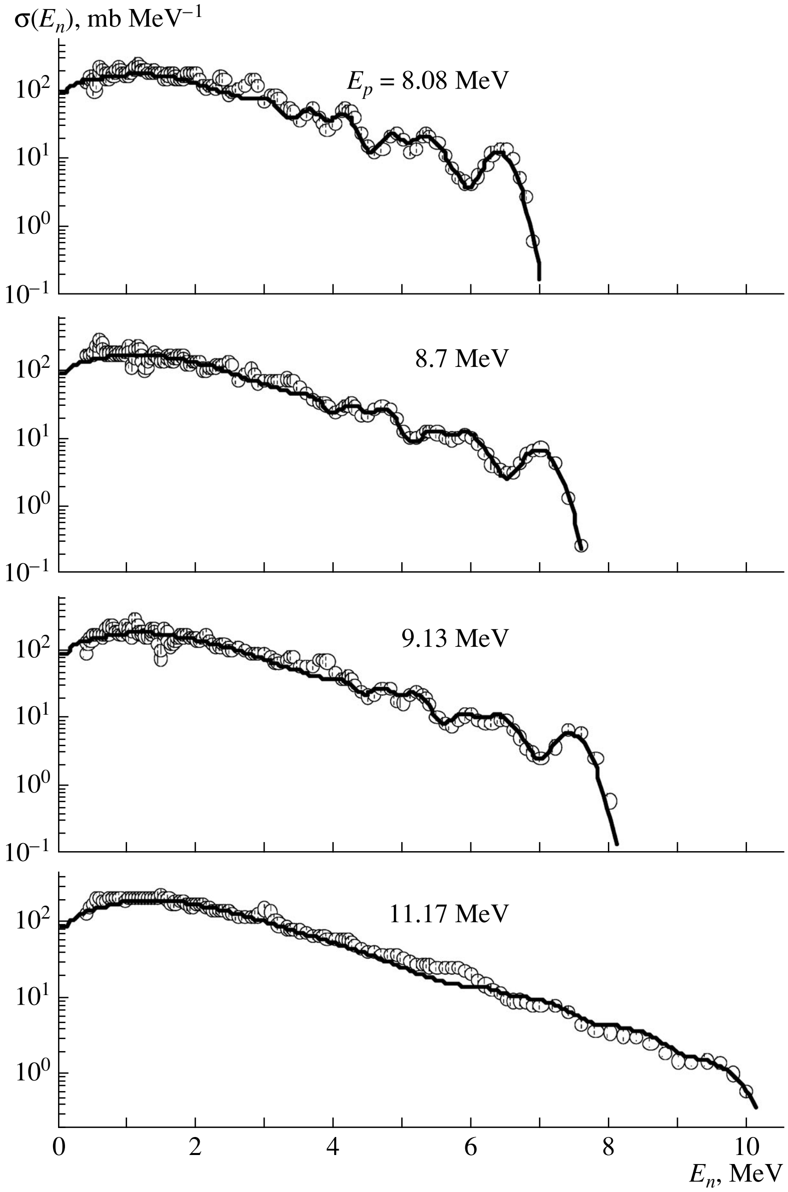

Fig. 1. Neutron spectra integrated with respect to the angle for the reaction ^{49}Ti(p, n)^{49}V: (points) experimental data and (curves) results of our calculations.

test the stability of the spectrometer and the quality of the pulse beam, we used an additional detector based on a fast plastic scintillator and a PMT-82 photomultiplier tube. This served for detecting the gamma-ray peak from the beam stopper of the Faraday cup. The electronic (structural scheme) circuits of the spectrometer, its detecting and storing parts, and the data-processing circuits were described in detail elsewhere [2]. The procedure for measuring the neutron spectrum consisted in measurements with and without a target in the same proton flux. The background was small in magnitude and was virtually uncorrelated in time. We also measured the spectra of neutrons from the reactions ^{48}Ti$(p, n)^{48}$V and ^{56}Fe$(p, n)^{56}$Co in order to take into account their contributions to the neutron spectra measured with ^{49}Ti and ^{57}Fe targets (enrichment to 60.7 and 88.6%, respectively). The measurements of the spectra of neutrons from the reaction ^{48}Ti$(d, n)^{49}$V were performed at an angle of 105° in order to avoid contributions of nonequilibrium deuteron-breakup processes. The results obtained by integrating, with respect to the angle, the spectra of neutrons emitted in the reactions ^{49}Ti(p, n) and ^{57}Fe(p, n) are presented in Figs. 1 and 2, while the results obtained by multiplying, by a factor of 4π, the spectra of neutrons from the reactions ^{48}Ti(d, n) and ^{56}Fe (d, n) are given in Figs. 3

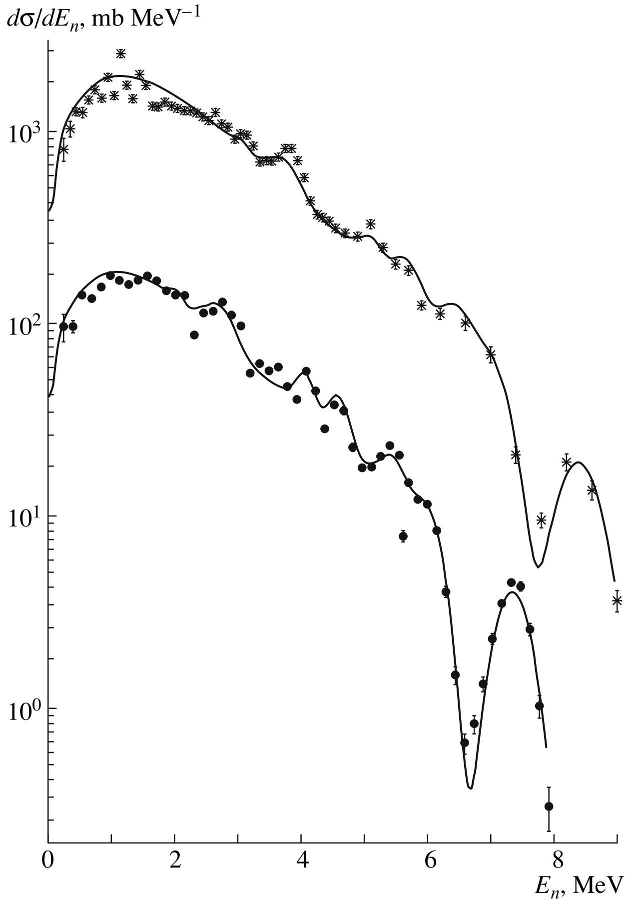

Fig. 2. Neutron spectra integrated with respect to the angle for the reaction ^{57}Fe$(p, n)^{57}$Co: (closed circles and asterisks) experimental data at $E_p = 9.2$ MeV and $E_p = 10.2$ MeV, respectively and (curves) results of our calculations. The values for $E_p = 10.2$ MeV are shifted by one order of magnitude.

and 4. A high resolution of about 0.6 ns m^{-1} and the stability of the time-of-flight spectrometer allowed us to identify reliably discrete low-lying levels along with the continuum part of the neutron spectrum.

DATA ANALYSIS

The method for determining the nuclear-level density from emission spectra is based on the fact that the nuclear-level density is one of the most important components in calculations based on the statistical model. In the present study, the neutron spectra in question were performed by using the Hauser–Feshbach mathematical formalism of the statistical theory of nuclear reactions. The procedure for determining the nuclear-level densities was as follows.

The model parameters of the level density were adjusted in such a way as to fit the cross section calculated by the Hauser–Feshbach formula to the cross-section value measured in the energy range of well-known low-lying levels. This procedure makes it possible to determine the total decay width of the compound nucleus involved.

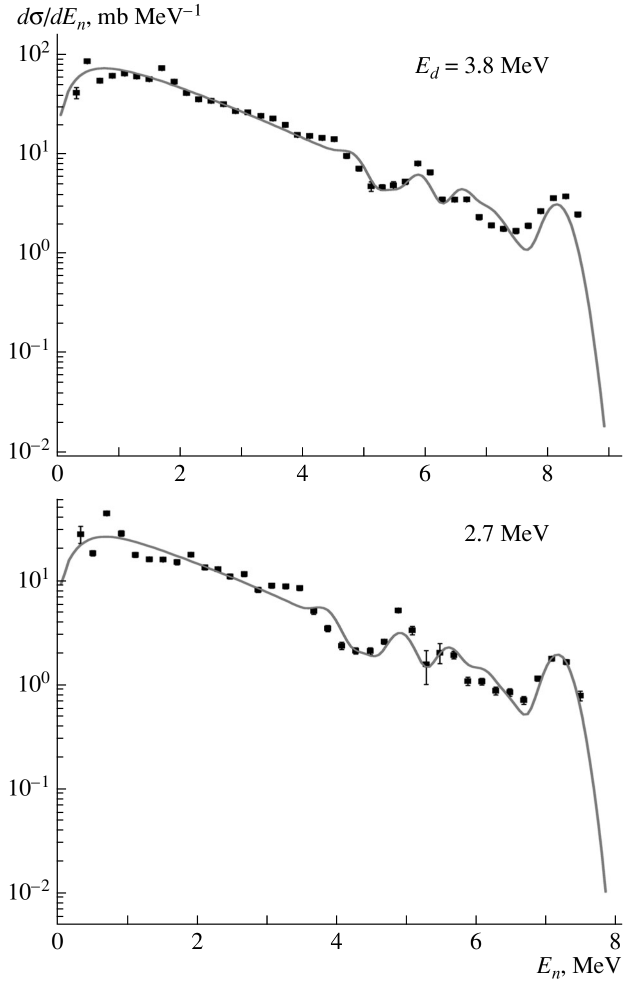

Fig. 3. Neutron spectra for the reaction ^{48}Ti$(d, n)^{49}$V upon integration with respect to the angle via multiplication by 4π: (points) experimental data and (curves) results of our calculations.

Starting from the model chosen for the nuclear-level density and employing, in subsequent iterations, the absolute values of the level density, we calculated the differential cross section for the continuum part of the spectrum and determined the absolute values of the nuclear-level density over a broad range of excitation energies from the best fit to the measured spectrum.

All of the calculations based on the optical and statistical models were performed with the aid of the GNASH [3] and PEAK-99 [4] codes. A determination of nuclear-level densities started from analyzing neutron spectra measured in (p, n) reaction at low proton energies, in which case one can guarantee the absence of contributions from processes other than equilibrium ones. At higher proton energies,

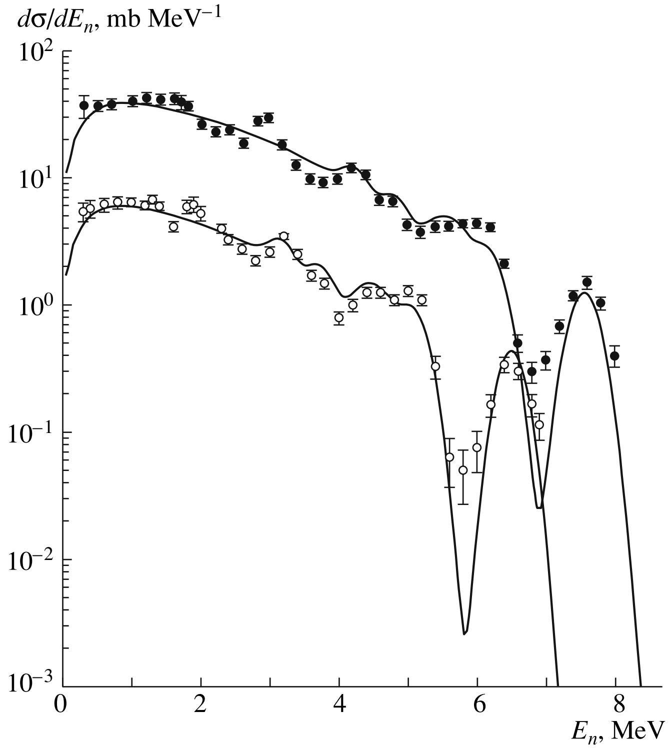

Fig. 4. Neutron spectra integrated with respect to the angle for the reaction ^{56}Fe $(d,n)^{57}$Co: (open and closed circles) experimental data at $E_d = 2.7$ MeV and $E_d = 3.8$ MeV, respectively, and (curves) results of our calculations.

the contributions of preequilibrium mechanisms were taken into account. In that case, the calculations were performed with the aid of a modified GNASH code, in which the equilibrium part of (p, n) reactions was calculated by using the absolute level density obtained from an analysis of the spectra corresponding to low proton energies. As soon as the proton energy reached its maximum value, we returned to the initial stage of the iteration process. The χ^2 criterion was used to reach an optimum consistency between the measured and calculated spectra. At low excitation energies, we calculated transitions to well-identified discrete levels of the residual nucleus. The same procedure was applied to the measured spectra of neutrons from the respective (d, n) reactions. In order to perform a comparison with experimental data, the calculated cross sections were averaged with respect to the excitation energy according to a normal distribution. The variance of the distribution corresponded to the spectrometer resolution. In order to determine reliably the nuclear-level density from the observed neutron spectra, it was necessary to establish correctly the energy dependence of the neutron optical potential in the energy range extending up to 10 MeV. In the present study, the optical potential was taken in the form of the Koning–Delaroche potential, whose parameters were determined on the basis of a broad set of experimental data on the interactions of neutrons and protons with nuclei [5].

RESULTS

The experimental spectra of neutrons from the reactions under consideration are shown in Figs. 1–4 along with their counterparts calculated according to the procedure described above. A comparison of these calculated and measured neutron spectra demonstrates good agreement both in the region of discrete levels and in the continuum part of the excitation spectrum. The extracted nuclear-level densities ρ are shown in Figs. 5 and 6 versus the excitation energy U for the ^{49}V and ^{57}Co nuclei excited in the reactions being studied. The uncertainty in the nuclear-level densities was estimated here at about 15 to 18%. Our results agree well with the data on low-lying levels from [6], data on proton S-wave resonances for ^{49}V from [7], and the results reported in [11] for ^{57}Co and obtained from an analysis of evaporated-neutron spectra in the reaction ^{57}Fe$(p, n)^{57}$Co and Ericson's fluctuations [12]. In the range of excitation energies between 2.0 and 4.0 MeV, there is a weak structure in the nuclear-level densities. Obviously, this structure stems from the inhomogeneity of the spectrum of single-particle states in the transition region between

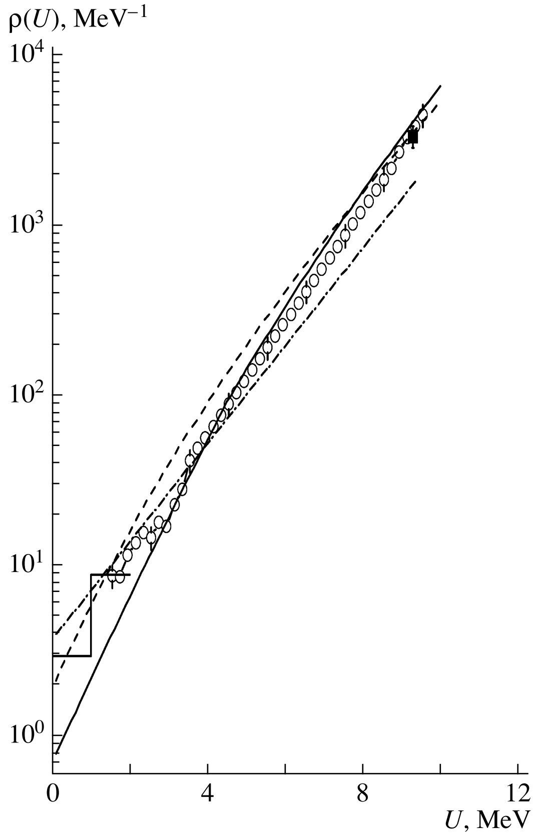

Fig. 5. Nuclear-level density in ^{49}V: (open circles) data obtained in the present study; (histogram) data on low-lying levels from [6]; (closed box) data on proton resonances from [7]; and (solid, dashed, and dash-dotted curves) results of the calculations based on, respectively, the generalized superfluid model of the nucleus [8], the back-shifted Fermi gas model [9], and the Gilbert–Cameron composite formula [10].

well-identified discrete states and the continuum part of the excitation spectrum.

Figures 5 and 6 show nuclear-level densities calculated according to a phenomenological version of the generalized superfluid model of the nucleus [8], the back-shifted Fermi gas model [9], and the Gilbert–Cameron composite formula [10] with the parameters recommended in the respective model systematics. One can see that the absolute values and energy dependences of the nuclear-level densities obtained in the present study differ substantially from the predictions of the model level-density systematics.

CONCLUSIONS

The spectra of neutrons from the reactions ^{49}Ti(p, n)^{49}V and ^{57}Fe (p, n)^{57}Co at proton energies between 8.1 and 11.2 MeV and from the reactions ^{48}Ti(d,n)^{49}V and ^{56}Fe (d,n)^{57}Co at the deuteron energies of 2.7 and 3.8 MeV were measured and were analyzed on the basis of the statistical theory of nuclear reactions. A comparison of the calculated and measured neutron spectra shows good agreement both in the region of discrete levels and in the continuum part of the excitation spectrum. The absolute nuclear-level densities in ^{49}V and ^{57}Co and their energy dependence were determined. In the transition region between well-identified discrete states and the continuum part of the excitation spectrum, one can observe a weakly pronounced structure in the nuclear-level densities, which is likely to stem from the inhomogeneity in the spectrum of single-particle states. A comparison showed that our data differ substantially from the predictions of model level-density systematics.

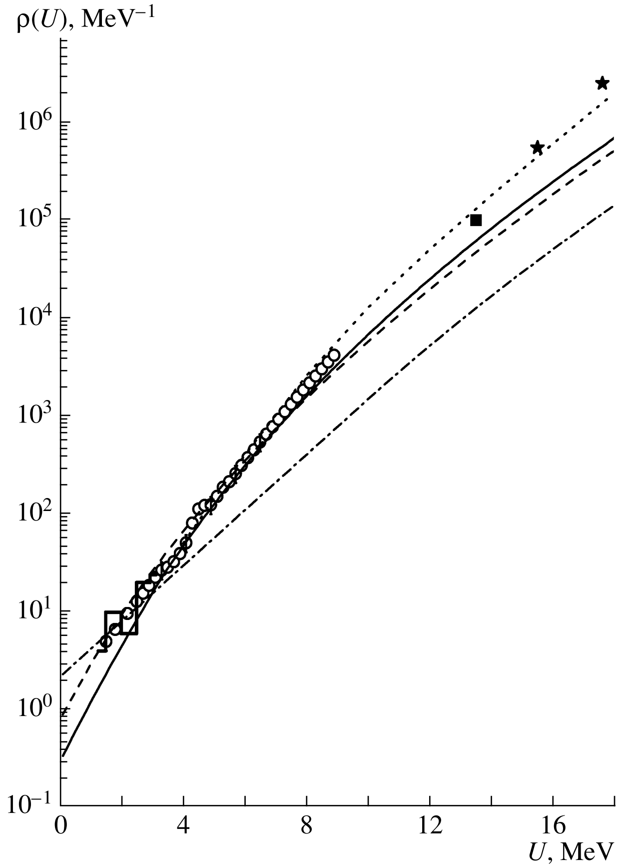

Fig. 6. Nuclear-level density in ^{57}Co: (open circles) data obtained in the present study; (histogram) data on low-lying levels [6]; (close boxes and two closed stars) data of fluctuation measurements performed in [11] and [12], respectively; (solid, dashed, and dash-dotted curves) results of the calculations based on, respectively, the generalized superfluid model of the nucleus [8], the back-shifted Fermi gas model [9], and the Gilbert–Cameron composite formula [10]; and (dotted curve) estimate from [11].

REFERENCES

1. W. Mannhart, Report IAEA-TECDOC-410 (Vienna, 1987).
2. V. G. Demenkov, B. V. Zhuravlev, A. A. Lychagin, et al., Instrum. Exp. Tech. **38**, 314 (1995).
3. P. G. Young, E. D. Arthur, and M. B. Chadwick, in *Proceedings of the IAEA Workshop on Nuclear Reaction Data and Nuclear Reactors: Physics, Design and Safety, Trieste, Italy, 1998* (World Sci., Singapore, 1998), Vol. 1, p. 227.
4. B. V. Zhuravlev and N. N. Titarenko, Preprint FEI-2819 (Inst. Phys. Power Eng., Obninsk, 2000).
5. A. J. Koning and J. D. Delaroche, Nucl. Phys. A **713**, 231 (2003).
6. ENSDF Database — Evaluated Nuclear Structure Data File. http://www-nds.iaea.or.at/
7. H. Vonach, M. Uhl, B. Strohmaier, et al., Phys. Rev. C **38**, 2541 (1988).
8. A. V. Ignatyuk, *Statistical Properties of Excited Atomic Nuclei* (Energoatomizdat, Moscow, 1980) [in Russian]; O. T. Grudzevich, A. V. Ignatyuk, and V. I. Plyaskin, in *Proceedings of the 1st International Conference on Neutron Physics, Kiev, 1987* (TsNIIatominform, Moscow, 1988), Vol. 2, p. 96.
9. W. Dilg, W. Schantl, H. Vonach, and M. Uhl, Nucl. Phys. A **217**, 269 (1973).
10. A. Gilbert and A. G. W. Cameron, Can. J. Phys. **43**, 1446 (1965).
11. V. Mishra, N. Boukharouba, C. T. Brient, et al., Phys. Rev. C **49**, 750 (1994).
12. J. Ernst, H. L. Harney, and K. Kotajima, Nucl. Phys. A **136**, 87 (1969).