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STATISTICAL PROPERTIES OF EXCITED NUCLEI IN THE MASS RANGE 47≤A≤59

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Abstract

Level densities and their energy dependences for nuclei in the mass range 47≤A≤59 have been determined from the measurements of neutron evaporation spectra in (p,n) reaction. Neutron spectra from (p,n) reaction on nuclei of ^{47}Ti, ^{48}Ti, ^{49}Ti, ^{53}Cr, ^{54}Cr, ^{57}Fe, ^{59}Co have been measured at proton energies between 7 and 11 MeV. The measurements of neutron spectra were performed by time-of-flight fast neutron spectrometer on the pulsed tandem accelerator EGP-15 of IPPE. The high resolution and stability of time-of-flight spectrometer allowed identify reliably the discrete low-lying levels together with continuum part of neutron spectra. Analyses of the measured data have been carried out in the framework of statistical equilibrium and pre-equilibrium models of nuclear reactions. The calculations are done with use of the exact formalism of the statistical theory as given by Hauser-Feshbach with the generalized superfluid model of nucleus, the back-shifted Fermi-gas model and the composite formula of Gilbert-Cameron for nuclear level density. The nuclear level densities of ^{47}V, ^{48}V, ^{49}V, ^{53}Mn, ^{54}Mn, ^{57}Co, ^{59}Ni and their energy dependences have been determined. The obtained results have been discussed in totality with existing experimental and model systematic data.

Introduction

The basic statistical function of excited nuclei is the nuclear level density. Knowledge of the level density values and their functional peculiarities is very important for the creation of consistent theoretical description of excited nucleus statistical properties and in making nuclear reaction cross-section calculations in the framework of statistical model. The general features of nuclear level density are known, but there are considerable uncertainties of its functional forms conditioned by the unhomogeneity of a single-particle state spectrum, residual interaction, effects of collective nature et al. The required accuracy of level density knowledge for nuclear cross-section calculation problems is ~ 10 % in a wide range of excitation energy from 0.1 MeV to 20 MeV, and the existing data are often differed in 1.5 times. The experimental data on the nuclear level densities for many nuclei are derived, in the main, from the analysis of neutron resonance data and low- lying states. But this information is limited to rather narrow ranges of excitation energy and spin, and its extrapolation can lead to essential errors both in absolute value of nuclear level density and its energy dependence, especially, in transition field from well-identified discrete states to continuum part of excitation spectrum. Obviously, it is necessary to attract other experimental methods of nuclear level density determination with scope of more wide ranges of excitation energy and spin. One of the information sources on nuclear level density in a range between the discrete states and the neutron binding energy with accuracy comparable with resonance capture data are the spectra of particles emitted in nuclear reactions. In this case the type of reaction and the energy of incident particles should be chosen so that the contribution of non-equilibrium processes was reduced to a minimum. These conditions are satisfied with the (p,n) reaction at proton energy up to 11 MeV. In this work the neutron spectra from (p,n) reaction on nuclei of ^{47}Ti, ^{48}Ti. ^{49}Ti, ^{53}Cr, ^{54}Cr, ^{57}Fe, ^{59}Co in proton energy range of (7-11) MeV have been measured and analyzed in the framework of statistical theory to study the nuclear level densities of ^{47}V, ^{48}V, ^{49}V, ^{53}Mn, ^{54}Mn, ^{57}Co, ^{59}Ni.

Experiment

Neutron spectra from (p,n) reaction on nuclei of ^{47}Ti, ^{48}Ti. ^{49}Ti, ^{53}Cr, ^{54}Cr, ^{57}Fe, ^{59}Co have been measured at proton energies between 7 and 11 MeV. The measurements of neutron spectra were performed by time-of-flight fast neutron spectrometer on the pulsed tandem accelerator EGP-15 of IPPE in the angle range of $(20\text{-}140)^0$. As the targets were used the self-supporting metal foils with thickness of 1.34, 0.88, 1.96, 1.37, 2.00, 4.08, 1.67 mg/cm^2 and enrichment of 76.1, 97.8, 60.7, 92.8, 79.7, 88.6, 99.9% for ^{47}Ti,^{48}Ti,^{49}Ti,^{53}Cr,^{54}Cr,^{57}Fe,^{59}Co respectively. Neutrons were detected by the scintillation detector with stilben crystal (d-40mm, h-40mm) and photomultiplier FEU-143. For decreasing of the background it was placed in the massive shielding and electronic discrimination of gamma-rays was used. The detector efficiency was determined by measuring of the ^{252}Cf prompt fission neutron spectrum by the time-of-flight method with use of a specially designed fast ionization chamber in the same geometry of the experiment. The detector efficiency was then reduced from comparison of measured spectrum with standard one [1]. For control of the spectrometer stability and quality of beam pulses was used additional detector on the basis of fast plastic scintillator and photomultiplier FEU-82, with help of which the peak of γ - quanta from beam stopper of Faradey-cup was registrated. The electronic circuits of the spectrometer, its detecting, storing and data processing circuits are described, in detail, in the paper [2]. The neutron spectrum measurement procedure has been consisted in measuring with target and without it for the same proton flux. The background was small in magnitude and practically uncorrelated over time. The high resolution (~0.6 ns/m) and stability of time-of-flight spectrometer allowed identify reliably the discrete low-lying levels together with continuum part of neutron spectra. Typical angle-integrated neutron emission spectra from (p,n) reaction on ^{49}Ti are presented in fig. 1.

Data analysis

The method of nuclear level density determination from emission spectra is based on the fact that the nuclear level density is one of the most critical components of statistical model calculations. In the present work the calculations of the measured neutron spectra have been carried out by means of Hauser-Feshbach formalism of statistical model. The procedure of nuclear level density determination consisted in following:

1. The model parameters of the level density are adjusted such that the cross-seection calculated by means of Hauser-Feshbach formula fits the measured value in the energy range of well-known low-lying levels. It means that the total decay width of compound nucleus is determined.
2. Using, at first, the chosen model of the level density and, in next iterations, the absolute values of the level density, the differential cross-section for continuum part of spectrum is calculated and the absolute level density is determined in a wide range of excitation energy from the best fit with the spectra measured.

All calculations in the framework of an optic-statistical approach have been carried out with the GNASH [3] and PEAK-99 codes [4]. Search of the nuclear level density is carried out, at first, from the analyses of measured neutron spectra in (p,n) reaction at low proton energy, for which it is possible to guarantee the lack of contribution in cross-section of (p,n) reaction all other mechanisms except statistical equilibrium one. At higher proton energies the contributions of pre-equilibrium mechanism were taken into account. In this case the calculations were carried out with use of the GNASH code, in which the statistical equilibrium part of (p,n) reaction was calculated with absolute level density obtained from analyses of spectra at low proton energies. At attainment of the maximum proton energy the return on the initial step of iteration process takes place.

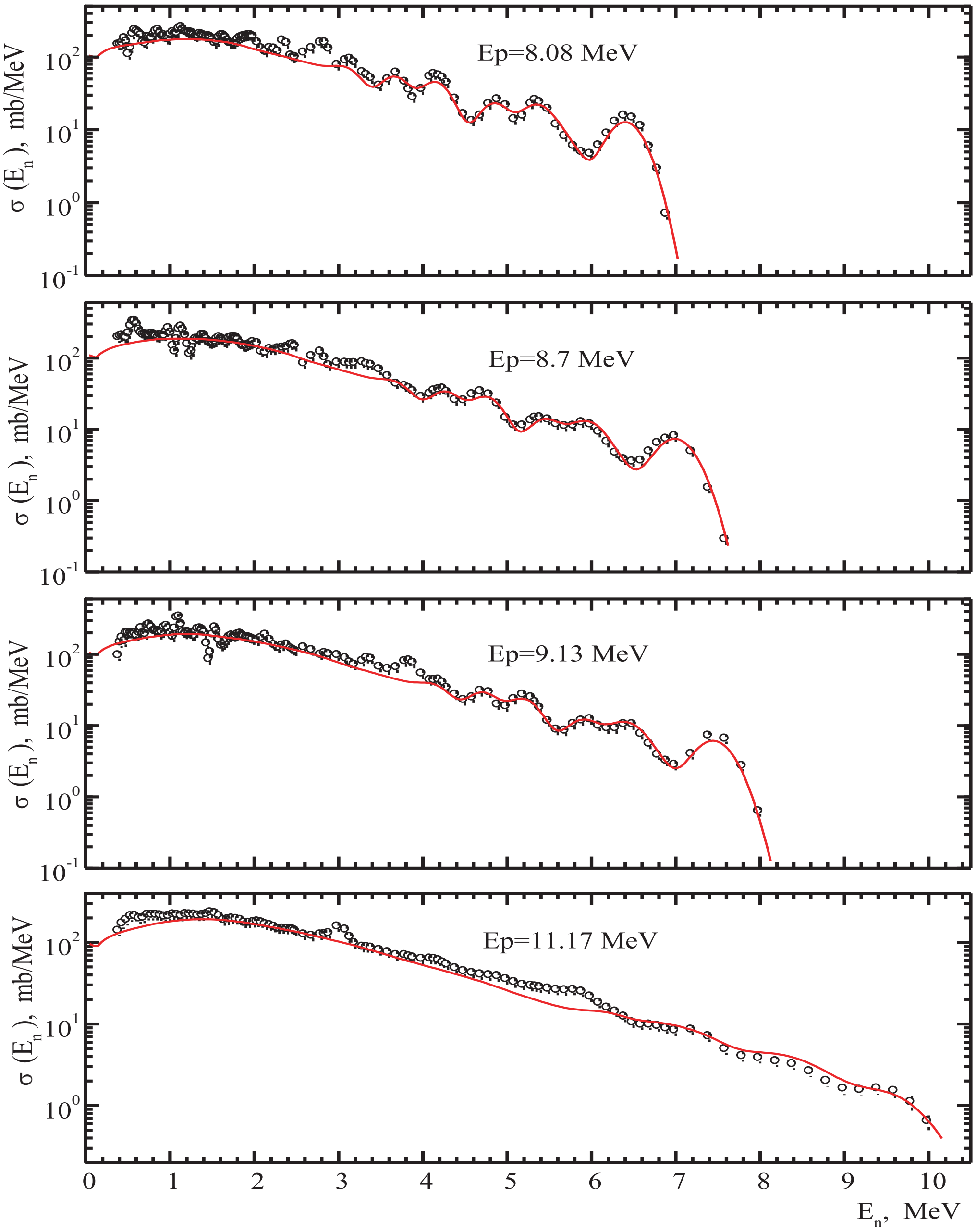

Fig.1. Angle-integrated neutron emission spectra from ^{49}Ti(p,n)^{49}V reaction. The symbols are experimental data, the curves - calculational results.

The criterion χ^2 was used for optimal fit between measured and calculated spectra. At low excitation energies the transitions to well-identified discrete levels of residual nucleus has been calculated. The calculated cross-sections for the comparison with the experimental data have been averaged over the excitation energy in line with normal distribution. The dispersion of the distribution corresponded to the spectrometer resolution. For a reliable determination of nuclear level density from observed neutron spectra it is necessary to set correctly the energy dependence of the neutron optical potential in the energy range up to 10 MeV. In this work as the optical potential was used the potential of Koning and Delaroche, the parameters of which were determined on the basis of wide totality of experimental data on interaction of neutrons and protons with nuclei[5].

Results

The best-fit spectra for ^{49}Ti (p,n)^{49}V reaction at all proton energies calculated according described procedure are shown in fig.1. The comparison of the neutron spectra calculated and measured demonstrates a good fit both discrete level and continuum parts for reactions considered. The extracted level densities for residual nuclei ^{47}V, ^{48}V, ^{49}V, ^{53}Mn, ^{54}Mn, ^{57}Co, ^{59}Ni excited in reactions studied are presented in figs. 2, 3, 4, 5, 6, 7, 8. The total uncertainties of the level densities are evaluated to (15–20)%. The results obtained are in agreement with low–lying level data [6], proton and neutron resonance data for ^{49}V [7], ^{53}Mn [8], ^{59}Ni [9, 10] and with results of work [11] for ^{57}Co, obtained also from analysis of neutron evaporation spectra in reaction ^{57}Fe(p,n)^{57}Co. Higher upper border of well-known low–lying levels (2-3 MeV) is observed the weak-marked structure in nuclear level densities. Obviously, such structure is connected with unhomogeneity of a single–particle state spectrum in transition field from well–identified discrete states to continuum part of excitation spectrum. In energy dependences of the nuclear level densities are displayed odd–even differences. For odd–odd ^{48}V absolute values of the level density more than for odd–even ^{47}V and ^{49}V; for odd–odd ^{54}Mn also more than for odd–even ^{53}Mn. Such differences in the nuclear level densities are connected with shift on pairing energy [12].

The obtained results on the nuclear level densities of ^{47}V, ^{48}V, ^{49}V, ^{53}Mn, ^{54}Mn, ^{57}Co, ^{59}Ni were compared with calculations in the framework of the phenomenological version of the generalized superfluid model of nucleus (GSN) [12], the back-shifted Fermi-gas model (BSFG) [13] and the composite formula of Gilbert–Cameron (G–C) [14]. As may be seen in figs. 2, 3, 4, 5, 6, 7, 8 the absolute values and energy dependences of nuclear level densities of ^{47}V, ^{48}V, ^{49}V, ^{53}Mn, ^{54}Mn, ^{57}Co, ^{59}Ni determined in the present work differ essentially in most cases from the predictions of the nuclear level density model systematics.

Conclusion

Differential neutron emission spectra in (p,n) reaction on nuclei of ^{47}Ti, ^{48}Ti, ^{49}Ti, ^{53}Cr, ^{54}Cr, ^{57}Fe, ^{59}Co in proton energy range of (7-11) MeV have been measured and analysed within the framework of statistical equilibrium and pre-equilibrium models of nuclear reactions. The absolute nuclear level densities of ^{47}V, ^{48}V, ^{49}V, ^{53}Mn, ^{54}Mn, ^{57}Co, ^{59}Ni and theirs energy dependences are determined. In transition field from well–identified discrete states to continuum part of excitation spectrum the weak-marked structure is observed in nuclear level densities connected with unhomogeneity of a single–particle state spectrum. In energy dependences of the nuclear level densities are displayed odd–even differences. It is shown also that the obtained data differ esstntially from the predictions of the nuclear level density model systematics.

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References

1. W. Mannhart. Repoprt IAEA-TECDOC-410, Vienna, 1987, p. 158.
2. V.G. Demenkov, B.V. Zhuravlev, A.A.Lychagin, V.I. Mil`shin, Trykova V.I.. Instruments and Experimental Techniques, v.38, № 3, 1995, p. 314-318.
3. P.G. Young, E.D. Arthur and M.B. Chadwick. Proc. of IAEA Workshop on Nuclear Reaction Data and Nuclear Reactors (Trieste, Italy, April 15 - May 17, 1996), World Scientific, Singapore, 1998, v.1, p.227.
4. B.V. Zhuravlev and N.N. Titarenko. Preprint IPPE-2819, Obninsk-2000.
5. A.J. Koning and J.D. Delaroche. Nucl. Phys. A, v.713, 2003, p.231.
6. ENSDF - evaluated nuclear structure and decay data.
7. E. Bilpuch et al. Phys. Lett. 35 B, (1971), 303.
8. J. Moses et al. Nucl. Phys. A 175, (1971), 556.
9. M.B. Chadwick, P. Oblozinsky et al. Nuclear Data Sheets. v. 107, N. 12, 2006, p. 2941.
10. B.V. Zhuravlev, N.N. Titarenko et al. In Proc. Of the 5 Inter. Seminar on Interaction of Neutrons with Nuclei. Dubna, May 14-17, 1997, JINR, E3-97-213, p. 247-254.
11. V. Mishra, N. Boukharouba, C.T. Brient et al. Phys. Rev. C, v. 49, N.2, 1994, p. 750.
12. A.V. Ignatyuk. Statistical properties of excited atomic nuclei. M.:Energoatomizdat, 1980. O.T. Grudzevich, A.V. Ignatyuk, V.I. Plyaskin. Neutron Physics (Proc. of the 1st Inter. Conf. on Neutron Physics, Kiev), 1987, v.2, p. 96.
13. W. Dilg, W. Schantl, H.Vonach and M. Uhl. Nuclear Physics A. v.217, 1973, p. 269.
14. A. Gilbert, A.G.W. Cameron. Can. J. Phys., v.43, 1965, p.1446.

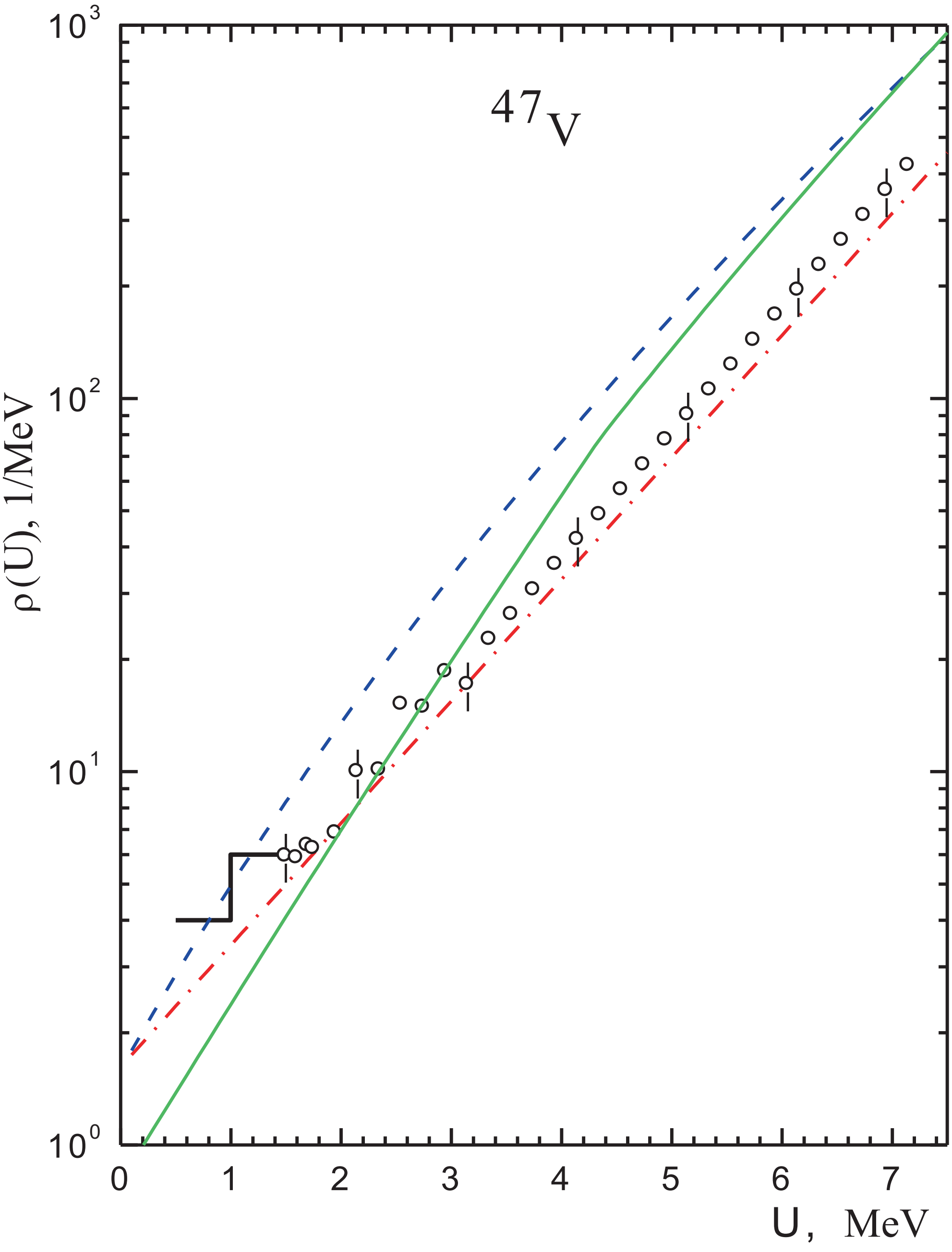

Fig. 2. Nuclear level density of ^{47}V. Experimental data: –o– – present work, histogram – low–lying level data [6]. The curves are results of calculations: solid curve – GSN [12], dashed curve – BSFG [13], dash–dotted curve – G–C [14] systematics.

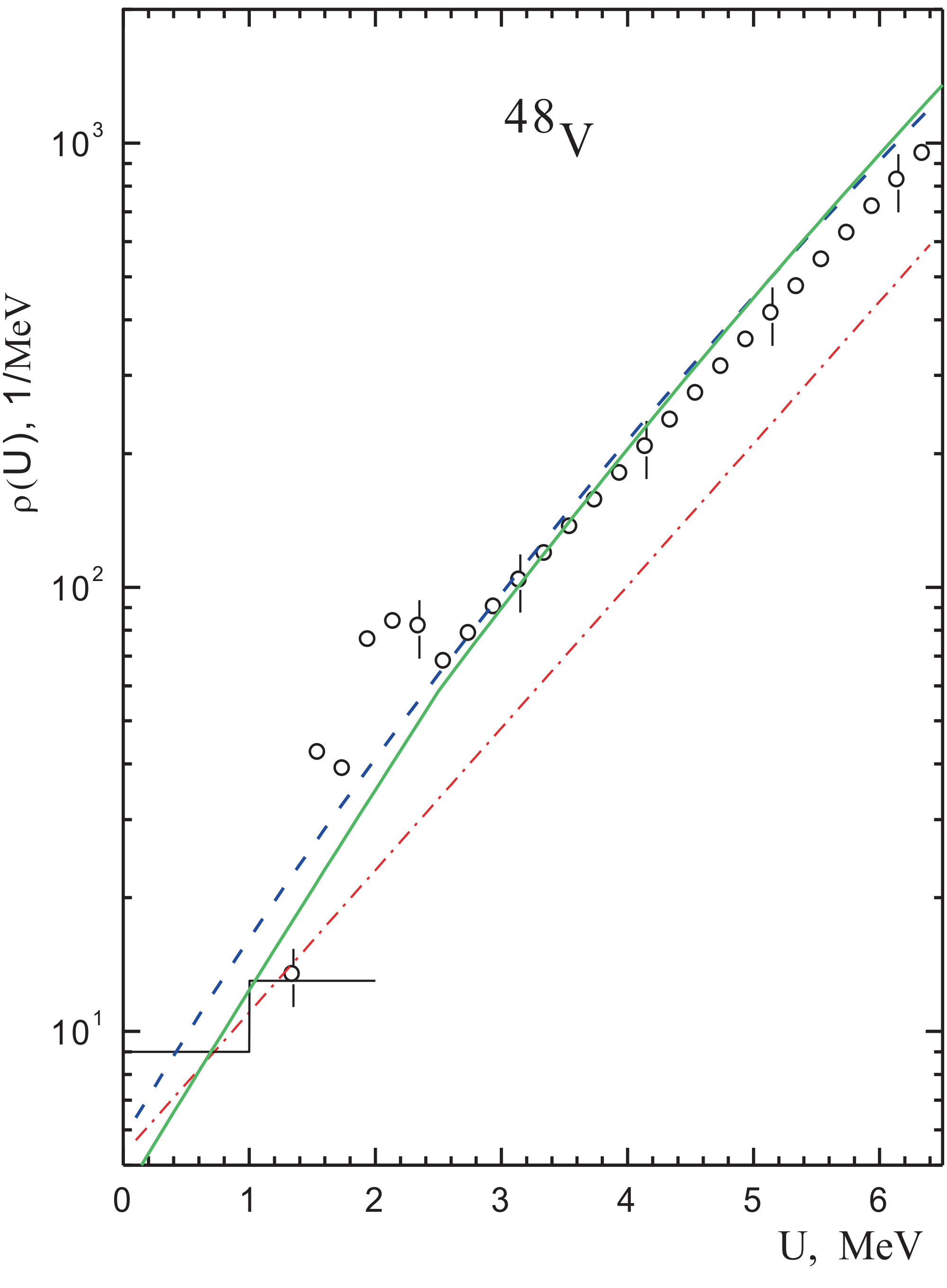

Fig. 3. Nuclear level density of ^{48}V. The rest of notation is identical to that in Fig. 2.

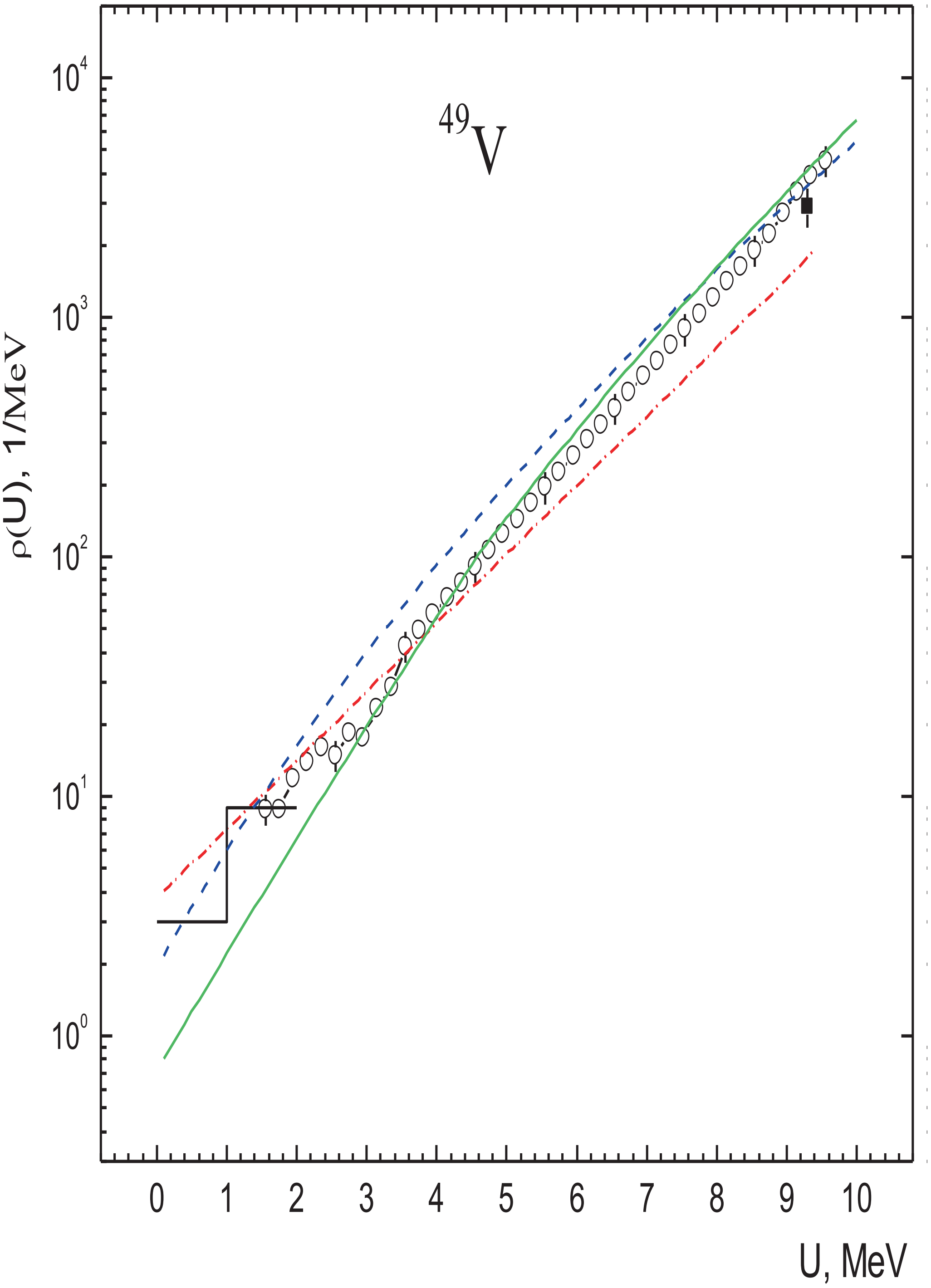

Fig. 4. Nuclear level density of ^{49}V. ■ – proton resonance data [7], the rest of notation is identical to that in Fig. 2.

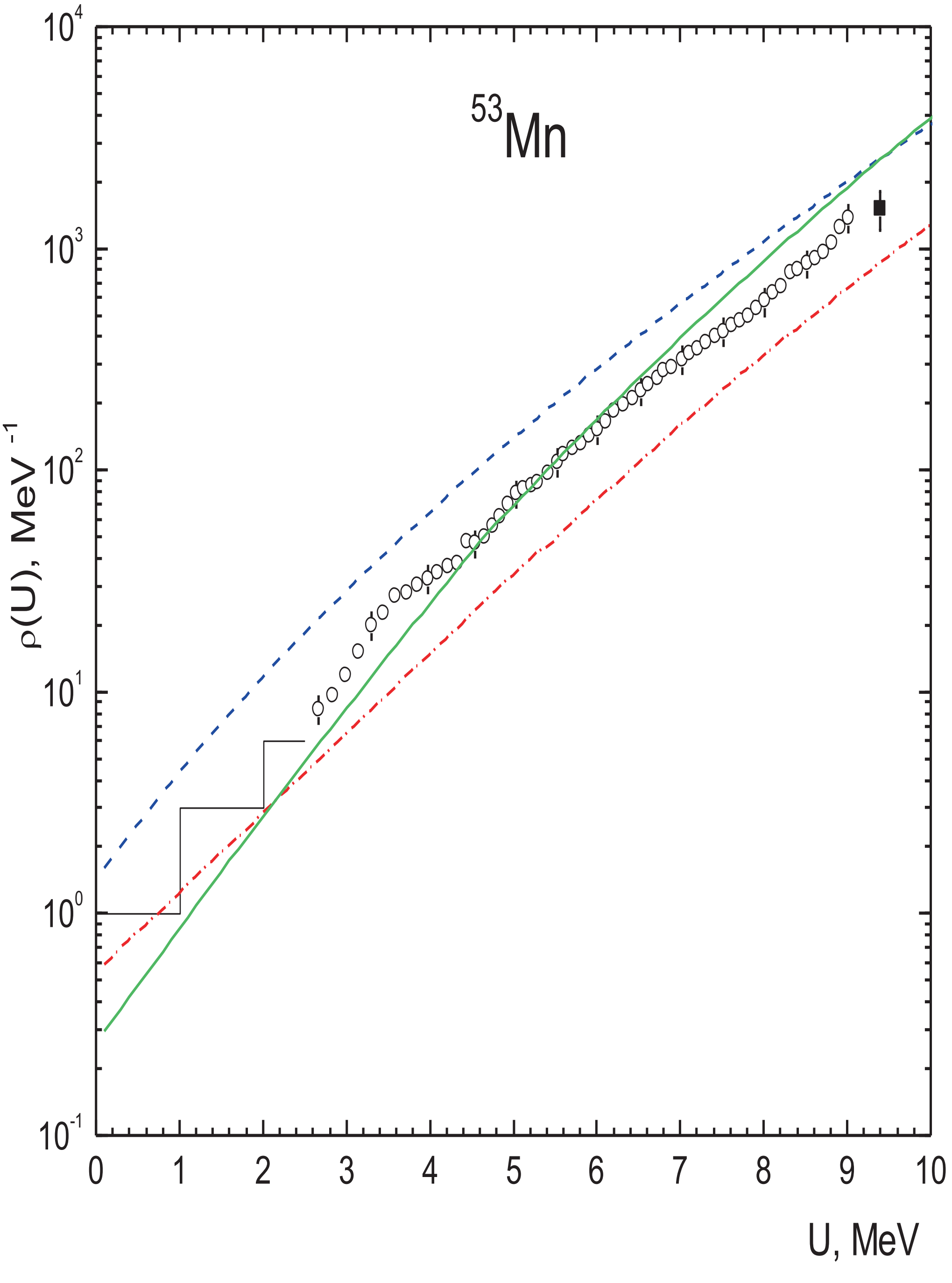

Fig. 5. Nuclear level density of ^{53}Mn. ■ – proton resonance data [8], the rest of notation is identical to that in Fig. 2.

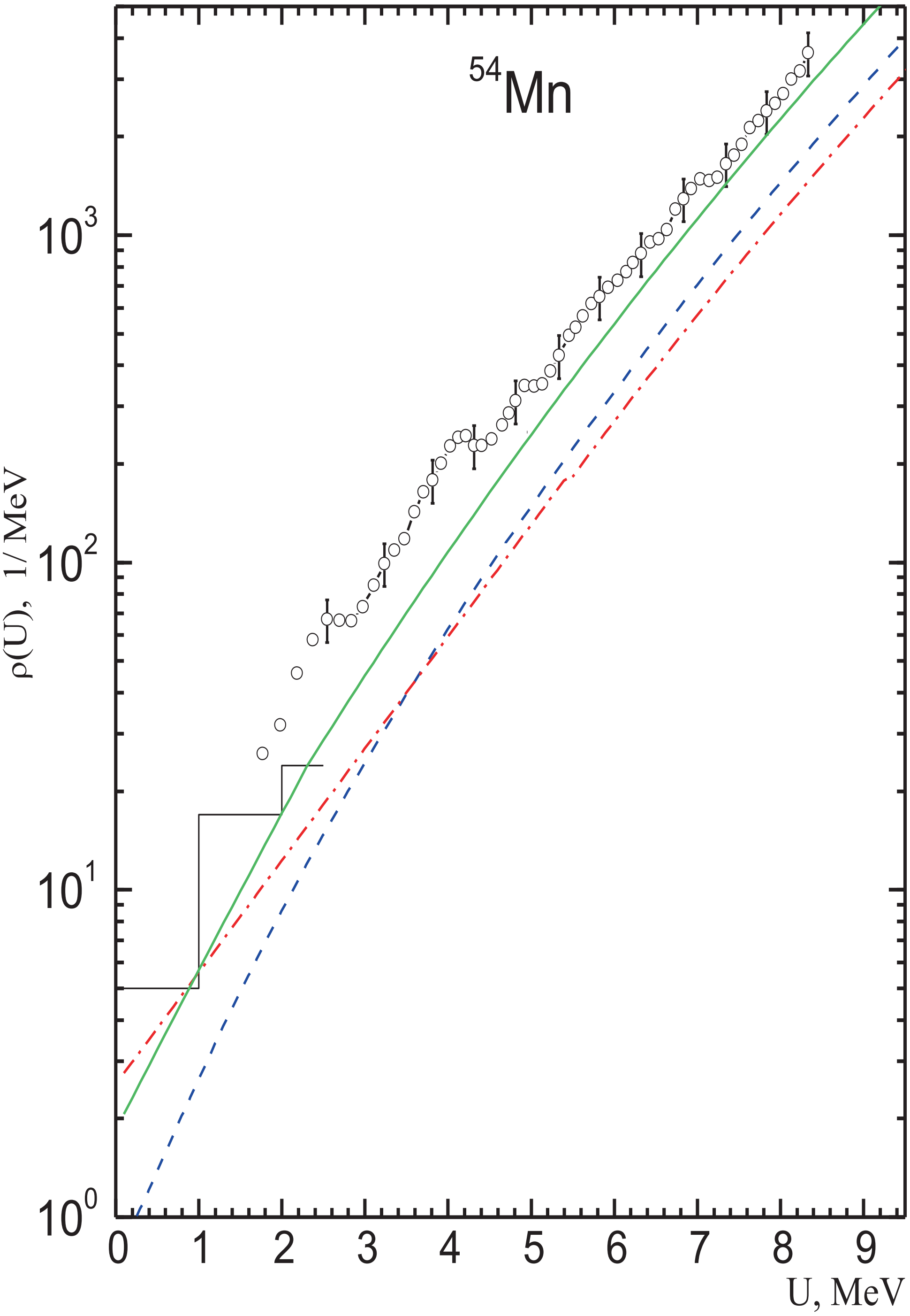

Fig. 6. Nuclear level density of ^{54}Mn. The rest of notation is identical to that in Fig. 2.

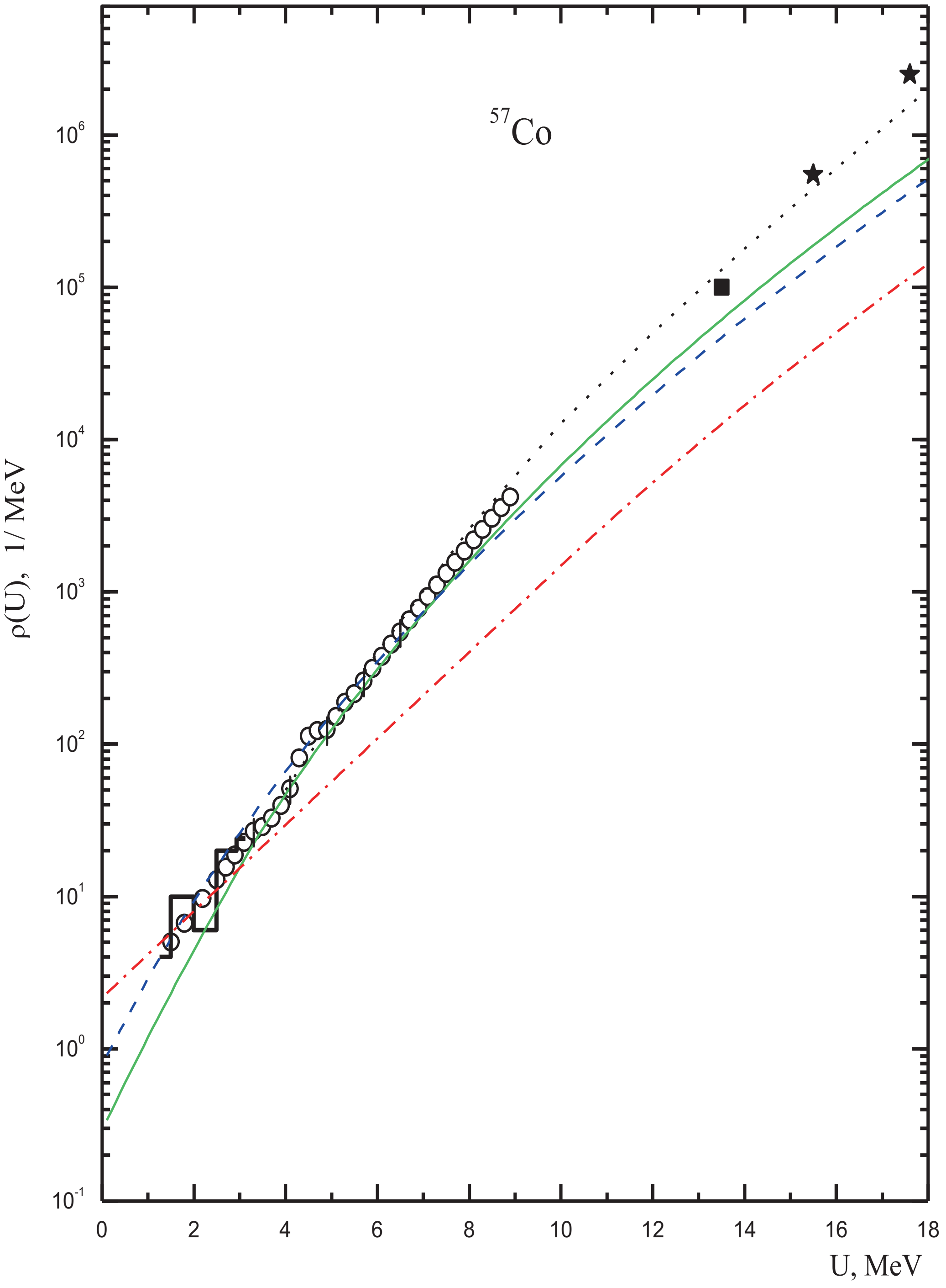

Fig. 5. Nuclear level density of ^{57}Co. ■, ★ – Ericson fluctuations data [11], dotted curve – evaluation on the basis of evaporation spectra and Ericson fluctuation data from work [11], the rest of notation is identical to that in Fig. 2.

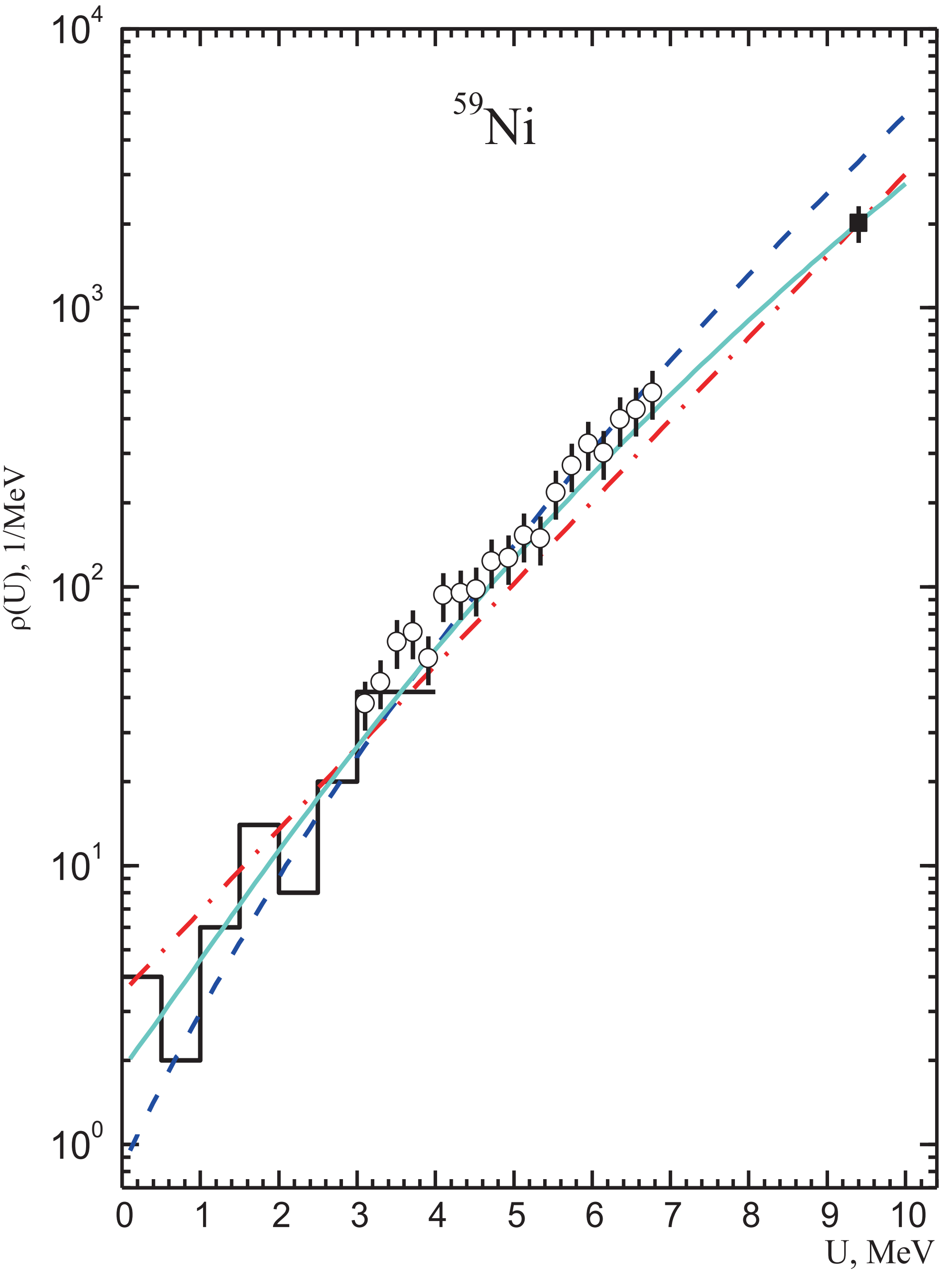

Fig. 8. Nuclear level density of ^{59}Ni. ■ – neutron resonance data [9, 10] (σ corresponds $I_{eff} / I_{rig} = 0.75$), the rest of notation is identical to that in Fig. 2.