NUCLEAR LEVEL DENSITIES OF ^{208}Bi AND ^{209}Po FROM NEUTRON SPECTRA IN (p,n) REACTION ON NUCLEI OF ^{208}Pb AND ^{209}Bi.

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Abstract

Neutron spectra from (p,n) reaction on nuclei of ^{208}Pb, ^{209}Bi have been measured at proton energies between 8 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 to identify reliably the discrete low-lying levels together with continuum part of neutron spectra. Analysis of the measured data have been carried in the framework of statistical equilibrium and pre-equilibrium models of nuclear reactions. The calculations are done using the exact formalism of the statistical theory as given by Hauser-Feshbach with generalized superfluid model of nucleus and back-shifted Fermi-gas model for nuclear level density. The nuclear level densities of ^{208}Bi, ^{209}Po, their energy dependences and model parameters have been determined. The obtained results have been discussed in totality with existing experimental and model systematics data.

Introduction

The general features of nuclear level density are known, but there are a considerable uncertainties of its functional forms conditioned by the shell inhomogeneity of a single-particle state spectrum, the coherent effects of collective nature, residual interaction. 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 (1.5-2) 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 regions 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 an 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 choosen so that the contribution of nonequilibrium processes was minimum. For the heavy nuclei these conditions are best 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 ^{208}Pb, ^{209}Bi in proton energy range of (8-11) MeV have been measured and analysed in the framework of statistical theory to study the nuclear level densities near filled shells.

Experiment

Neutron spectra from (p,n) reaction on nuclei of ^{208}Pb, ^{209}Bi have been measured at proton energies between 8 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 at the angle range of $(20\text{-}140)^0$. As the targets were used the self-supporting metal foils with thickness of 4.20, 7.79 mg/cm^2 and enrichment of 98.3, 99.5% for ^{208}Pb and ^{209}Bi 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 to 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 ^{208}Pb 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 component 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 greater proton energies the contributions of preequilibrium 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 excitation energy the return on the beginning step of iteration process takes place.

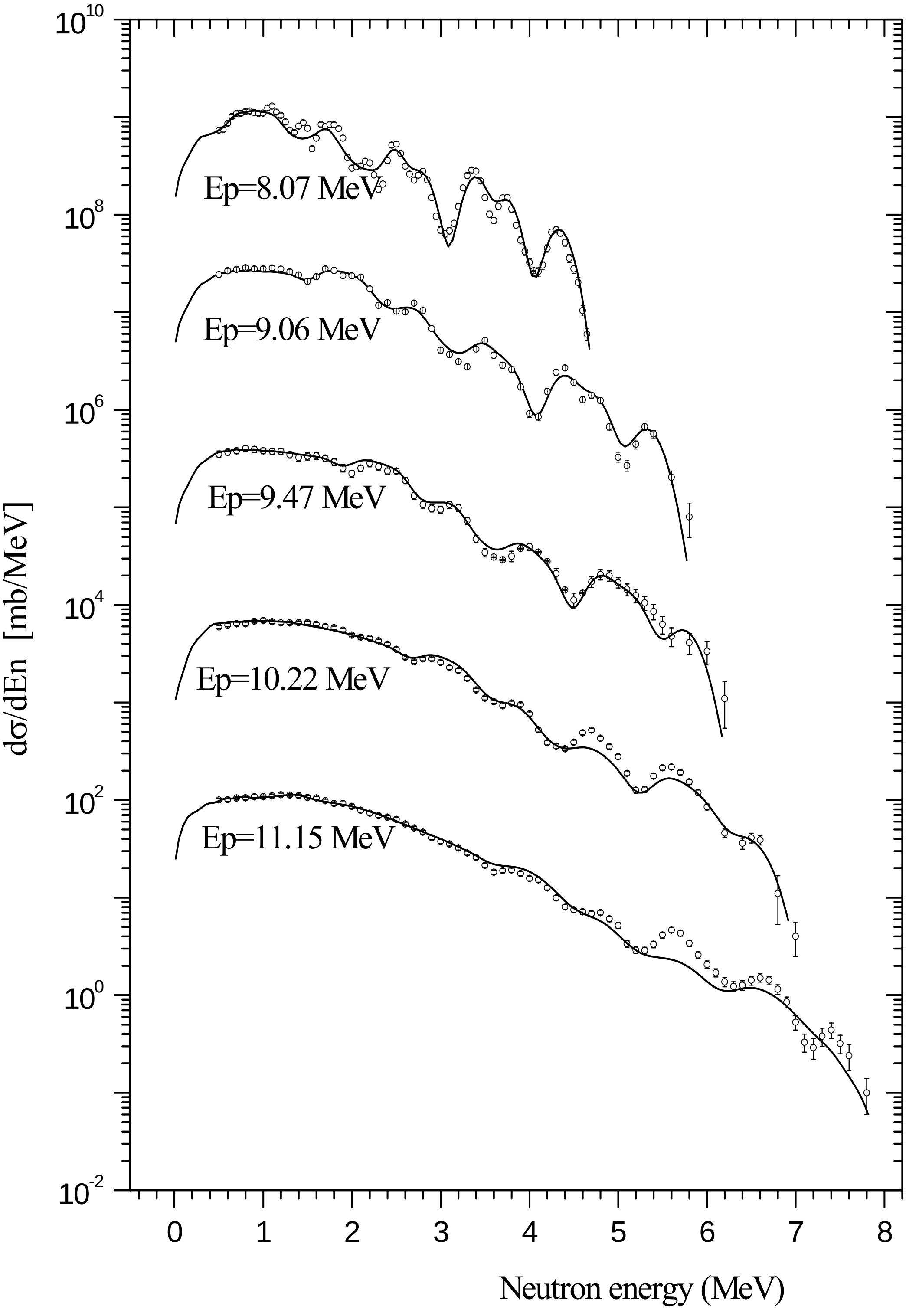

Fig.1. Angle-integrated neutron emission spectra from $^{208}Pb(p,n)^{208}Bi$ reaction. The symbols are experimental data, the curves - calculational results. The values at E_p=10.22, 9.47, 9.06, 8.07 MeV are displaced on 2, 4, 6 and 8 orders of magnitude, accordingly.

The criterion χ^2 was used for optimal fit between experimental and calculational 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 low. 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 9 MeV. In this work as the optical potential was used the potential of Lane model, the parameters of which were determined on the basis of wide totality of experimental data on interaction of neutrons and protons with nuclei of Pb and Bi [5].

Results

The best-fit spectra for ^{208}Pb(p,n)^{208}Bi reactions 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 of ^{208}Bi and ^{209}Po excited in reactions studied are presented in figs. 2 and 3. The total uncertainties of the level densities amount to ~17 %. As can be seen the values obtained in the present work for ^{208}Bi and ^{209}Po mainly coincide in the limits of errors with results of work [6], obtained by us earlier also from the measurements neutron spectra from (p,n) reaction at proton energies of 7 and 11 MeV on 150 cm cyclotron time-of-flight facility. The results obtained are in a good agreement also with low-lying level data [7] for both nuclei and with data of work [8] for ^{209}Po at excitation energy about 7.5 MeV. Below $U=E_c$ the differential neutron emission spectrum is no longer proportional to the level density and the structure in this excitation energy range is due to discrete states normalization on which was made. But the better resolution realized in the present measurements allowed to observe the structure in the nuclear level density of ^{208}Bi and ^{209}Po at excitation energies essentially higher upper border (~2 MeV) of well-known low-lying levels. Obviously, such structure is connected with the shell unhomogeneties of a single-particle state spectrum for nuclei near magic Z=82 and N=126.

The obtained results on the nuclear level densities of ^{208}Bi and ^{209}Po were compared with calculations in the framework of the phenomenological version of the generalized superfluid model of nucleus (GSN) [9] and the back-shifted Fermi-gas model (BSFG) [10]. The values of nuclear level density parameters, corresponding to the optimal fit of the obtained results and recommended in model systematics GSN [9] and BSFG [10] are presented in table.

Table. Nuclear level density model parameters.

Model		**GSN**					**BSFG** c)			
Parameter Nucleus	**$\tilde{a}$**	**Δ_o**	**δW**	**γ**	**C_v**	**ω_{2+}**	**a**	**Δ**	**E_c**	**N_L**
^{208}Bi a)	19,5	0,67	-12,2	0,064	0,030	0,79	13,8	-0,17	1,94	42
b)	19,4	0,83	-11,7	0,064	0,045	0,85	11,4	-1,23	1,94	42
^{209}Po a)	19,5	1,40	-11,9	0,064	0,030	0,65	15,0	0,59	1,76	12
b)	19,5	0,64	-10,7	0,064	0,030	0,65	–	–	1,76	12

a) Parameters correspond the best fit of the obtained results,
b) Parameters recommended in systematics GSN [9] и BSFG [10],
c) BSFG calculations have been carried out with rigid body moment of inertia.

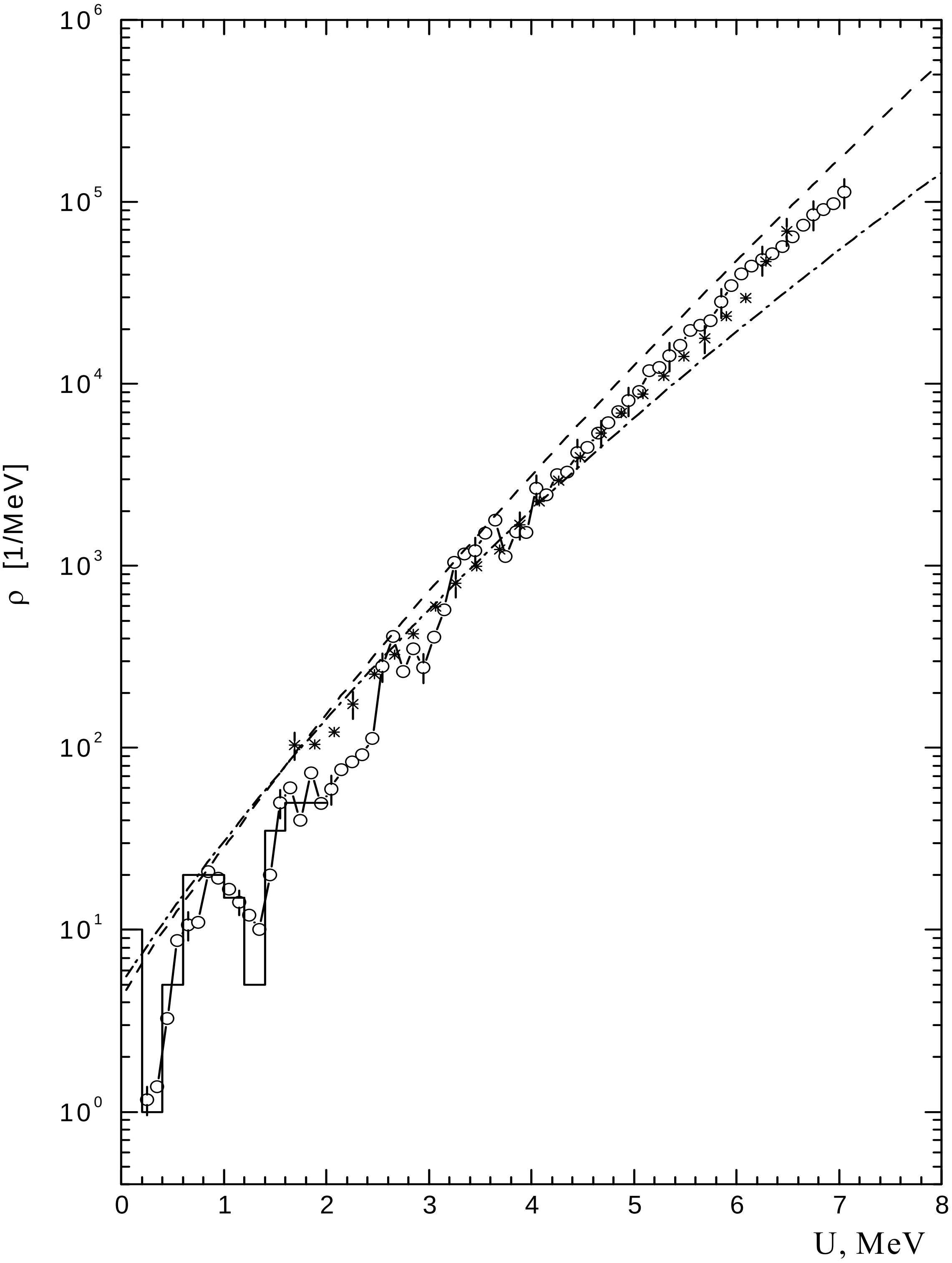

Fig. 2. Nuclear level density of ^{208}Bi. Experimental data: –o– - present work, T - [6], histogram - low-lying level data [7]. The curves are results of calculations: dashed curve - GSN [9], dash-dotted curve - BSFG [10] systematics.

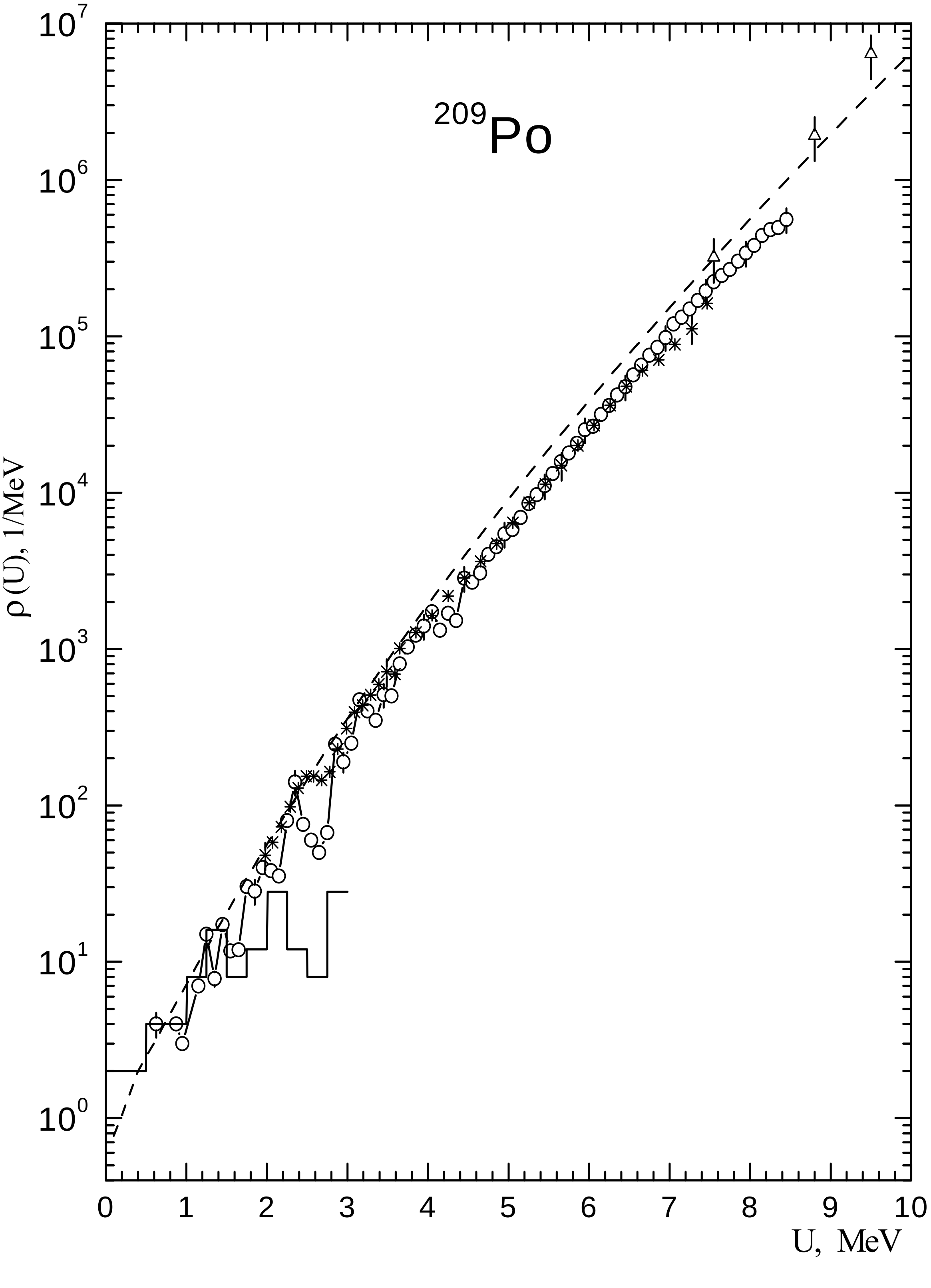

Fig. 3. Nuclear level density of ^{209}Po. Designations are the same as in fig. 2. Δ – [8].

As may be seen in figs. 2, 3 and in table the energy dependences and model parameters of nuclear level density ^{208}Bi and ^{209}Po determined in the present work are quite close to recommended ones in the phenomenological version of the generalized superfluid model of nucleus [9] and differ essentially for ^{208}Bi from the prediction of back-shifted Fermi-gas model [10].

Conclusion

Differential neutron emission spectra in reactions of ^{208}Pb(p,n)^{208}Bi and ^{209}Bi(p,n)^{209}Po in proton energy range of (8-11) 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 ^{208}Bi and ^{209}Po, theirs energy dependences and model parameters are determined. In energy dependences of the nuclear level density at excitation energy range of (1–4) MeV are displayed the structure connected with the shell unhomogeneties of a single-particle state spectra.

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