NUCLEAR LEVEL DENSITIES NEAR Z=50 FROM NEUTRON EVAPORATION SPECTRA IN (p,n) REACTION

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Abstract

Excitation functions, neutron spectra and angular distributions in (p,n) reactions on isotopes of ^{116}Sn, ^{118}Sn, ^{122}Sn, ^{124}Sn have been measured in proton energy range of (7-11) MeV. The measurements were performed by time-of-flight fast neutron spectrometer on the pulsed tandem accelerator EGP-15 of IPPE. 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. Analysis 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 using the exact formalism of the statistical theory as given by Hauser-Feshbach. The nuclear level densities of ^{116}Sb, ^{118}Sb, ^{122}Sb, ^{124}Sb, their energy dependences and model parameters have been determined. In energy dependences of the nuclear level density in excitation energy range of (0-2) MeV is displayed the structure connected with shell unhomogeneties of a single-particle state spectrum for nuclei near filled shells. The isotopic dependence of nuclear level density is found out and explained. It is shown also that the obtained data differ essentially from the predictions of nuclear level density model systematics.

Introduction

Nuclear level density is an area of considerable interest in nuclear physics being very important for the creation of consistent theoretical description of excited nucleus properties and in making nuclear reaction cross-section calculations in the framework of statistical model. Latter includes nucleosynthesis study in nuclear astrophysics. The general features of nuclear level density are known, but the existing data are differed often in 1.5 times, and its isotopic dependence, knowledge of which is very important for astrophysical nucleosynthesis calculations, are studied poorly for lack of the experimental information. The experimental data on the nuclear level densities for many nuclei are derived, in the main, from the analysis of low-lying level and neutron resonance data. But this information is limited to rather narrow ranges of excitation energy, spin and (N-Z) value, 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, spin and (N-Z) value. Such method has been the study of 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 nonequilibrium processes was minimum. For the middle and heavy nuclei these conditions are best satisfied with (p,n) reaction at proton energy up to 11 MeV. In the present work the differential neutron emission cross-sections for (p,n) reaction on nuclei of ^{116}Sn, ^{118}Sn, ^{122}Sn, ^{124}Sn, in proton energy range of (7 - 11) MeV have been measured and analysed in the framework of statistical theory of nuclear reactions to study the features of nuclear level density near filled shell Z=50 and its isotopic dependence.

Experiment

Neutron spectra from (p,n) reaction on nuclei of ^{116}Sn, ^{118}Sn, ^{122}Sn, ^{124}Sn, 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 4.00, 4.98, 2,10; 3.80 mg/cm^2 and enrichment of 97.8, 98.7, 97.5, 98.3 % for ^{116}Sn, ^{118}Sn, ^{122}Sn, ^{124}Sn 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 reduced then 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 ^{118}Sn are presented in figs 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 [4] codes. 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 and second step of (p,pn) and (p,2n) reactions were taken into account. In this case the calculations were carried out with use of the modernized 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. 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. Search of the nucleon optical potential parameters for A=116, 118, 122, 124 were carried out in the framework of coupled-channels optical model approach with using of all accessible experimental data on neutron and proton scattering on isotopes of tin. It allowed to obtain the well-founded evaluation of cross-sections for all isotopes of tin in all open nuclear reaction channels up to 20 MeV. Potential parameters and procedure of optical model calculations will be discussed in separate work. Parameter "k" accounted for interaction between particle-hole states and influenced on pre-equilibrium contribution was chosen equal 150 MeV^3, that is in the range of recommended values (130-170) MeV^3. The single-particle level spacing g=A/13. The factor which is taking into account distinction of neutrons and protons in the internuclear cascade was calculated in the assumption that in each pair interaction the proton and neutron are created with relative probabilities Z/A and N/A.

Results

The best-fit spectra for ^{118}Sn(p,n)^{118}Sb 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 of ^{116}Sb, ^{118}Sb, ^{122}Sb, ^{124}Sb excited in reactions studied are presented in figs. 2,3. The total uncertainties of the level densities amount to (13-18)%. The results obtained in the present work are in an agreement with low-lying state data [5] and with neutron resonance data [6]. Some difference from low-lying levels data for ^{122}Sb in excitation energy range of (0.5-1.0) MeV is conditioned by a loss of levels, that can see from cumulated number of levels presented in fig.4. The structure observed in excitation energy range of (0-2) MeV is connected with the shell unhomogeneties of a single-particle spectrum for nuclei near by Z=50.

For the chain of excited nuclei of Sb (Z=51, N=65, 67, 71, 73) is observed the essential decreasing of the nuclear level density with increase of (N-Z) (see values of parameter "a" in the table and figs.2, 3). It can be explained by effect connected with isospin. For nuclei with number of neutrons N and protons Z the allowed range of isospins is from T_{min}=(N-Z)/2 and above. With increase of (N-Z)/2 allowed range will be shorten and number of levels have to decrease. As one can see in fig.4, the nuclear level density parameter values " ã " of the generalized superfluid model of nucleus [7] determined in the work [10] also from neutron spectra in (p,n) reaction analysis [11,12] for nuclei of ^{116}Sb, ^{117}Sb, ^{118}Sb, ^{119}Sb, ^{122}Sb are in a good agreement with results of the present work and correspond to the dependence from (N-Z) just noticed by us.

The analyses of the differential neutron emission cross-sections was carried out with the generalized superfluid model of nucleus (GSN) [7], the back-shifted Fermi-gas model (BSFG) [8] and the composite formula of Gilbert - Cameron (G - C) [9] for nuclear level density. The values of nuclear level density parameters, corresponding to the optimal fit both in the discrete and continuum parts of neutron spectra, and also recommended in model systematics GSN [7], BSFG [8], G-C [9] are presented in table. As can be seen in figs. 2,3 and in table in most cases the absolute values, energy dependences and model parameters of nuclear level density for ^{116}Sb, ^{118}Sb, ^{122}Sb, ^{124}Sb determined in the present work differ strongly from the prediction of nuclear level density model systematics. Only the result of calculation with parameters recommended in systematics of G - C for ^{122}Sb and ^{124}Sb close to determined ones in the present work.

Conclusion

Differential neutron emission spectra in (p,n) reaction on isotopes of ^{116}Sn, ^{118}Sn, ^{122}Sn, ^{124}Sn have been measured and analyzed in the framework of statistical equilibrium and preequilibrium models of nuclear reactions. The absolute nuclear level densities of ^{116}Sb, ^{118}Sb, ^{122}Sb, ^{124}Sb, theirs energy dependences and model parameters are determined. In energy dependences of the nuclear level density in excitation energy range of (0-2) MeV is displayed the structure connected with the shell unhomogeneties of a single-particle state spectrum. The isotopic dependence of nuclear level density is found out. It is shown also that the obtained data differ essentially from the predictions of nuclear level density model systematics.

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Table. Nuclear level density parameters.

Model		GSN						G - C					BSFG c)			
Parameter Nucleus		$\tilde{a}$	Δ_o	δW	γ	C_v	ω_{2+}	**a**	Δ	E_x	**T**	E_o	**a**	Δ	E_c	N_L
^{116}Sb	a)	15.6	0.68	0.25	0.082	0.037	1.00	19.0	0	1.77	0.41	-0.30	19.0	-0.05	0.95	24
	b)	11.2	1.12	0.25	0.082	0.037	1.00	17.4	0	2.64	0.50	-0.56	15.3	-0.78	0.95	24
^{118}Sb	a)	16.9	0.61	0.52	0.082	0.037	1.00	20.5	0	2.51	0.44	-0.72	20.4	-0.05	0.32	12
	b)	11.4	1.11	0.52	0.082	0.037	1.00	17.9	0	2.59	0.50	-0.85	15.2	-0.92	0.32	12
^{122}Sb	a)	15.6	0.00	-0.34	0.081	0.037	1.00	16.6	0.22	3.35	0.55	-0.75	16.2	0.10	1.07	28
	b)	11.7	0.00	-0.34	0.081	0.037	1.00	16.5	0.22	3.39	0.55	-0.77	14.9	-1.21	1.07	28
^{124}Sb	a)	12.4	0.69	-1.23	0.080	0.037	1.00	15.6	0	4.36	0.65	-1.55	15.4	-0.50	0.48	26
	b)	11.9	1.08	-1.23	0.080	0.037	1.00	15.3	0	4.49	0.66	-1.61	14.0	-1.39	0.48	26

a) Parameters corresponding to the best fit spectra calculated and measured,

b) Parameters recommended in systematics GSN [7], BSFG [8], G - C [9],

c) BSFG calculations have been carried out with rigid body moment of inertia.

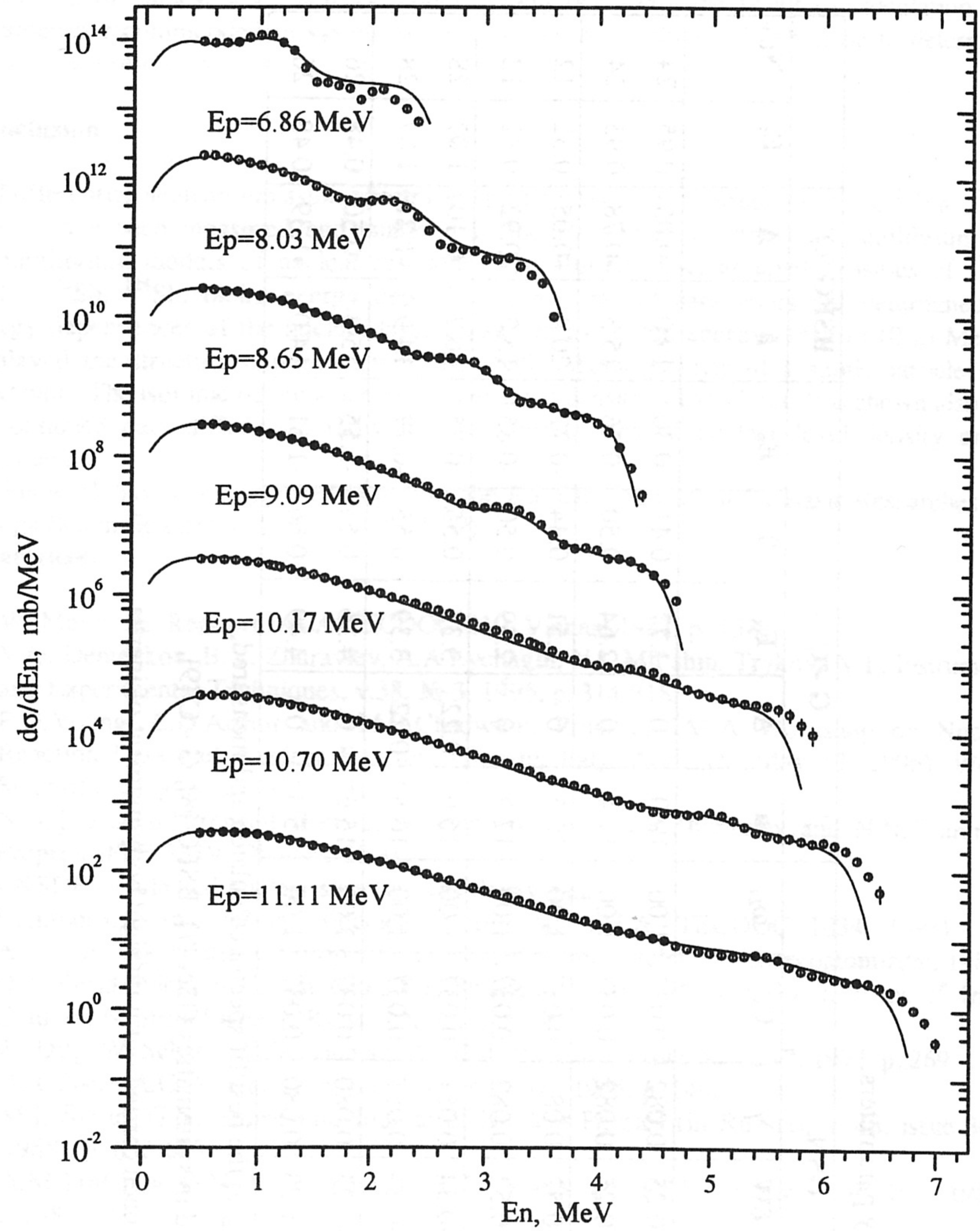

Fig.1. Angle-integrated neutron emission spectra from ^{118}Sn (p,n)^{118}Sb reaction. The symbols are experimental data, the curves - calculational results. The values at Ep =10.70; 10.17; 9.09; 8.65; 8.03; 6.86 are displaced on 2, 4, 6, 8, 10, 12 orders of magnitude, accordingly.

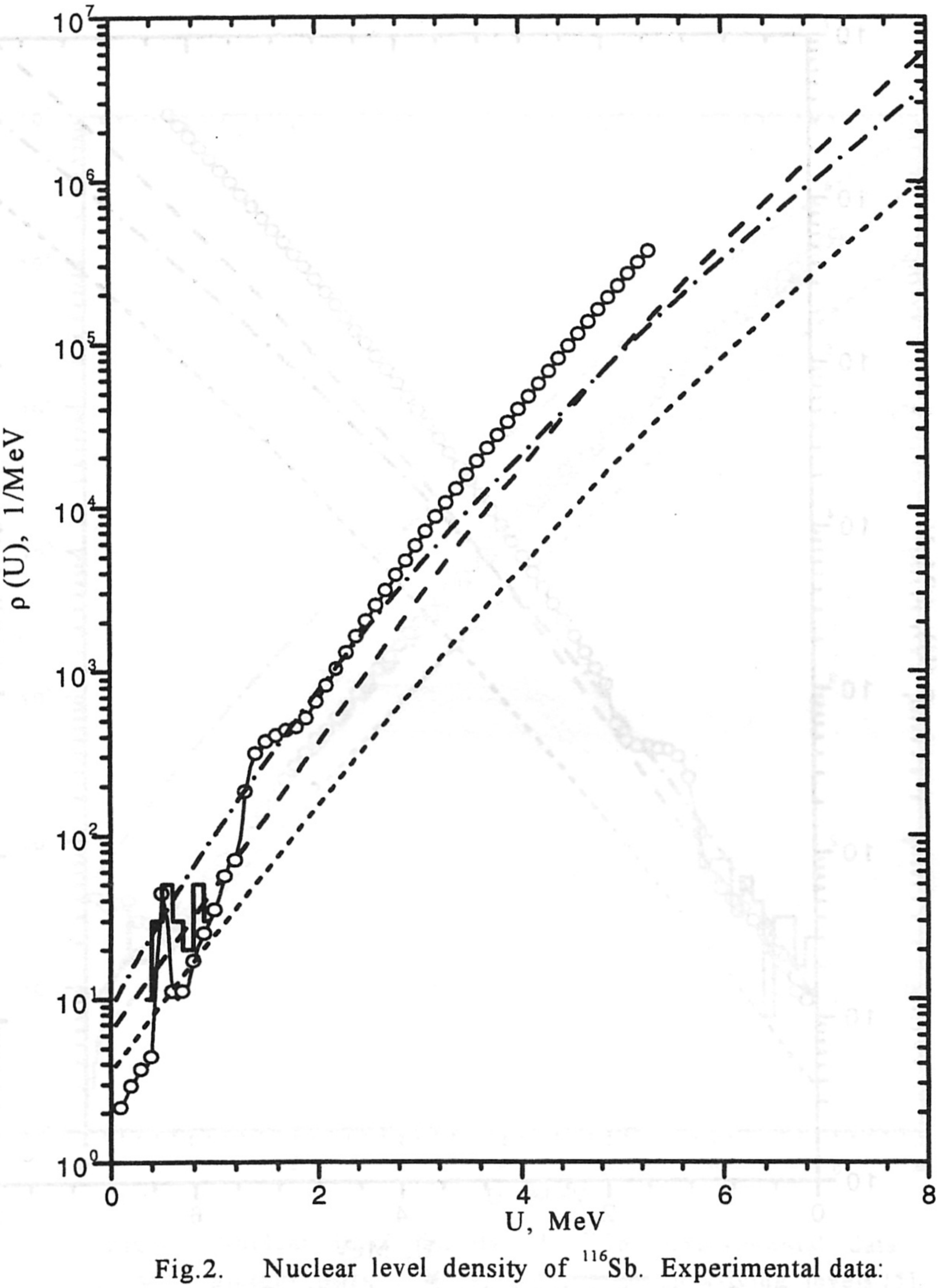

Fig.2. Nuclear level density of ^{116}Sb. Experimental data: —○— - present work, ——— - low-lying levels [5]. The curves are calculated results: ------ - GSN [7], —·—·- - BSFG [8], — — — - G-C [9] systematics.

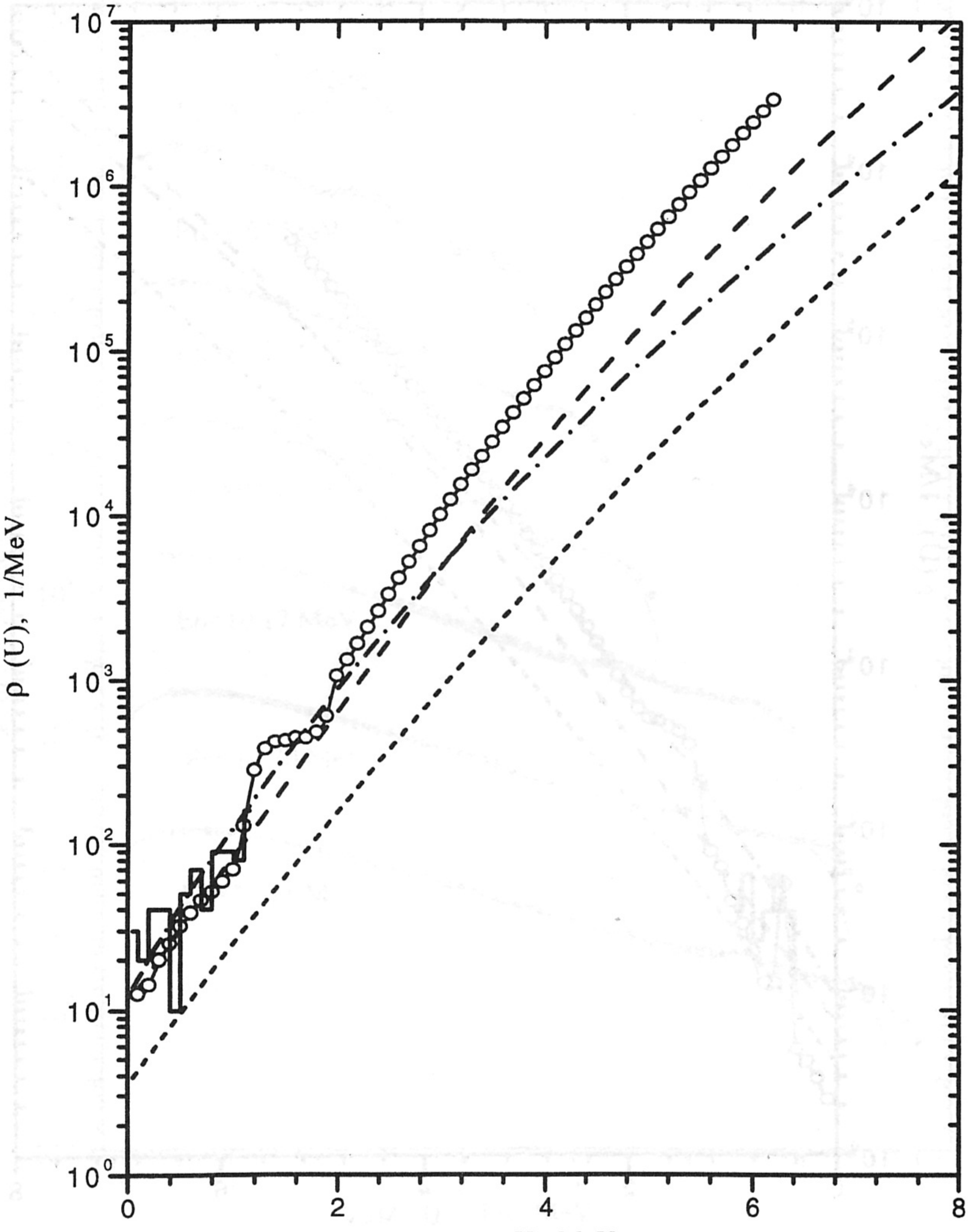

Fig.3. Nuclear level density of ^{118}Sb. Experimental data: —○— - present work, ——— - low-lying levels [5]. The curves are calculated results: ------ - GSN [7], -·-·- - BSFG [8], — — — - G-C [9] systematics.

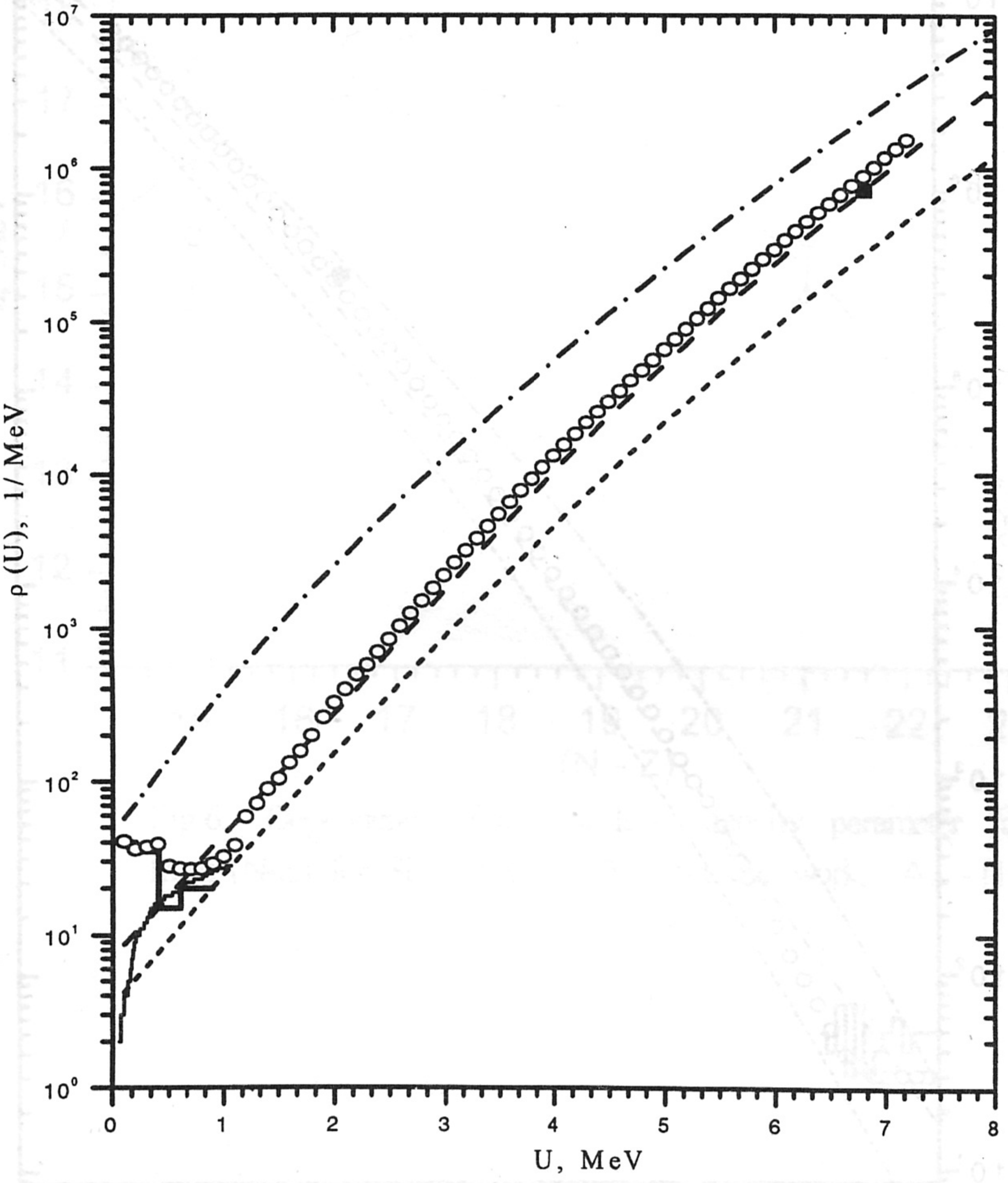

Fig.4. Nuclear level density of ^{122}Sb. Experimental data: ○ - present work, ■ - [6], ━━━ - low-lying levels [5], ─── - cumulated number of levels [5]. The curves are calculated results: ------ - GSN [7], —·—·- - BSFG [8], — — — - G-C [9] systematics.

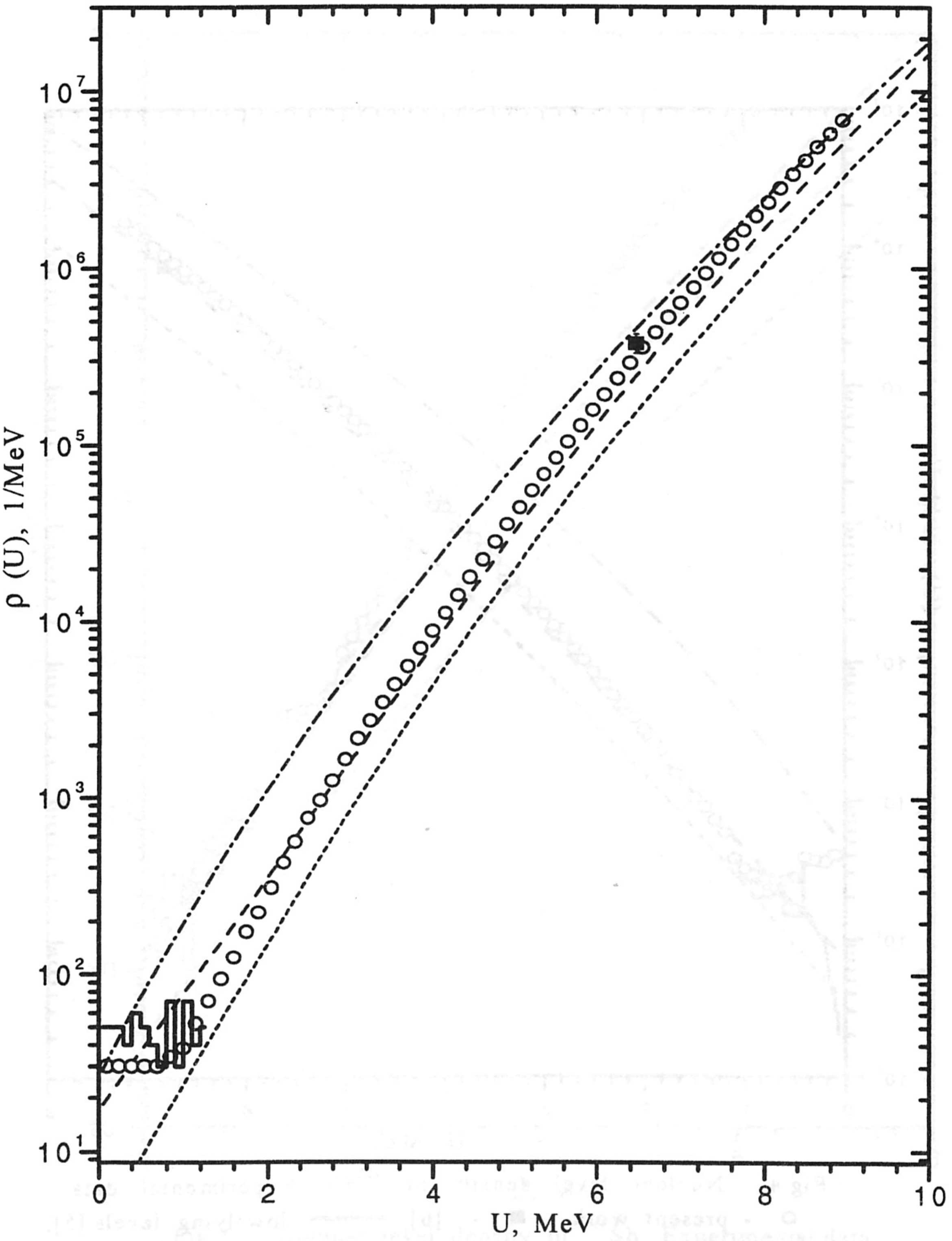

Fig.5. Nuclear level density of ^{124}Sb. Experimental data: ○ - present work, ■ - [6], ——— - low-lying levels [5]. The curves are calculated results: -------- - GSN [7], -·-·-·- - BSFG [8], – – – – - G-C [9] systematics.

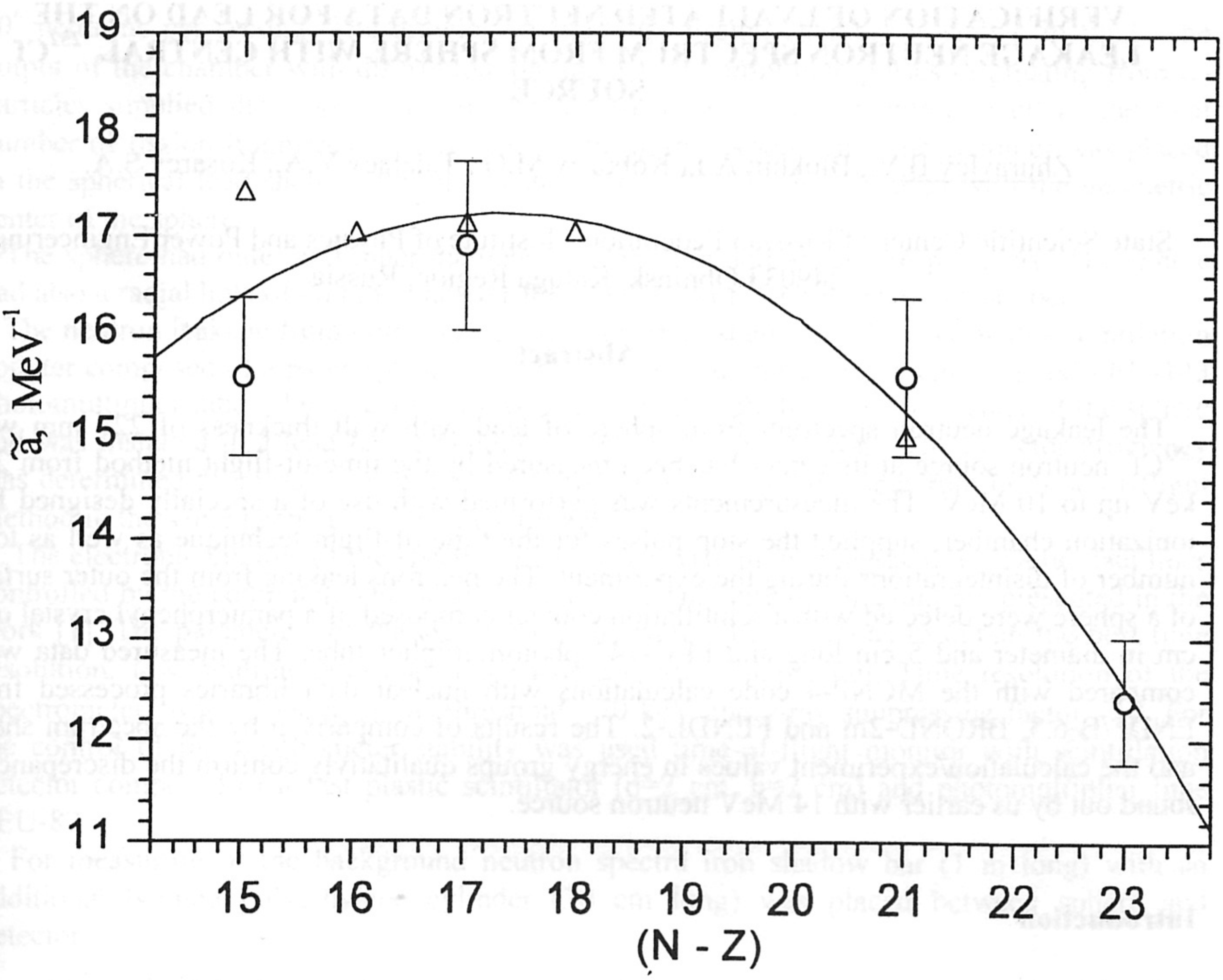

Fig.6. Dependence of nuclear level density parameter "ã" from (N-Z) for Sb isotopes. ○ - present work, △ - [10].