NONSTATISTICAL EFFECTS IN RESONANCES OF HEAVY NUCLEI

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1. Introduction

In the report of the Kurchatov Institute (Moscow) [1] at the First Geneva Conference (1955) on the Peaceful Use of Atomic Energy, attention was drawn to the proximity of the positions of neutron resonances of different heavy isotopes (at $E_n \approx 0.3$ eV in target nuclei ^{239,241}Pu and ^{241,243}Am). This effect was later studied by Yu. Konakhovich and M. Pevsner in ^{229}Th [2] (this work was supported by I.V. Kurchatov), but as a result, no resonance was found in this isotope at this energy.

The systematic character of the proximity of the resonances positions (at 0.296 eV, 0.265 eV, 0.205 eV and 0.419 eV) in the compound nuclei ^{240,242}Pu and ^{242,244}Am cannot be checked using spacing distributions due to the very small interval under consideration. But the grouping of resonance positions at 5 eV was discussed in [3-6], and a combined study of spacing D distributions of Pu and Am isotopes was possible. In ^{242}Am (Fig. 1), fine structures were observed with intervals D=9 keV, 76 keV, 38 keV, 45 keV and 101 keV (at low excitations) and D=1.32 keV, 2.07 keV, 2.76 keV and 10.24 keV (in resonances).

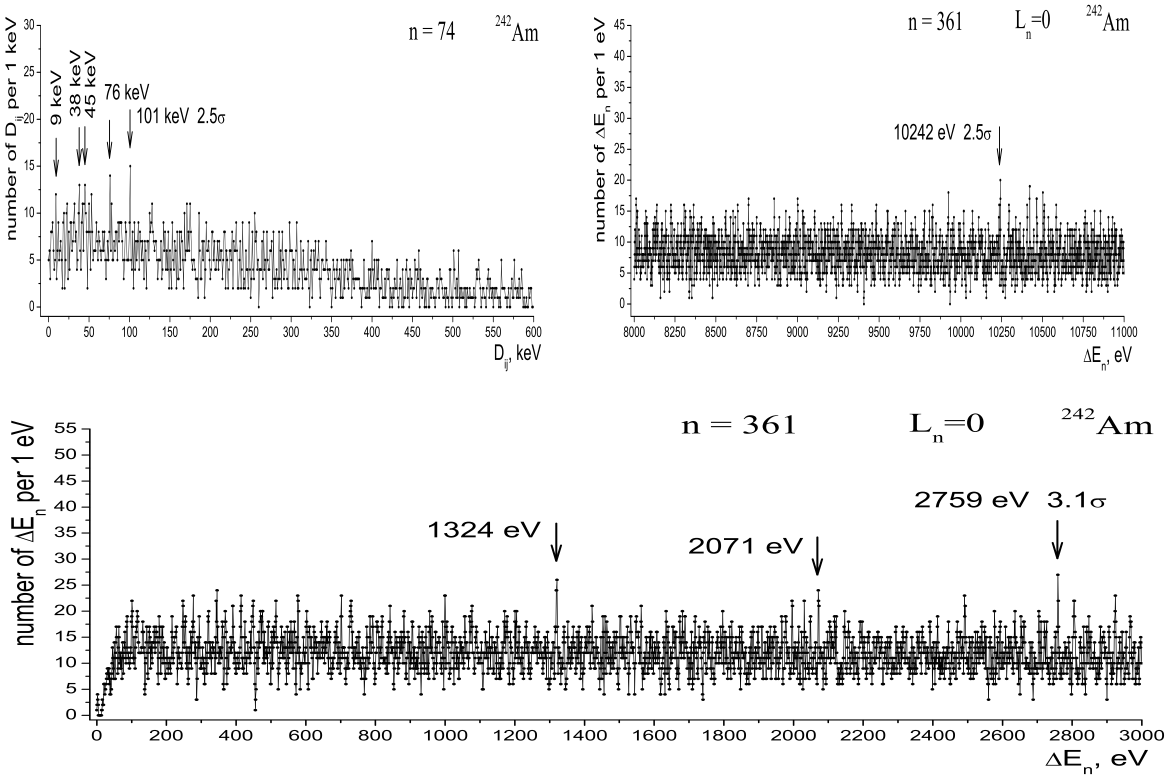

Fig. 1. *Top left:* Spacing distributions in low-lying states of ^{242}Am.
Top right and bottom: Spacing distribution in ^{242}Am neutron resonances.

The superfine structure in the neutron resonance spectra of plutonium isotopes is shown in Fig. 2. Here the coincidence of the maxima in the resonance spacing distributions in three neighbouring isotopes ^{241,243,245}Pu with D=99 eV=18×5.5 eV is shown (the Figure is from [5], where the specific properties of heavy nuclei were discussed). Many authors reported the observation of a grouping of small intervals in the neutron resonance spacing and the resonance positions (called hyperfine structure in [6]). Such effects (with stable intervals of 1 eV and larger) can be considered as the next order effects in the spectra of nuclei, where fine structure effects (with intervals of the order of 1 keV and larger) take place. For example, in heavy isotopes, a fine structure in mass values (with intervals of about 170 keV) was found by V. Andreev [7]. Stable intervals with values 1 eV and larger were attributed to superfine structure (the name was proposed by I.M. Frank [8]). First this effect was considered by W. Havens [9]. The presence of the grouping effect at 5.5 eV, 66 eV and 94 eV in the positions of resonances (see Fig. 6, top in the previous report at this meeting [10,11]) was reported in [3,4]. The superfine structure in the resonance spacing of many nuclei (with the parameter 11 eV=$\delta'' = 8\varepsilon'' = 8\times1.34$ eV) was discussed in [12-15]. Considering the stable intervals of the hyperfine structure (with the value less than the superfine parameter 1.3 eV=ε''), as the next order effect of the observed superfine structure in the ^{240}Pu 0^+ levels (Fig. 2), one estimates their values as 650 eV×$\alpha/2\pi$ ≈0.75 eV. For obtaining a meaningful result, very accurate data are needed.

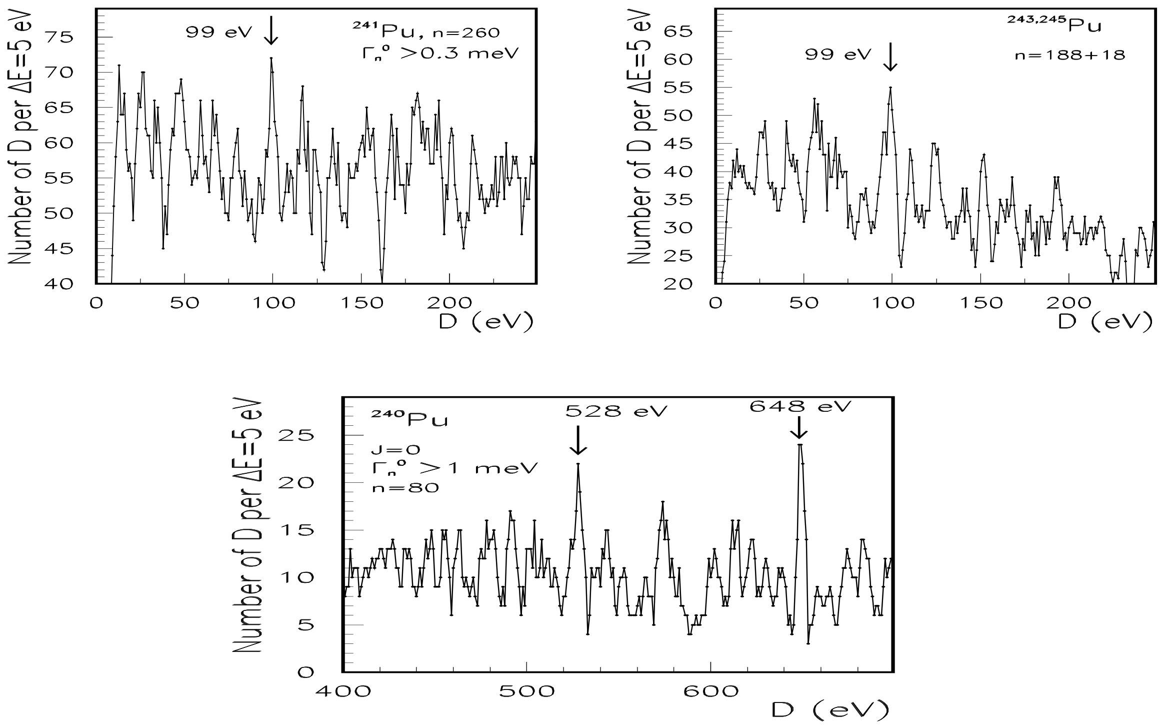

Fig. 2. *Top:* D distributions in ^{241,243,245}Pu resonances. *Bottom:* The same for ^{240}Pu.

Stability of 2^+ excitation values 42.8-42.0-44.5-44.2 keV ^{240,241,242,244}Pu (see the double boxed values in Table 1) is in the ratio 99(1) eV/86(2) keV=115·10^{-5}, which is close to the QED radiative correction $\alpha/2\pi = 116\cdot10^{-5}$ (see the first and last lines of Table 2 in the previous work [10]). Such interconnection of the ratios between the superfine and fine structure nuclear intervals and the QED radiative correction is observed in many other heavy nuclei, as shown in the bottom part of this Table in [10].

Table 1. Excitations in heavy nuclei close to 42.5 keV=$\varepsilon_o/24$ and m(85 keV=$\varepsilon_o/12$) [5].

Nucleus	^{229}Th	^{230}Th	^{231}Th	^{232}Th	^{233}Th	^{231}U	^{232}U	^{233}U	^{234}U	^{235}U	^{236}U
J^π_o,J^π_i,2J^π_i	5^+,7^+	0^+,2^+	5^+,7^+	0^+,2^+	5^-,7^-	5^-,7^-	0^+,2^+	5^+,7^+	0^+,2^+	7^-,9^-	0^+,2^+
E^*,keV	42.4	53.2	42.0	49.4	44.3	45.1	47.6	40.3	43.5	46.3	45.2
m	1/2	1/2	1/2	(1/2)	(1/2)	(1/2)	1/2	1/2	1/2	1/2	1/2
m·85 keV	42.5	42.5	42.5	42.5	42.5	42.5	42.5	42.5	42.5	42.5	42.5
Nucleus	^{237}U	^{238}U				^{239}U					^{240}U
J^π_o,J^π_i,2J^π_i	3^+,5^+	0^+,2^+	1^-	D	D	5^+,7^+	(7^+)	D	D	1-5	0^+,2^+
E^*,keV	44.9	44.9	680	45	680	42.5	169	43	170	1295	45(1)
m	1/2	1/2	8	1/2	8	1/2	2	1/2	2	δm_N	1/2
m·85 keV,	42.5	42.5	682	42.5	682	42.5	170	42.5	170	1293	42.5
Nucleus	^{235}Pu	^{236}Pu	^{237}Pu	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu	^{243}Pu	^{244}	^{246}Pu
J^π_o,J^π_i,2J^π_i	5^+,7^+	0^+,2^+	7^-,9^-	0^+,2^+	3^+,5^+	0^+,2^+	5^+,7^+	0^+,2^+	7^+,9^+	0^+,2^+	0^+,2^+
E^*,keV	41.9	44.6	47.7	44.1	49.4	42.8	42.0	44.5	58.1	44.2	46.7
m	1/2	1/2	1/2	1/2	1/2	1/2	1/2	1/2	1/2	1/2	1/2
m·85 keV	42.5	42.5	42.5	42.5	42.5	42.5	42.5	42.5	42.5	42.5	42.5

The possibility to check the influence of physical condensate within a nuclear medium should be studied in different regions of the nuclear chart. In the regions of collective excitations, such an analysis can be based on the expected relation between fine structure and superfine structure ($D = k{\times}5.5$ eV) corresponding to next order effects with the QED radiative correction parameter $\alpha/2\pi$. The proximity of neutron resonances was first noticed in uranium (5.98 eV, 5.16 eV, 5.45 eV, 6.67 eV in the target $^{232-238}$U). The period in the superfine structure intervals 5.5 eV/4=1.38 eV=ε'' is close to the positions of the first neutron resonances ^{238}Np (1.32-1.48 eV) [6,16,17]. The superfine period $\varepsilon_\circ \cdot (\alpha/2\pi)^2$ corresponds to a stable $E(8^+) = \varepsilon_\circ/2 \approx$511 keV (497-522=518-518-516-514-497-518 keV in $^{234-238}$U, $^{236-242}$Pu), due to the relation 6:20:42:72 for excitations with J=2, 4, 6, 8.

The observed discreteness in the spectrum and the possible appearance of an additional hyperfine structure, similar to that observed as resonance positions in isotopes with Z=92-95 (as the next order effect to the established stability of superfine structure excitations), is the subject of further analysis. Besides the role of real nuclear excitations considered in connection with nonstatistical effects in $^{241-245}$Pu spectra (42.5 keV×2$\cdot(\alpha/2\pi)$=99 eV) and maxima at 43-45 keV in D-distributions for many isotopes (see Fig. 8 [10], Figs. 2, 3) it was noticed that the parameter k in the relation $E^*(2^+) = 6k$ coincides with the QED correction to the stable nuclear interval $6m_e$ found in many nuclei [16].

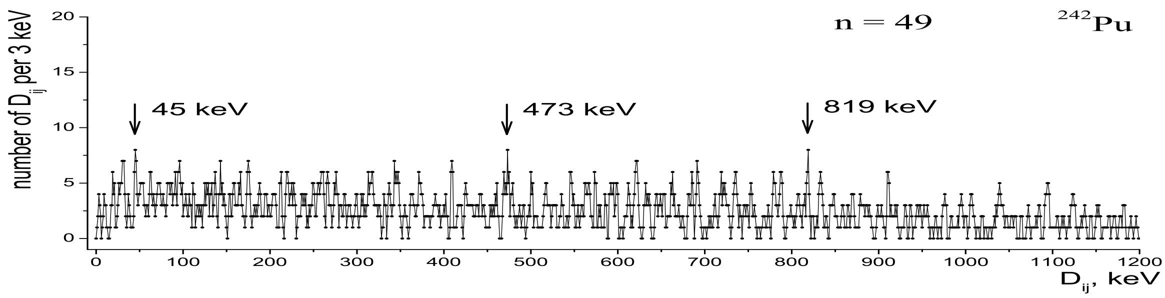

Fig. 3. Spacing distributions in levels of ^{242}Pu, maximum at 45 keV is considered in text.

2. Analysis of spectroscopic data of ^{238,239}U

Analysis of the spacing distributions of low-lying levels of different heavy nuclei allows to confirm the stable character of the parameter $42.5\,\mathrm{keV}{=}6{\times}6\varepsilon'$.

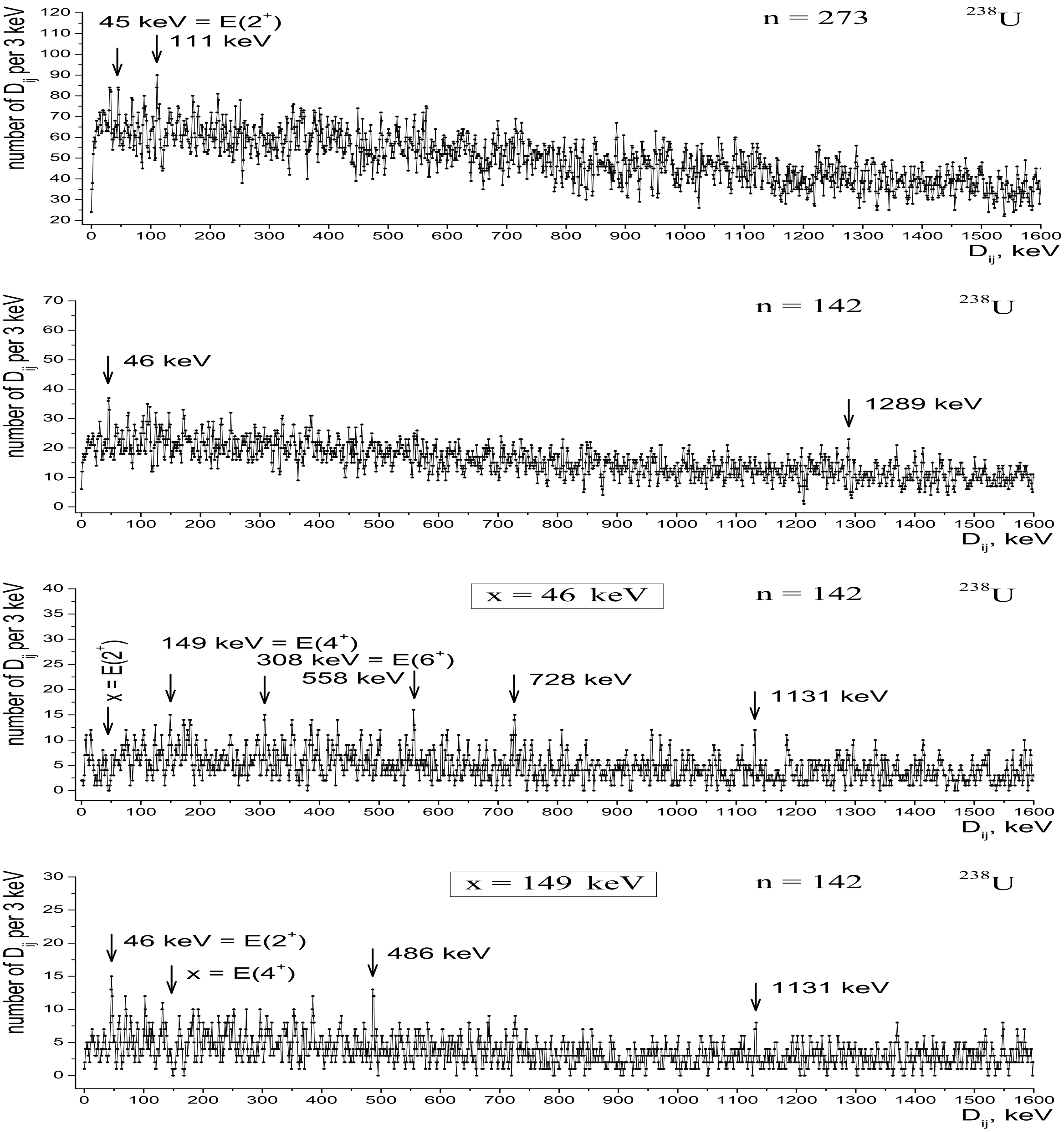

Fig. 4. *Top*: *D*-distributions in all 273 levels and in 142 positive-parity levels of ^{238}U. *Bottom*: Adjacent spacing distributions in levels of ^{238}U for $x{=}46\,\mathrm{keV}$ and $x{=}149\,\mathrm{keV}$.

First levels ^{238}U, E^{*}=44.916 keV and ^{239}U, E^{*}=42.543 keV=1.182 eV×36 have corresponding maxima in the spacing distributions of their low-lying levels (Figs. 4 and 5). The value 42.5 k3V is close to the excitations of many nuclei (Table 1, 6 double boxed values).

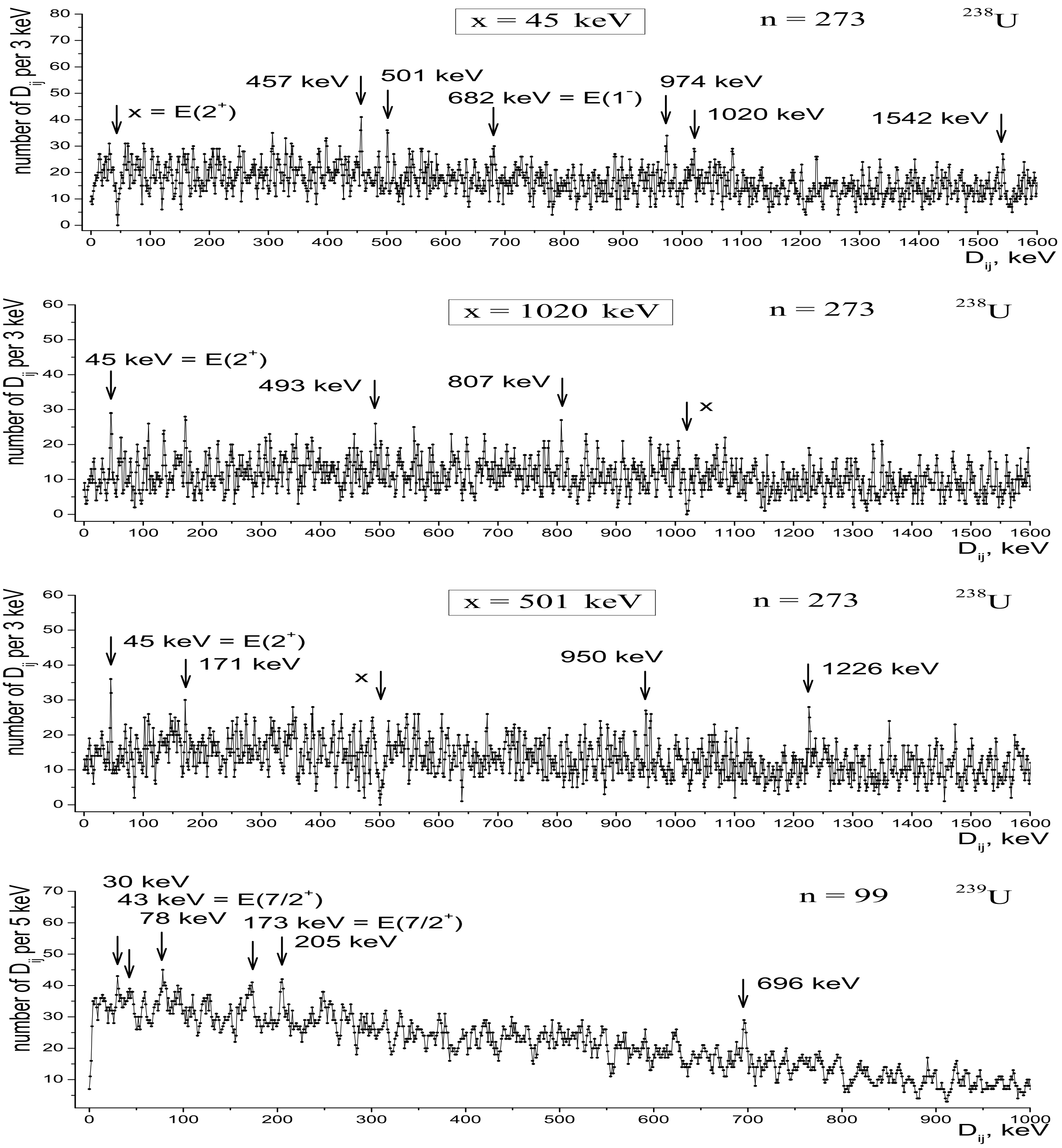

Fig. 5. *Top*: Adjacent spacing distributions in levels ^{238}U for x=45 keV, 1020 keV, 501 keV. *Bottom*: Spacing distributions in levels of ^{239}U.

3. Additional analysis of neutron resonance data

All existing neutron resonance data collected in Springer Compilations [7] on the target ^{238}U (n=897 for s-wave and n=2661 p-wave resonances) were analyzed and compared with data on low-lying levels ^{239}U (Fig. 5, bottom). The interval D=97 eV≈ $9\delta''$ in the resonance spectrum (Fig. 8, top) is analogous to the interval 99 eV in the data for plutonium (Fig. 2, top).

The spacing distributions in all 897 L=0 neutron resonances ^{239}U and in 233 resonances with $\Gamma_n^\circ \geq 1$ meV are shown in Fig. 5. The exact equidistance between the maxima at 193-388-583-776 eV in the D-distribution for strong resonances (Fig. 6, bottom) and the proximity of the maximum at 776 eV to 793 eV≈ $4\times198\,eV = 4\times18\delta''$ means confirmation of the superfine structure in the spectrum of strong resonances found earlier in Th [10].

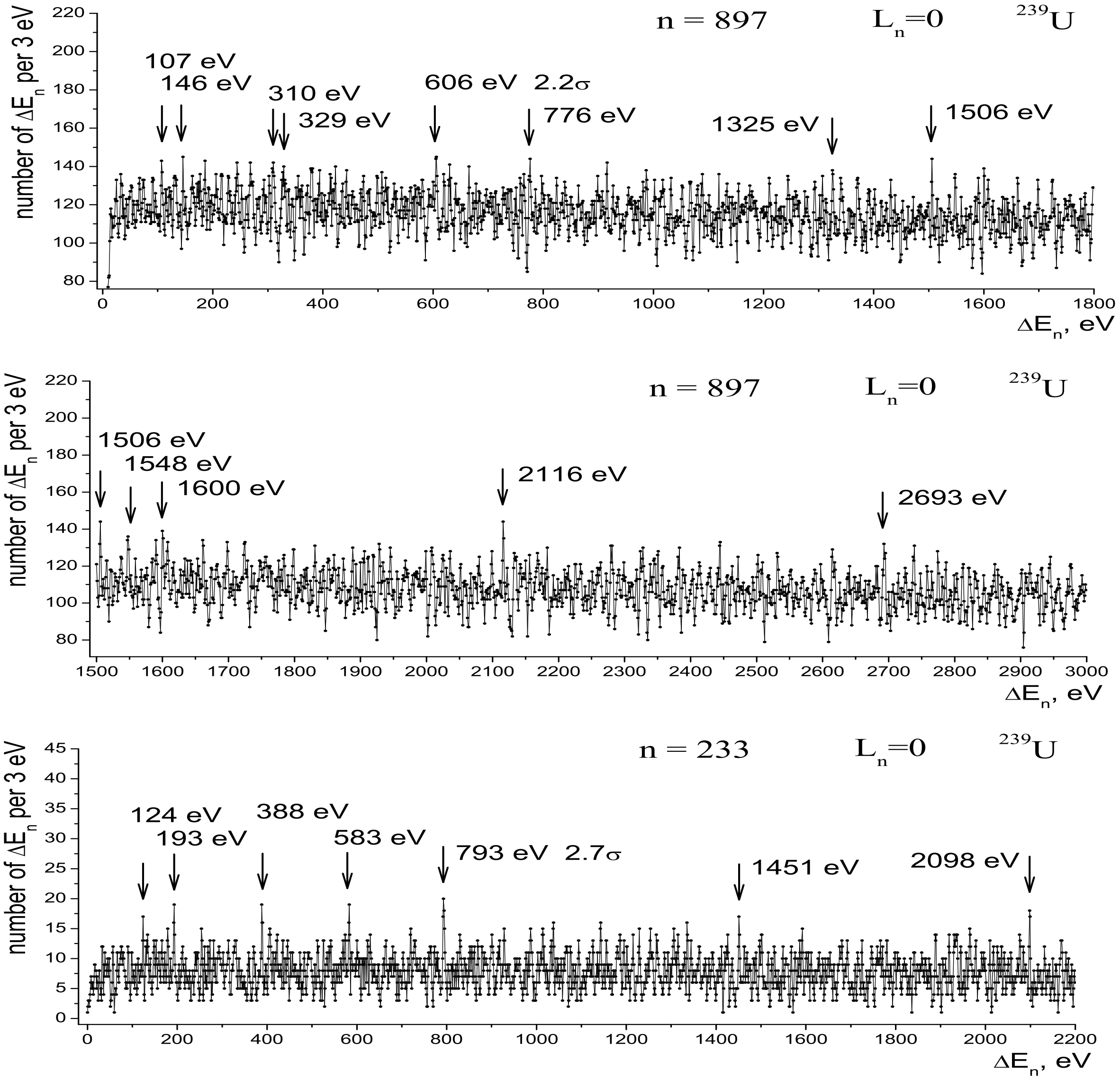

Fig. 6. *Top and center:* Spacing distribution in all 897 L=0 neutron resonances of ^{239}U. *Bottom:* The same for 233 strong resonances with $\Gamma_n^\circ \geq 1$ meV.

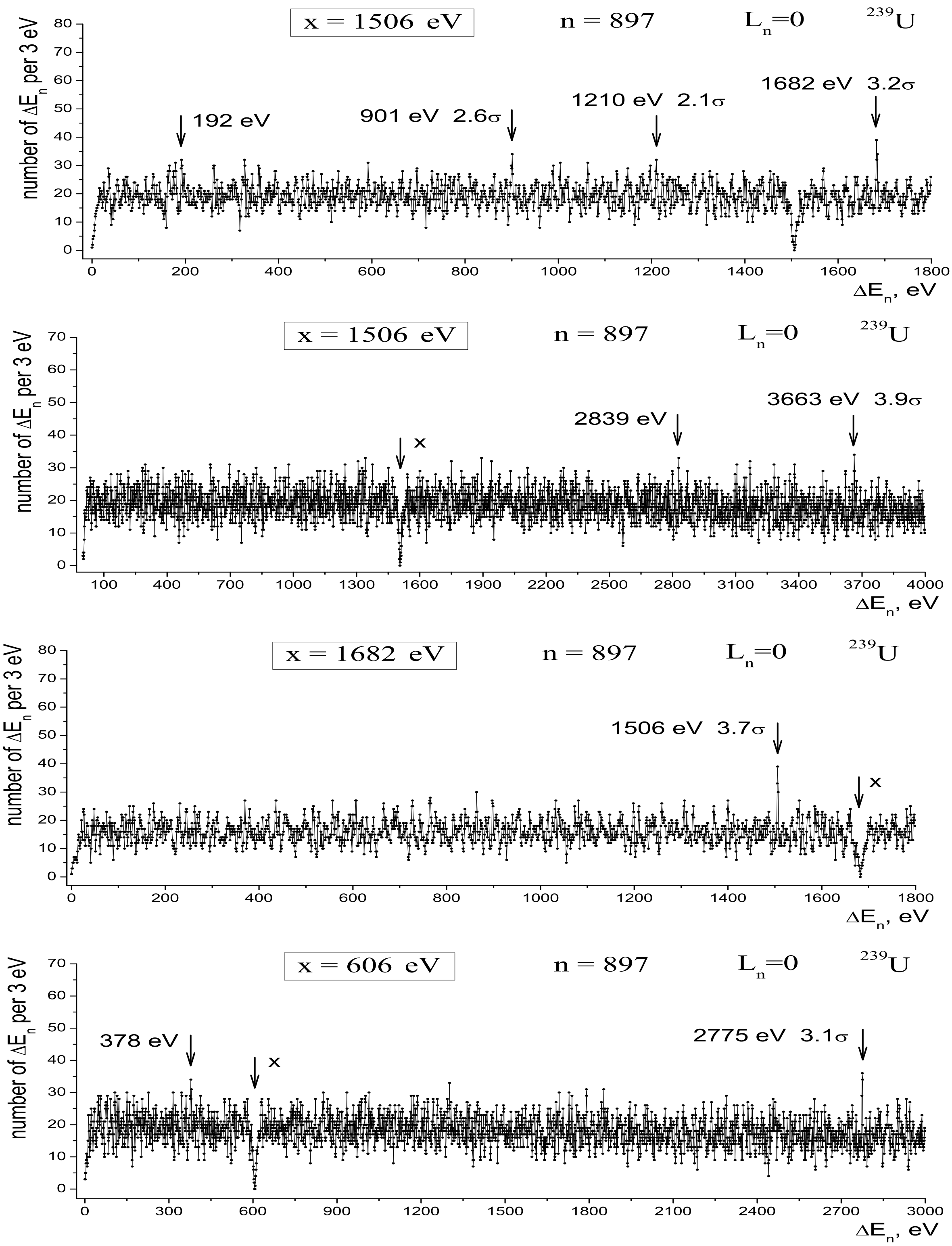

Fig. 7. Adjacent spacing distributions in L=0 neutron resonances of ^{239}U for x=1506 eV (two regions), for x= 1682 eV and for x=606 eV.

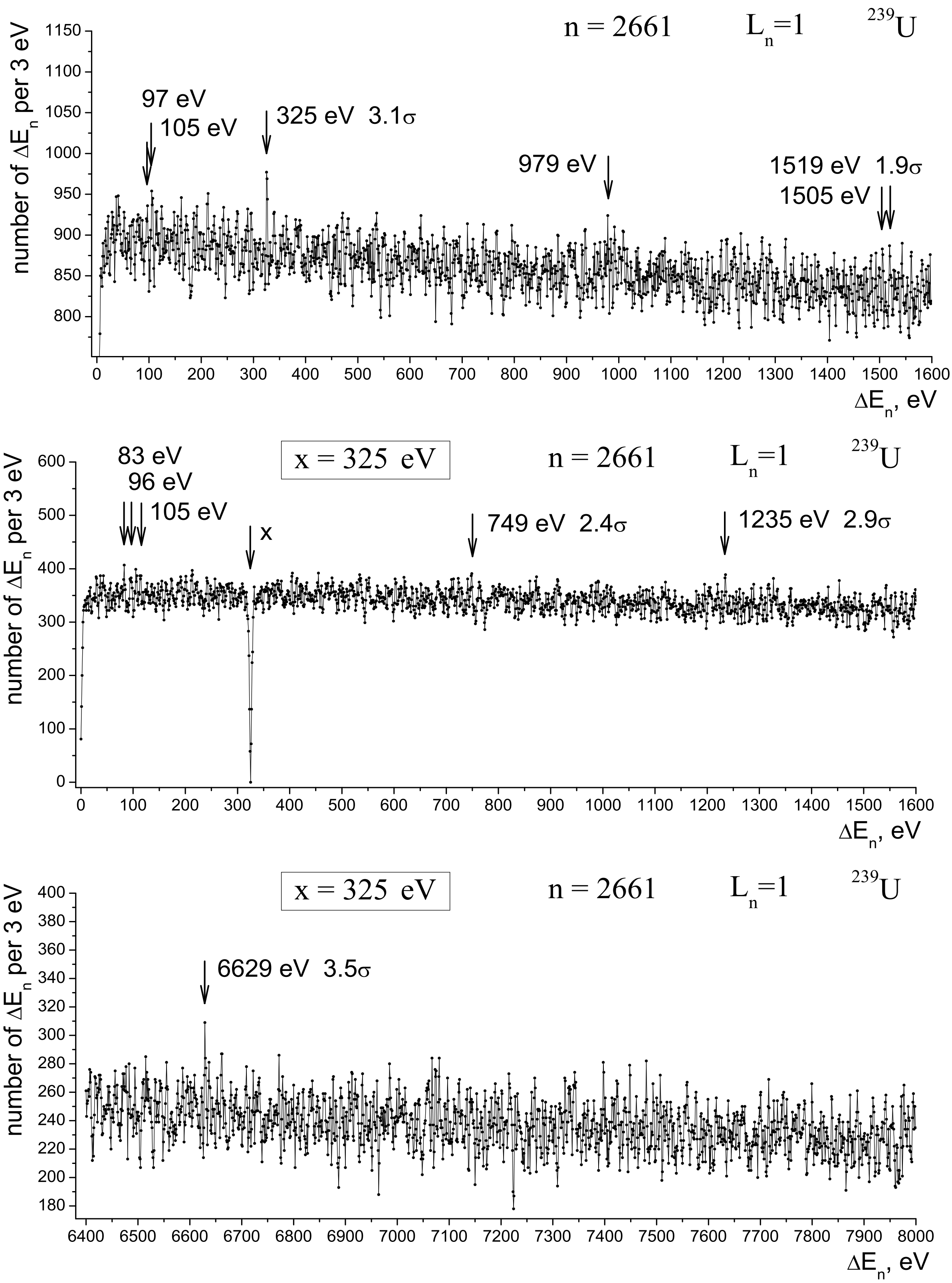

Fig. 8. *Top*: Spacing distributions in L=1 neutron resonances of ^{239}U.
Bottom: Adjacent spacing distributions in L=1 neutron resonances of ^{239}U for x=325 eV (two regions).

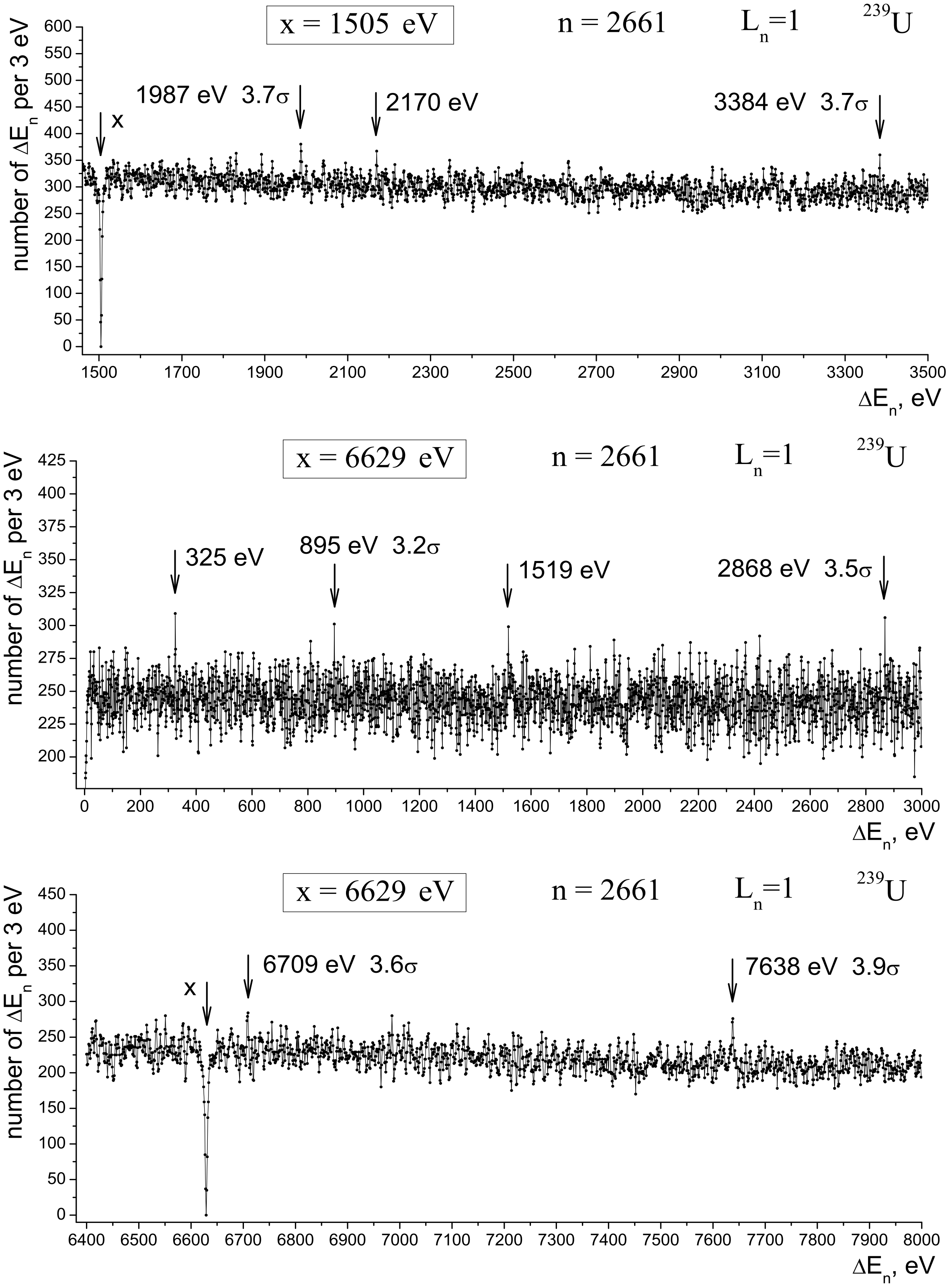

Fig. 9. Adjacent spacing distributions in L=1 neutron resonances of ^{239}U for x=1505 eV and for x=6629 eV (two regions).

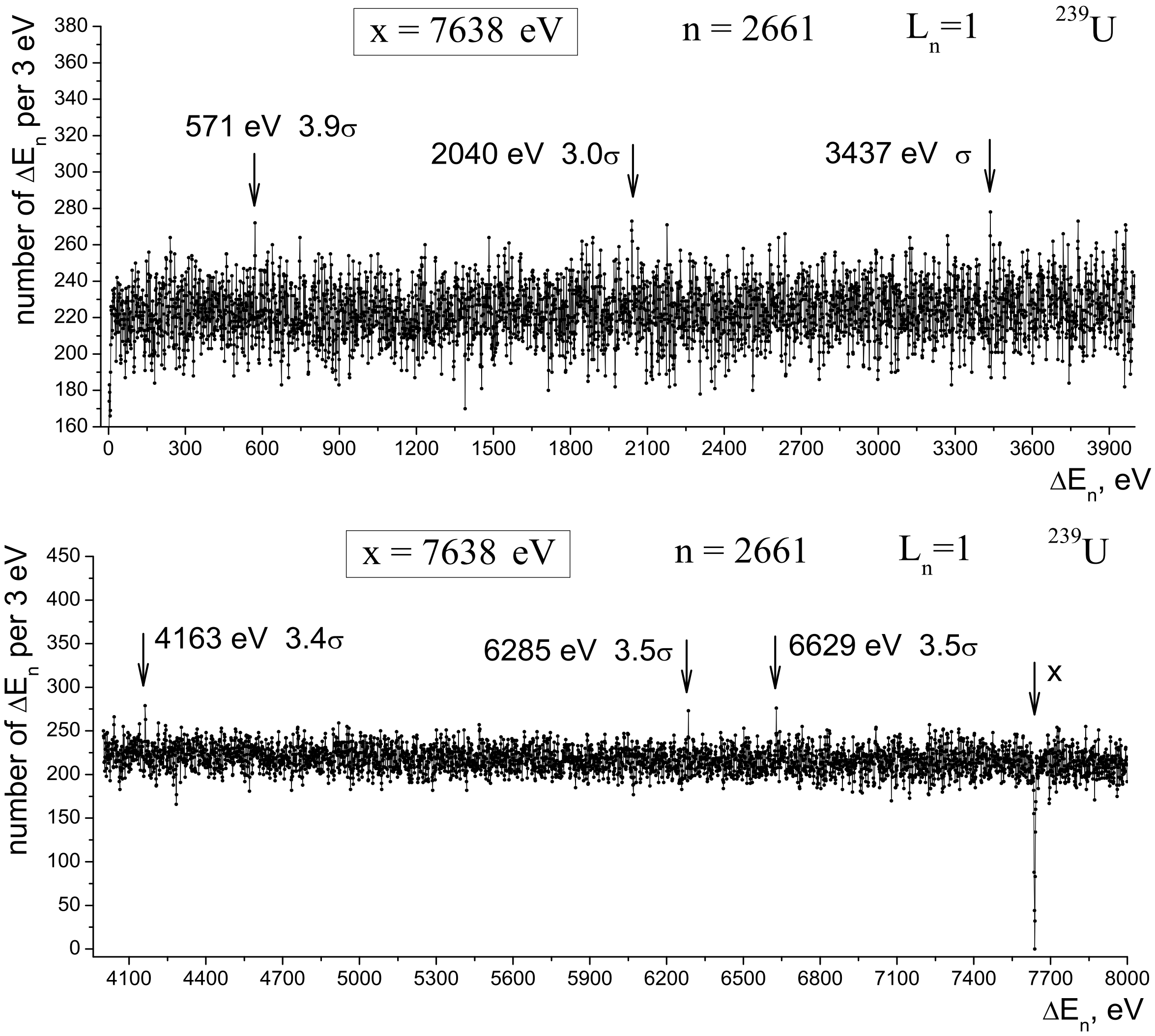

Fig. 10. Adjacent spacing distributions in L=1 neutron resonances of ^{239}U for x=7638 eV (two regions).

Nucleons and the electron are stable particles that determine the visible mass of the universe. They are in a ratio that is very accurately estimated in the CODATA review as m_n/m_e=1838.6836605(11). The electron-based SM development considered here is derived from the fact that the exactly known shift of the neutron mass from 115·16m_e - m_e is δm_n = 161.6491(6) keV, which is equal to 1/8 of the nucleon mass splitting δm_N=1293.3322(4) keV. The unexpectedly exact ratio $\delta m_N : \delta m_n = 8.00086(3) \approx 8 \times 1.0001(1)$ allows the following representation:

$$m_n = 115 \cdot 16 m_e - m_e - \delta m_N/8 \quad m_p = 115 \cdot 16 m_e - m_e - 9\delta m_N/8 \tag{1}$$

Y. Nambu noted that " a) When we discover new phenomena which we do not understand, the first thing to do is to collect data and try to find some empirical regularities among them, b) one next tries to build concrete models, c) finally there emerges a real theory ... Standard Model qualifies as such a theory ". We discuss here the development of the Electron-based Constituent Quark Model and some aspects of modern Standard Model. Y. Nambu continued: " Standard Model ... is theoretically unsatisfactory ... a) the unification of forces is only partially realized, and b) there are too many input parameters, especially concerning the masses, which are not explained. The nature can be at the same time more complicated than we think, and simpler in a way we do not know yet. ... we are now at the step of a new cycle. The mass problem is already an early signal for it." According to S. Weiberg, we are "still searching a solution " for the mass problem in the Standard Model.

Analysis of neutron resonance data allows us to confirm two main conclusions from empirical observations on particle properties.

1. There is a distinguished role of the electron mass, its correction and symmetry motivated relations in the particle masses. CODATA relations concern particle physics, as well as nuclear spectroscopy, the appearance of nuclear parameters related to $m_e = 3{\times}170\,\mathrm{keV}$ and $\delta m_N = 8{\times}161\,\mathrm{keV}$ (CODATA structure parameters $m_e/3$ and $\delta m_N/8$ became common for all nuclear parameters). In the spacing distribution for all positive-parity states of ^{238}U (Fig. 4, 2nd line), only two maxima were observed: at 46 keV, which corresponds to stable 2^+ excitations, and D=1289 keV$\approx \delta m_N = 8{\times}161\,\mathrm{keV}$, the second CODATA parameter.

2. It was suggested by R. Feynman and D. Shirkov, that QED radiative correction, known as $\alpha/2\pi = 116\cdot 10^{-5}$ in the case of an anomalous magnetic moment of the electron, can be applied to the electron mass. Empirically, the ratios equal to $\alpha/2\pi = 116\cdot 10^{-5}$ were found between the constituent quark mass, the electron mass, and the parameters of the fine and superfine structure [6].

In the spacing distribution of all 897 L=0 neutron resonances ^{239}U (Fig. 6, top) and in the spacing distribution of 2661 L=1 resonances, the same stable interval D=1505-1506 eV was found. Its appearance can be connected with the stable character of CODATA parameters (in ^{239}U there is an excitation of 1295 kev$\approx \delta m_N$). In these works [10,11], we try to check the stable nuclear excitations related to CODATA fine structure parameters.

In the spacing distribution for 233 L=0 strong resonances ($\Gamma_n^\circ \geq 1\,\mathrm{meV}$), the exactly equidistant maxima are observed at 193-388-583-776 eV (Fig. 6, bottom), where the maximum at 776 eV (in all resonances, Fig. 6, top) is close to the maximum at 793 eV$\approx 4\times 198\,eV = 4\times 18\delta''$. The probability of the random appearance of four equidistant maxima (in resonances with $\Gamma_n^\circ \geq 1\,\mathrm{meV}$), shown in Fig. 6, bottom, is very small. K. Ideno and M. Ohkubo developed the "Period" program to study such effects [14].

Neutron resonance spectroscopy was developed in response to practical demands. Massifs of resonance data for thorium, uranium, neptunium and plutonium isotopes are the results of measurements performed due to practical applications and world-wide scientific traditions of information collection. In our case, it was W. Furman's initiative to continue the collection of nuclear data started at JINR to be published by Springer (editors W. Martienssen, H. Schopper).

There is a large amount of neutron resonance data for other construction isotopes, but now is the time to measure the resonance structure of many other elements. For example, the cross section of near-magic antimony was measured and analyzed by M. Ohkubo many years ago. The possibility of using neutron resonance data to solve some fundamental problems is shown here.

4. Conclusions

The well-known effect of stability of low-lying excitations in heavy nuclei was used in this work to confirm the discreteness in the neutron resonance spacing distribution due to the possible influence of physical condensate considered by D. Schirkov. The application of new physics based on the distinguished role of the electron was discussed by F. Wilczek [19]. The fundamental aspects of nonstatistical effects in neutron resonance spectra discussed here are considered in [20,21].

The pion parameters $(f_\pi, m_\pi, \Delta M_\Delta)$ corresponding to N=16, 17 and 18 of the period $\delta = 16m_\pi$ (Table 2 in [11] and Table 5 in [18]) were considered here together with the basic parameters of the NRCQM model ($N = 3 \times 16 = 48$ and $N = 3 \times 18 = 54$). All of them manifest themselves directly as maxima in the spacing distribution between the particle masses (from the PDG–2016 and PDG–2020 compilations), similar to what was done earlier with the masses of baryon isosinglets [6]. CODATA relations and discreteness in particle masses and parameters are the main elements of a "data-driven science" approach in production of the Electron-based Constituent Quark Model (ECQM).

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