Neutron resonances in the

Constituent Quark Model

S.I. Sukhoruchkin

Petersburg Nuclear Physics Institute NRC
"Kurchatov institute" 188300 Gatchina Russia

Measurements of the neutron cross-sections of heavy nuclei and their analysis at the IAE and ITEP, carried out in the 1950s and later, found out deviations from statistical model in distributions of positions and spacings of neutron resonance levels. This work is a review of the analysis of nuclear states energies and particle mass spectrum, based on the distinguished role of the electron, its symmetry, and radiative correction.

Neutron resonance spectroscopy is a part of Nuclear physics based on the Standard Model (SM) as a theory of all interactions.
Empirical observation were used during production of the Electron-based Constituent Quark Model (ECQM).

Analysis of neutron resonance data

Resonance parameters that are investigated within neutron resonance spectroscopy demonstrate the same symmetry motivated relations observed between stable nuclear intervals and in particle masses. There are fine and superfine structures with periods ε'=1.2 keV and ε''=1.4 eV=5.5 eV/4, equal to the first and second QED radiative corrections to empirically found period of 1022 keV = ε_0 =2m_e in few-particle excitations and binding energies.

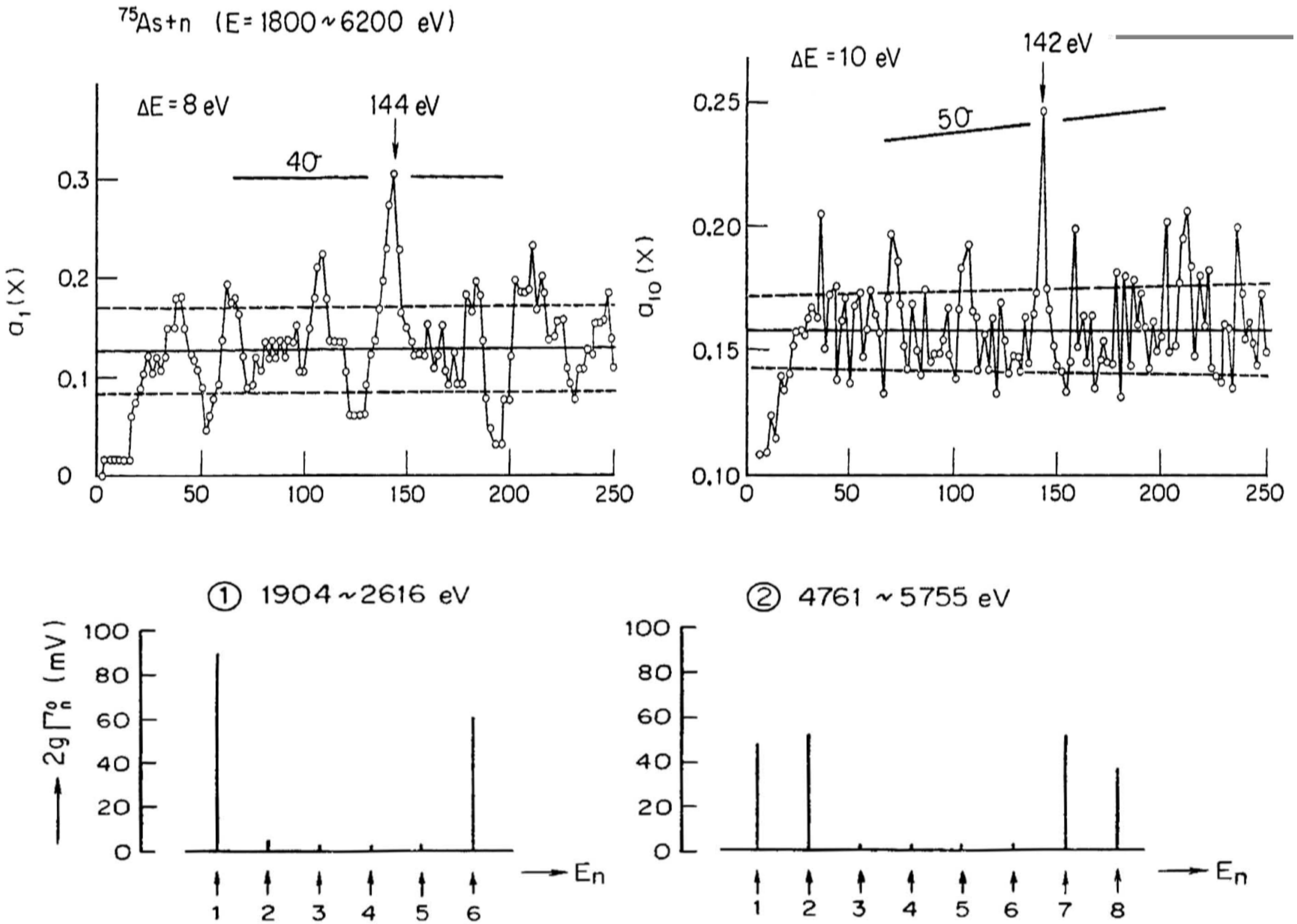


Figure 1. Periodicity in target ^{75}As neutron resonance positions (K. Ideno, M. Ohkubo, J. Phys. Soc. Jpn. 30 (1971) 620).

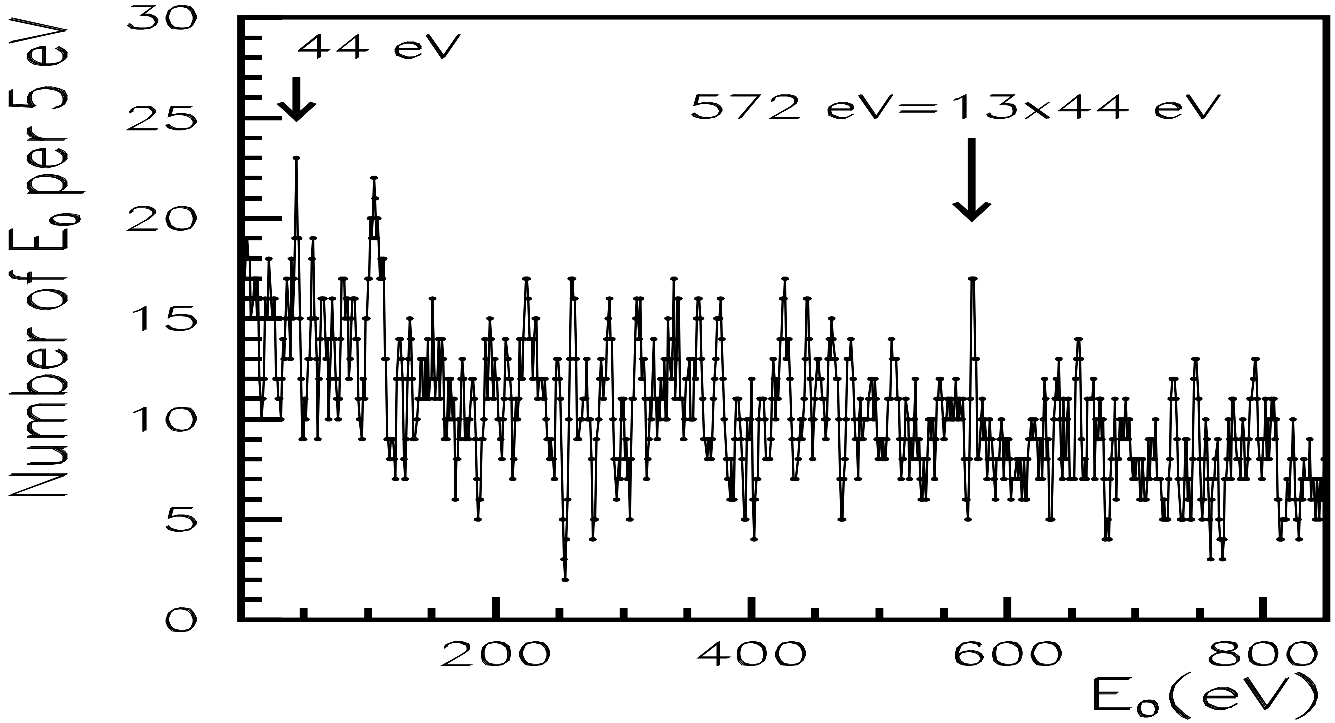
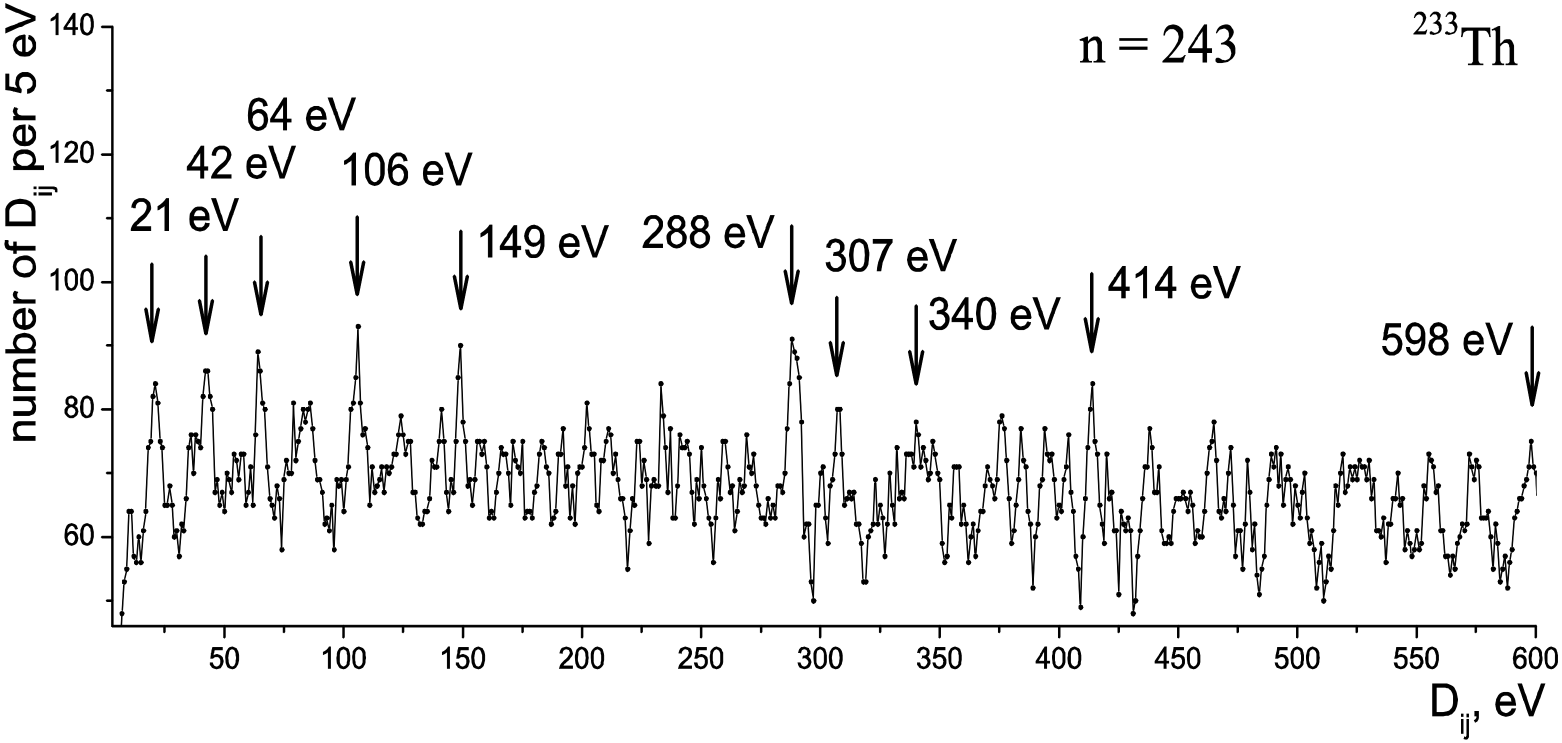


Figure 2. Similar correlations were found earlier in strong resonances of many different isotopes (Figure 2). Distribution of relatively strong neutron resonance positions of all nuclei with Z=33-56 [3].

Thorium isotopes have 90 protons corresponding to filled $f_{7/2}$ subshell. It was marked long ago that spacing distribution of its L=0 resonances has a clear nonstatistical character. On the histogram with averaging parameter 5 eV (Fig. 3a) equidistancy of maxima at *k*=1, 2, 3, 5 of the estimated period 11 eV corresponds (as *k*=288/11=26) to the strongest maximum at *D*=288 eV (marked with arrow).

Figure 3a. Spacing distribution of all L=0 neutron resonances in ^{233}Th.



Fixing all such intervals (x=288 eV) in the spectrum of all s-wave resonances (Fig. 3b), one obtains maximum at the doubled value 576 eV. Such an interval corresponds to a distance between strong neutron resonances (maximum at 573 eV in Fig. 3c, with a deviation from the random level of ≈3σ, selection of resonances with reduced neutron widths greater than 1 meV).

Figure 3b. Spacing distribution of L=0 neutron resonances in ^{233}Th adjacent to intervals *D*=*x*=288 eV.

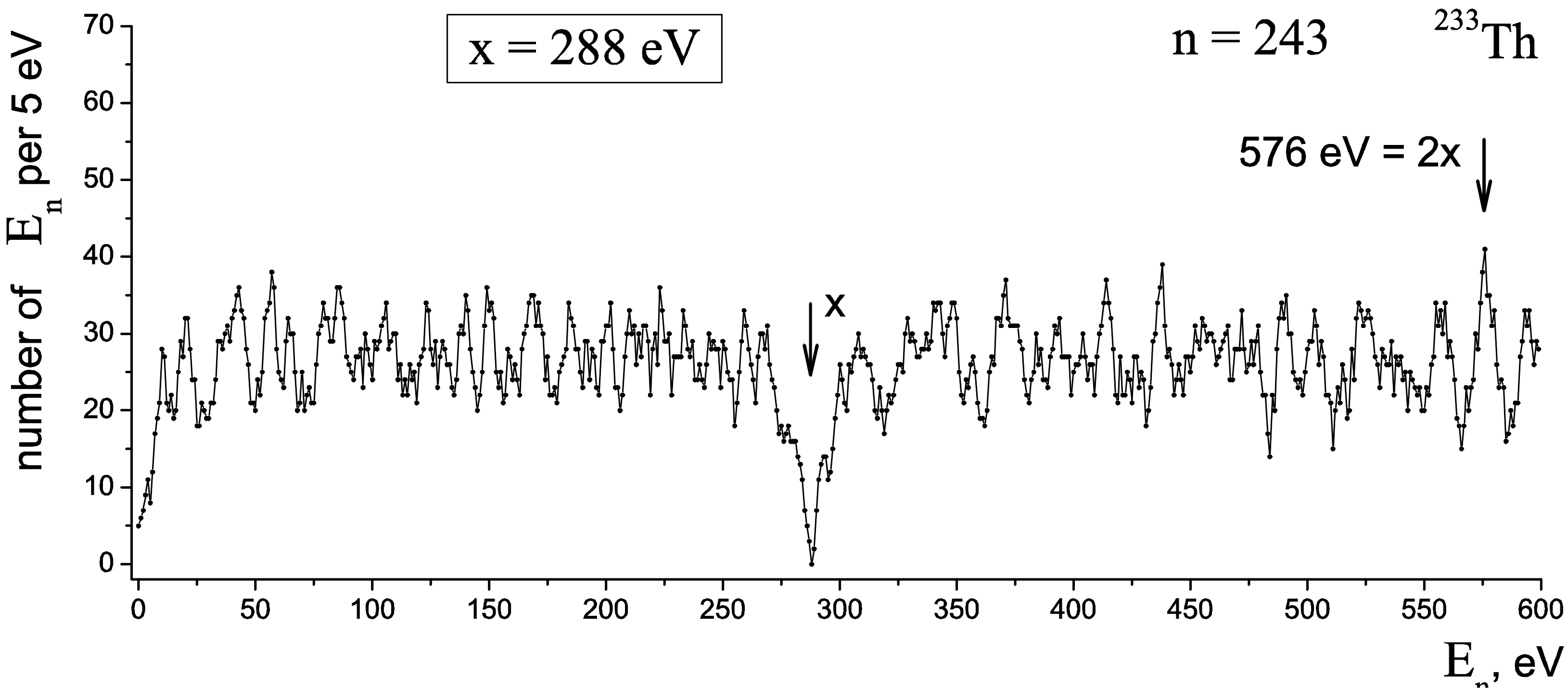
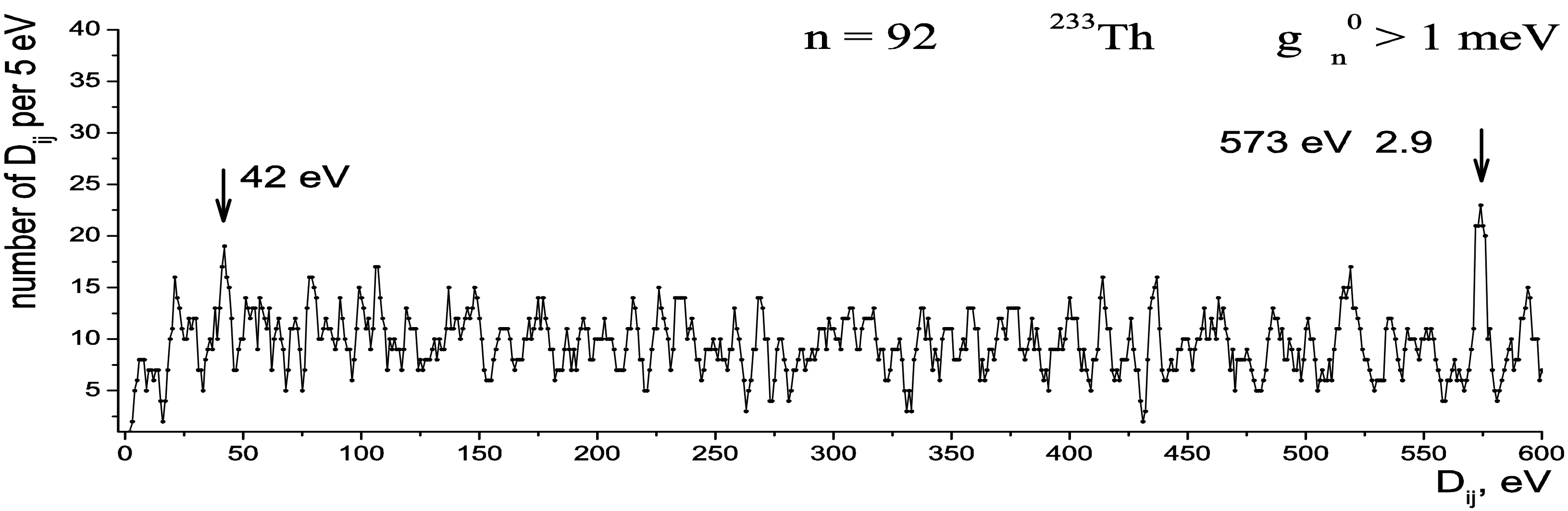


Figure 3c. Spacing distribution ^{233}Th all L=0 strong neutron resonances ($g\Gamma_n^o \geq 1.1$ meV). Resonance at 570 eV means that neutron separation energy is correlated with a period 573 eV. Small maximum at 42 eV corresponds to a ratio 1:13 between the states with relatively large single-particle component in the wave function.



The spectrum of highly excited states ^{236}U contains 3164 states with spacing distribution shown in Figure 4a (all states have L=0).

Neutron resonances were selected according to spin *J* (n=1438 for J=3 and n=1734 for J=4), and respective spacing distributions are given in Figure 4b,c.

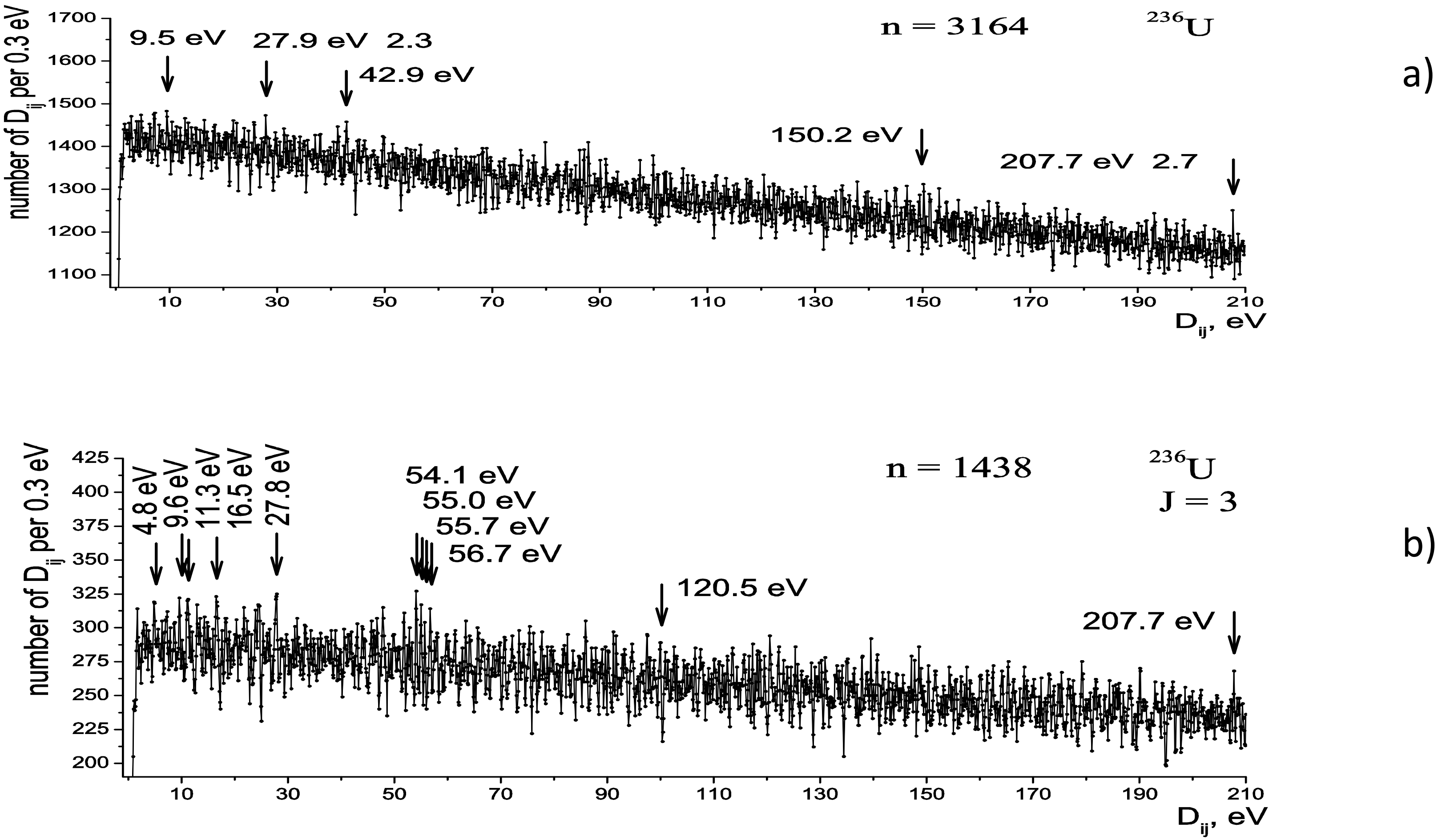


Figure 4. a) Total spacing distribution in all ^{236}U resonances. b) The same for resonances with *J*=3.

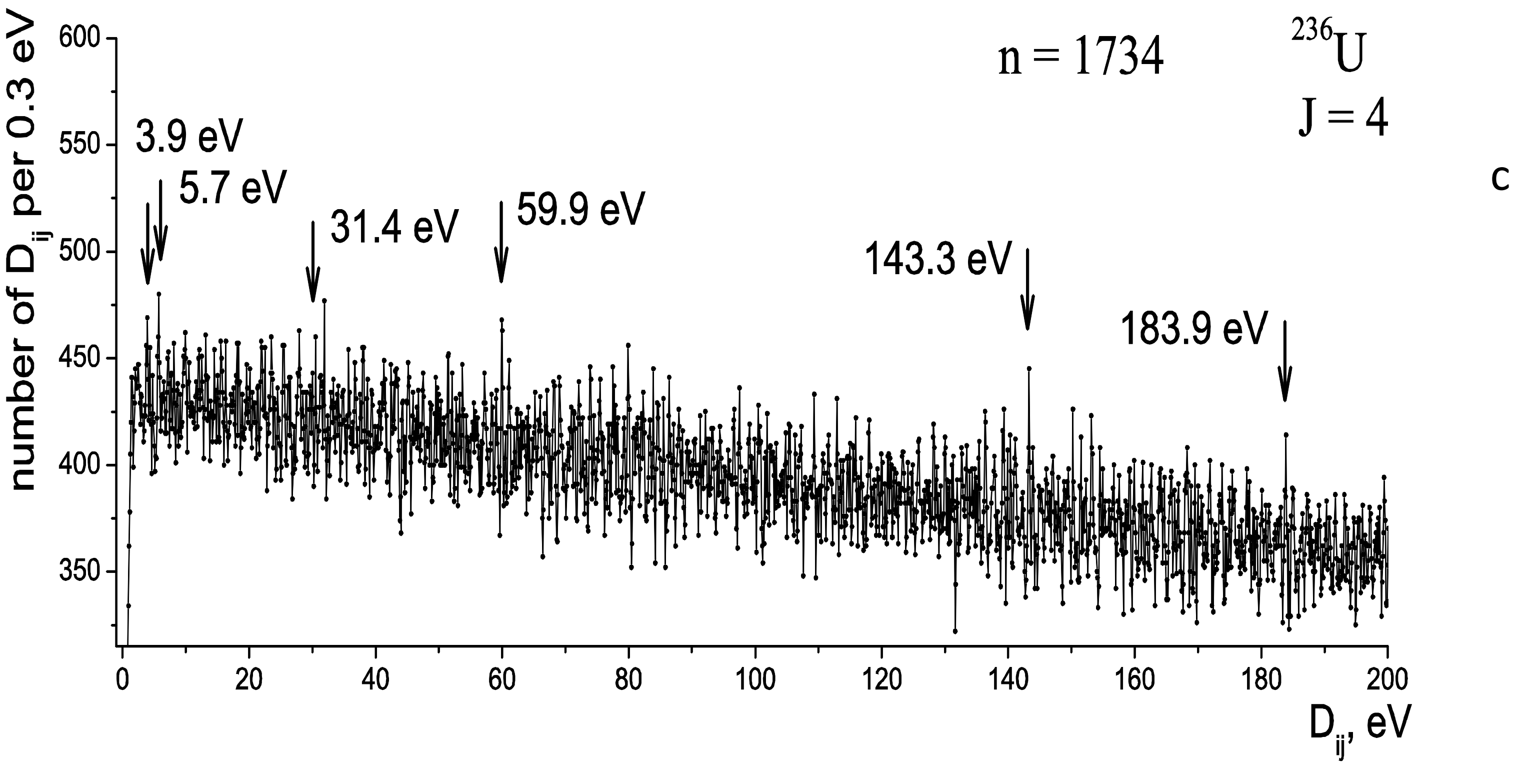


Figure 4c. Spacing distribution of all ^{236}U resonances, *J*=4.

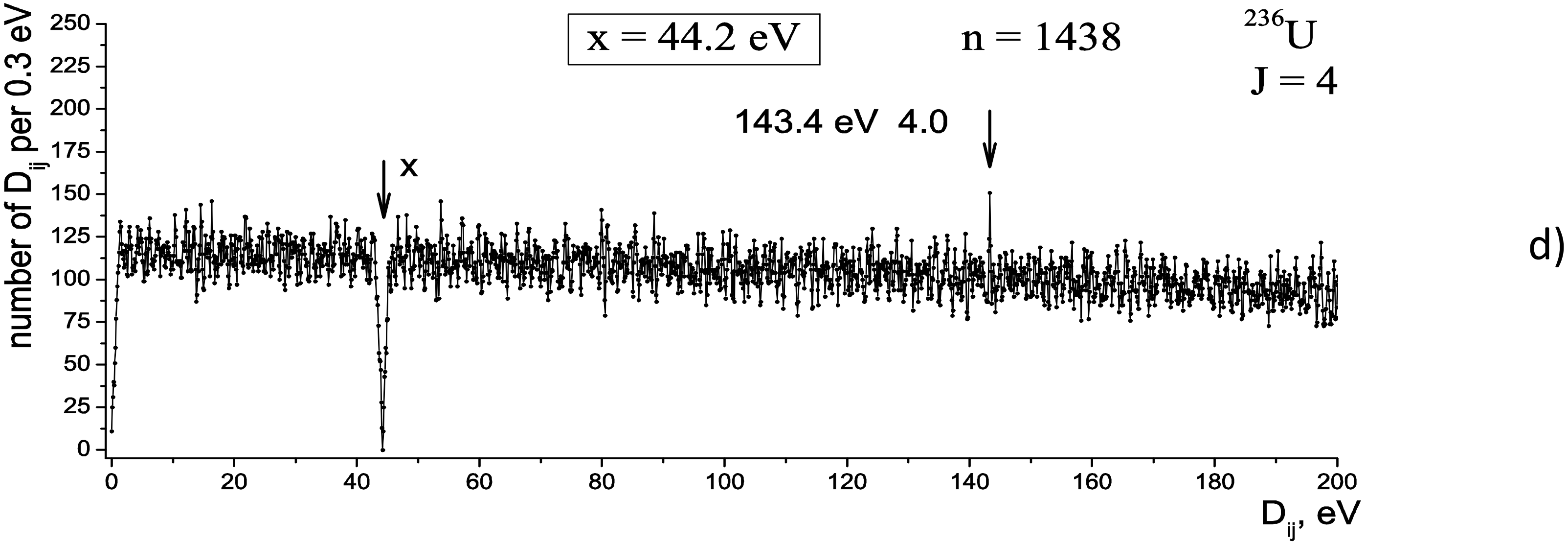


Figure 4d. Adjacent interval distribution in *J*=4 ^{236}U resonances, fixed interval *x*=44.2 eV. Deviation 4.0σ in maximum at 143.4 eV is marked. An exact ratio 13:4 is between intervals under consideration (143.4 eV and 44.2 eV).

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

Nucleus	^{229}Th	^{230}Th	^{230}Th	^{231}Th	^{232}U		^{234}U			^{236}U	
J_o^π, J_i^π	$\frac{5}{2}^+,\frac{7}{2}^+$	$0^+,8^+$	D	$\frac{5}{2}^+,\frac{7}{2}^+$	$0^+,2^+$	$0^+,12^+$	2^+	8^+	12^+	$0^+,2^+$	8^+
E^*,keV	$\boxed{42.5}$	594	594	$\boxed{42.0}$	47.6	1111	43.5	$\boxed{497}$	1024	45.2	$\boxed{522}$
m	1/2	7	7	1/2	(1/2)	13	1/2	6	12	1/2	12
m·85 keV	42.5	595	595	42.5	42.5	1112	42.5	511	1022	42.5	511

Nucleus	^{236}U		^{237}U	^{238}U			^{239}U				^{240}U
J_o^π, J_i^π	D	D	$\frac{1}{2}^+,\frac{17}{2}^+$	$0^+,2^+$	8^+	D	$\frac{5}{2}^+,\frac{7}{2}^+$	D	D	D	$0^+,2^+$
E^*,keV	512	1022	$\boxed{518}$	44.9	$\boxed{518}$	512	$\boxed{42.5}$	43	87	170	45(1)
m	6	12	6	1/2	6	6	1/2	1/2	1	2	(1/2)
m·85 keV	511	1022	511	42.5	511	511	42.5	42.5	85	170	42.5

Nucleus	^{236}Pu		^{236}Pu		^{240}Pu		^{241}Pu	^{242}Pu		^{244}Pu	
J_o^π, J_i^π	$0^+,2^+$	8^+	$0^+,2^+$	8^+	$0^+,2^+$	8^+	$\frac{5}{2}^+,\frac{7}{2}^+$	$0^+,2^+$	8^+	2^+	8^+
E^*,keV	44.6	$\boxed{516}$	44.1	$\boxed{514}$	$\boxed{42.8}$	497	$\boxed{42.0}$	44.5	$\boxed{518}$	44.2	535
m	1/2	6	1/2	6	1/2	6	1/2	1/2	6	1/2	6
m·85 keV	42.5	511	42.5	511	42.5	511	42.5	42.5	511	42.5	511

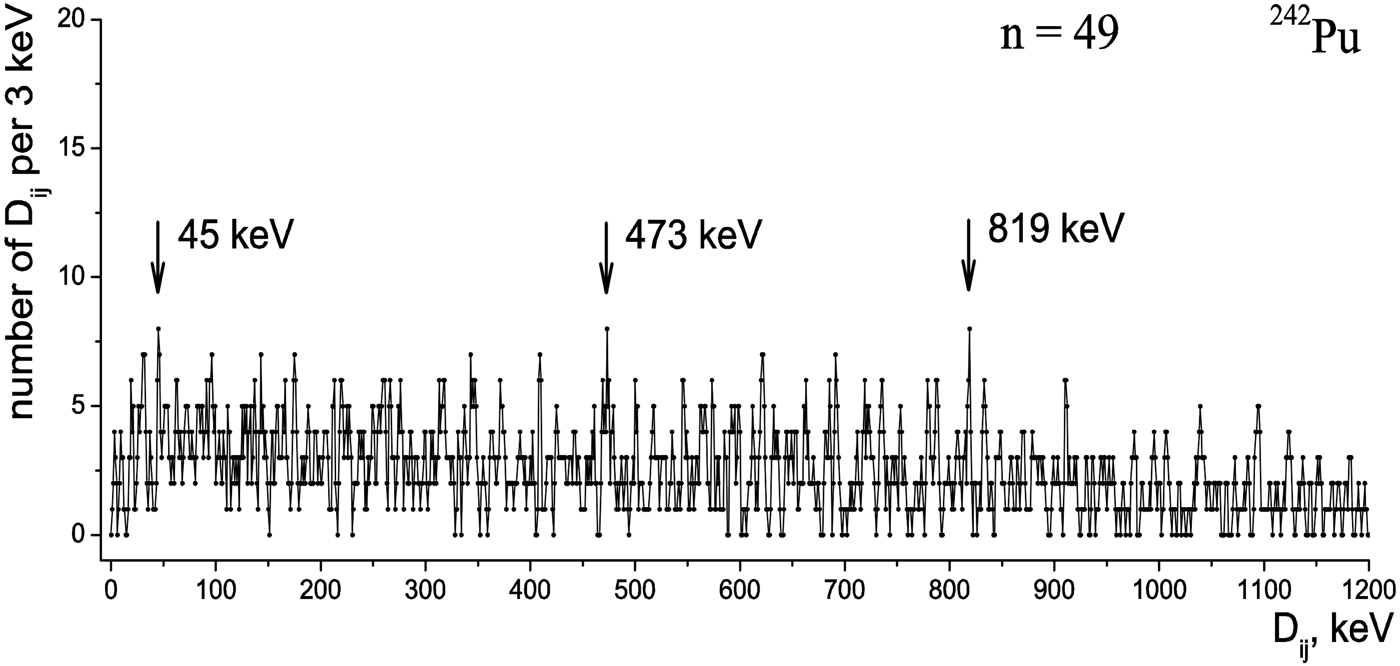


Figure 5. Spacing distributions in levels of ^{242}Pu, maximum at 45 keV.

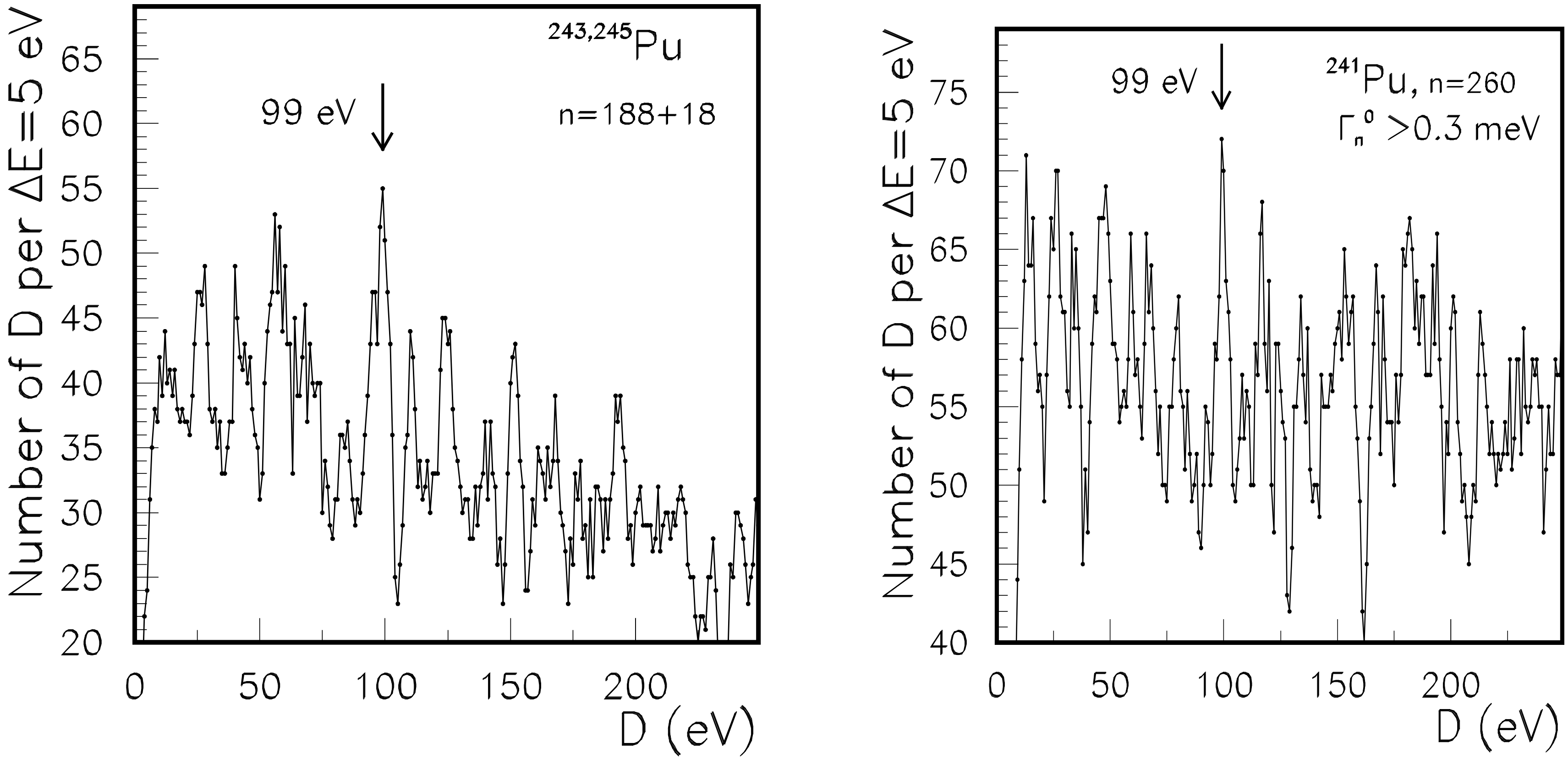


Figure 6. *D* - distributions in neutron resonances of heavy compound nuclei [4]. The doubled period of 99 eV (198 eV) was observed in neighbor ^{239}U (Fig. 7).

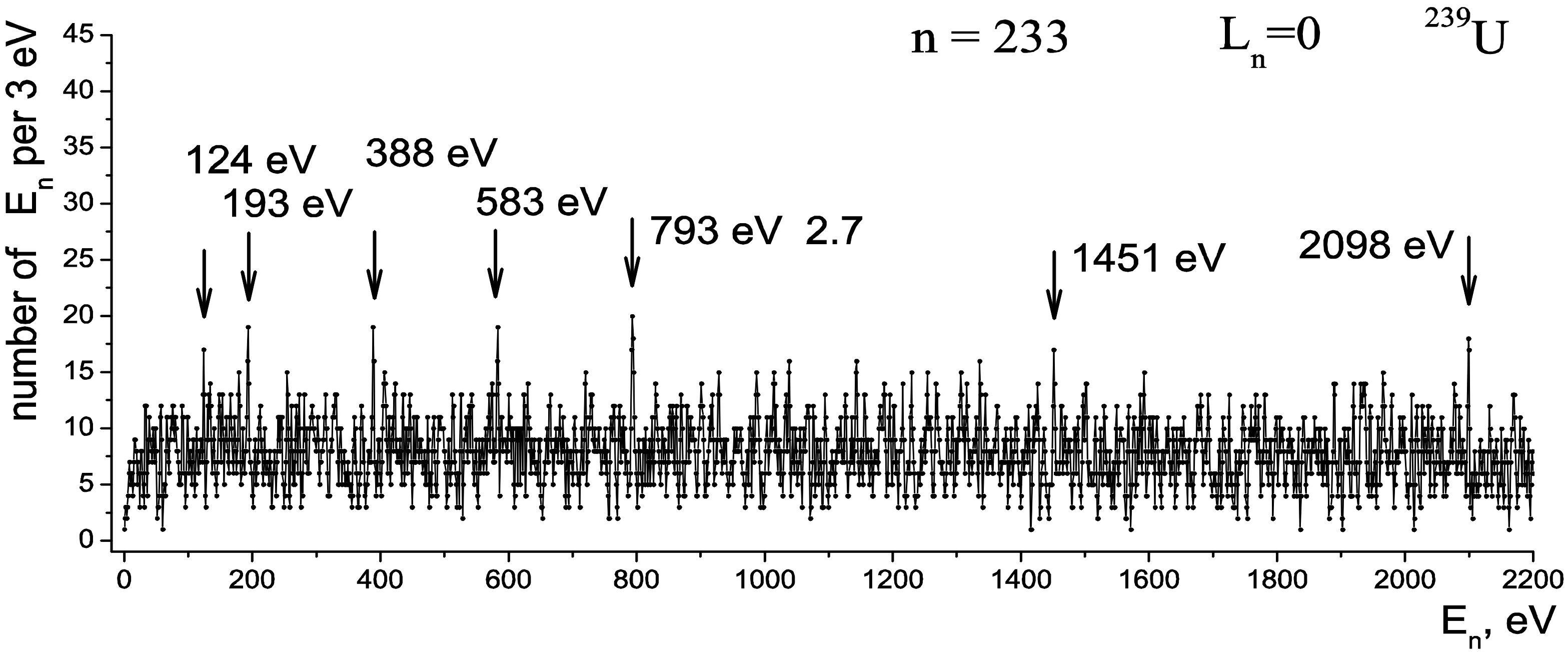


Figure 7. Spacing distribution for 233 L=0 strong neutron resonances ^{239}U with $\Gamma_n^0 \geq 1$ meV. Equidistant maxima at 193 eV, 388 eV, 583 eV and 793 eV correspond to the doubled period 99 eV (198 eV). Intervals 9×11 eV and 13×11 eV are distinguished in heavy nuclei.

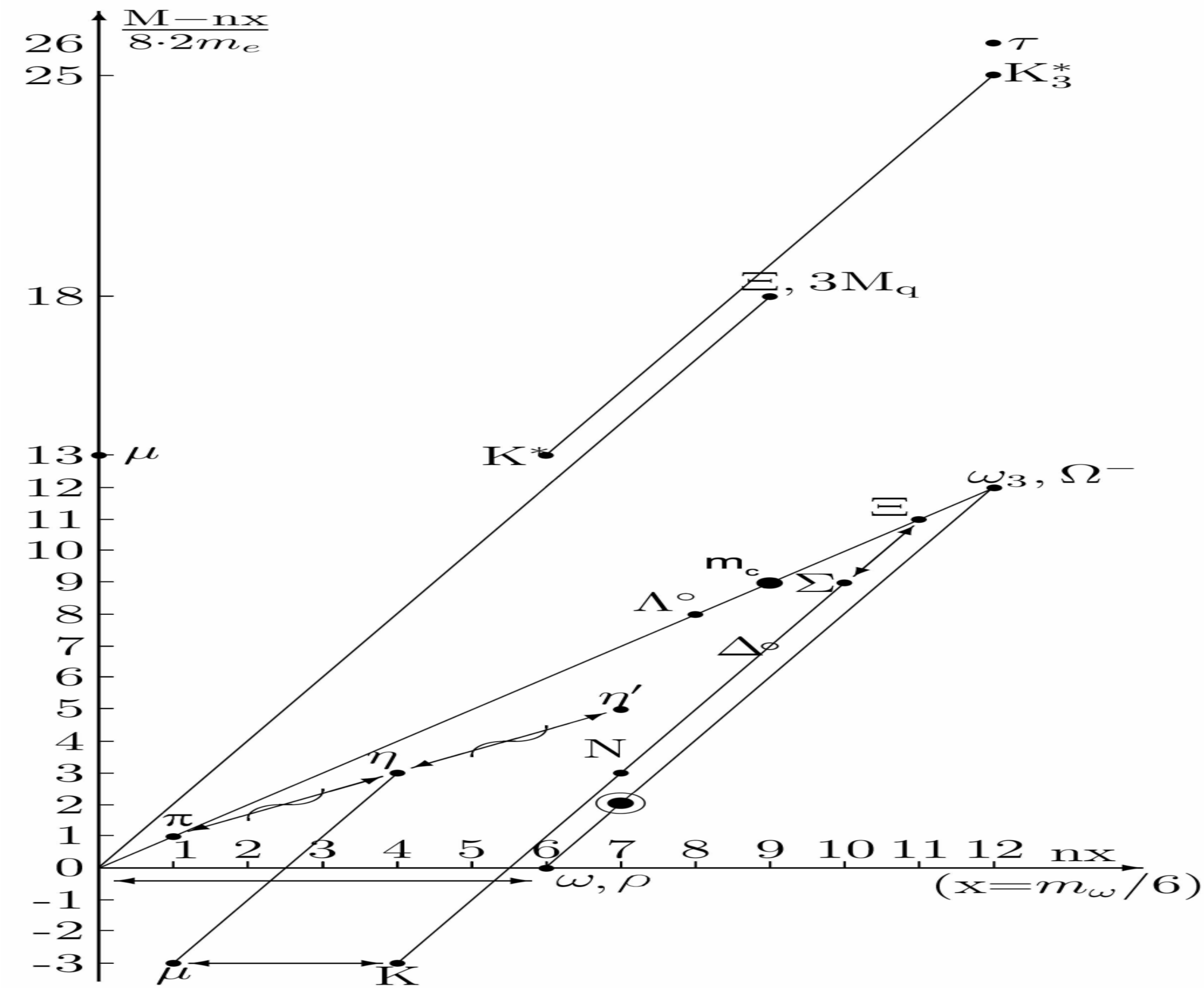
Analysis of particle masses

A symmetry motivated approach to the problem of the particle mass spectrum is due to the fact that the electron and nucleons add up to the visible mass of the Universe. Ratio of their masses is very accurately estimated in CODATA review as $\mathbf{m_n/m_e=1838.6836605(11)}$. The lepton ratio $\boldsymbol{L} = \mathbf{207}$ is close to $\mathbf{m_\mu/m_e = 13\times16\text{-}1}$.

The representation of the nucleon masses in terms of the electron mass and a period **$16m_e = \delta$** allows to check the same representation in the discreteness effect in the energies of nuclear states and particle masses. The values of the pion parameters f_π=130 MeV, m_π=140 MeV, ΔM_Δ=147 MeV, as well as parameters of the Constituent Quark Model $M_q = 3\Delta M_\Delta$=441 MeV and $M_q^\omega = 3f_\pi$=391 MeV, contain an empirical discreteness parameter - the period **δ**.

Lepton parameters are considered together with parameters of a very successful Nonrelativistic Constituent Quark Model: pion parameters $f_\pi = 130$ MeV, $m_\pi = 140$ MeV and constituent quark masses $M_q = m_\Xi/3 = 441$ MeV, $M^\omega_q = m_\omega/2 = 391$ MeV. Mass of τ-lepton is equal to $2m_\mu + 4M^\omega_q$. This means that the muon mass is the distinguished parameter:

$$m_\tau - m_\mu = m_\mu + 4M^\omega_q.$$



$\frac{M-nx}{8\cdot 2m_e}$
26
25
18
13
12
11
10
9
8
7
6
5
4
3
2
1
0
−1
−2
−3
τ
K_3^*
Ξ, $3M_q$
K^*
μ
ω_3, Ω^-
Ξ
m_c
Σ
Λ°
Δ°
η'
N
η
π
1 2 3 4 5 6 7 8 9 10 11 12 nx
ω, ρ
$(x = m_\omega/6)$
μ
K

Fig. 8.

Figure 8. The evolution of the baryon mass from $3M_q$ to Δ-baryon and nucleon masses is shown here in a two-dimensional representation: the values on the horizontal axis are given in units $16 \cdot 16m_e = f_\pi = 130.7$ MeV, remainders $M_i - n(16 \cdot 16m_e)$ are along the vertical axis in units $16m_e$. Lines with three different slopes correspond to the three pion parameters $f_\pi = 16\delta$, $m_{\pi\pm} = 17\delta$ and $\Delta M_\Delta = 18\delta$.

In these work, we consider additional empirical observations in the particle mass spectrum and nuclear data using the combined analysis of all particle masses from the PDG-2020 compilation.

Fundamental character of similarity between correlations in particle masses and nuclear data is based on empirical relations between the electron mass and masses of leptons, hadrons and fundamental fields.

Leptons and hadrons form observed correlations in mass spectrum with a common period 8.176 MeV = δ = $16m_e$ (shown in Figure 1 from [2]) that masses of the fundamental fields $M_Z=m_\mu(\alpha/2\pi)^{-1}$ and $M_H{}^o=m_e/3\ (\alpha/2\pi)^{-2}$, and the main parameter of the ECQM and NRCQM models $M_q=m_e(\alpha/2\pi)^{-1}$ are interconnected with symmetry motivated relations and common QED correction.

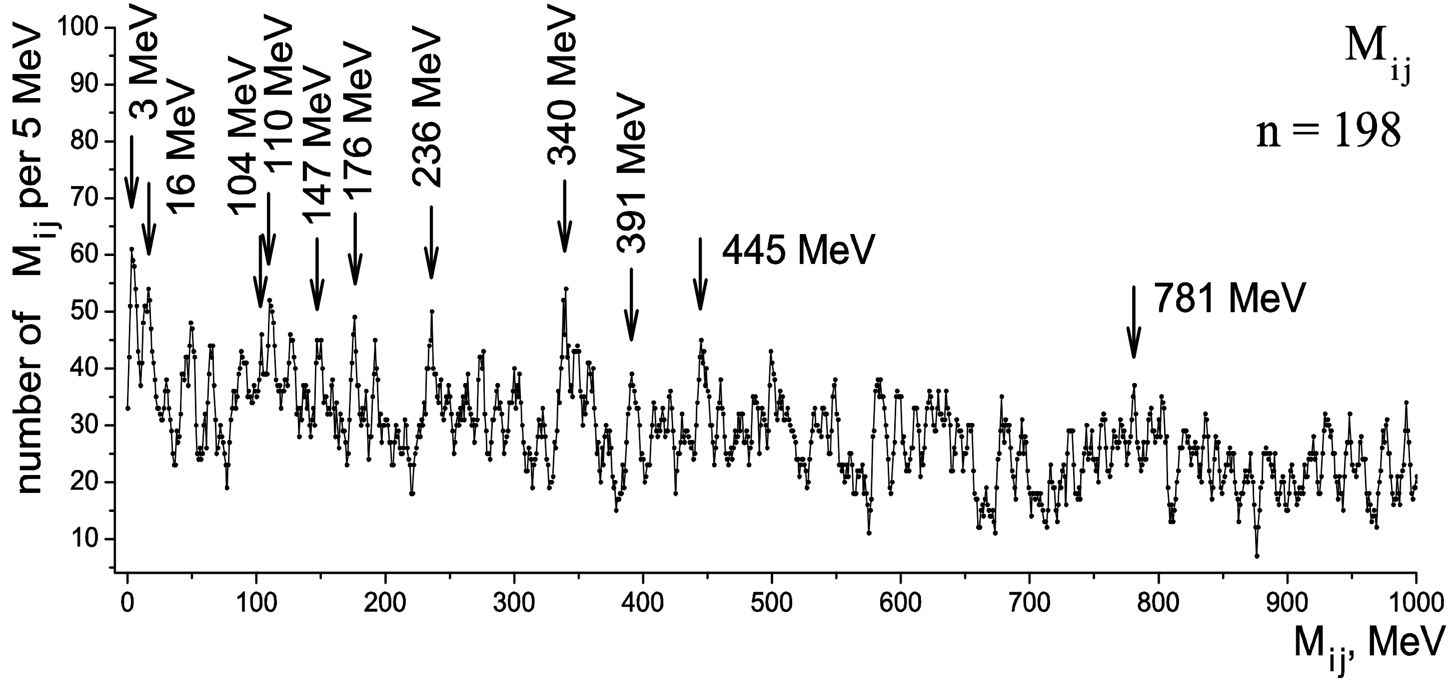


Figure 10a. ΔM distribution of all differences between particle masses from PDG-2020. Maxima at 16 MeV **= 2δ** =2 × 16m_e,
391 MeV = $m_\omega/2$, 445 MeV=M_q, 781 MeV=m $_\omega$

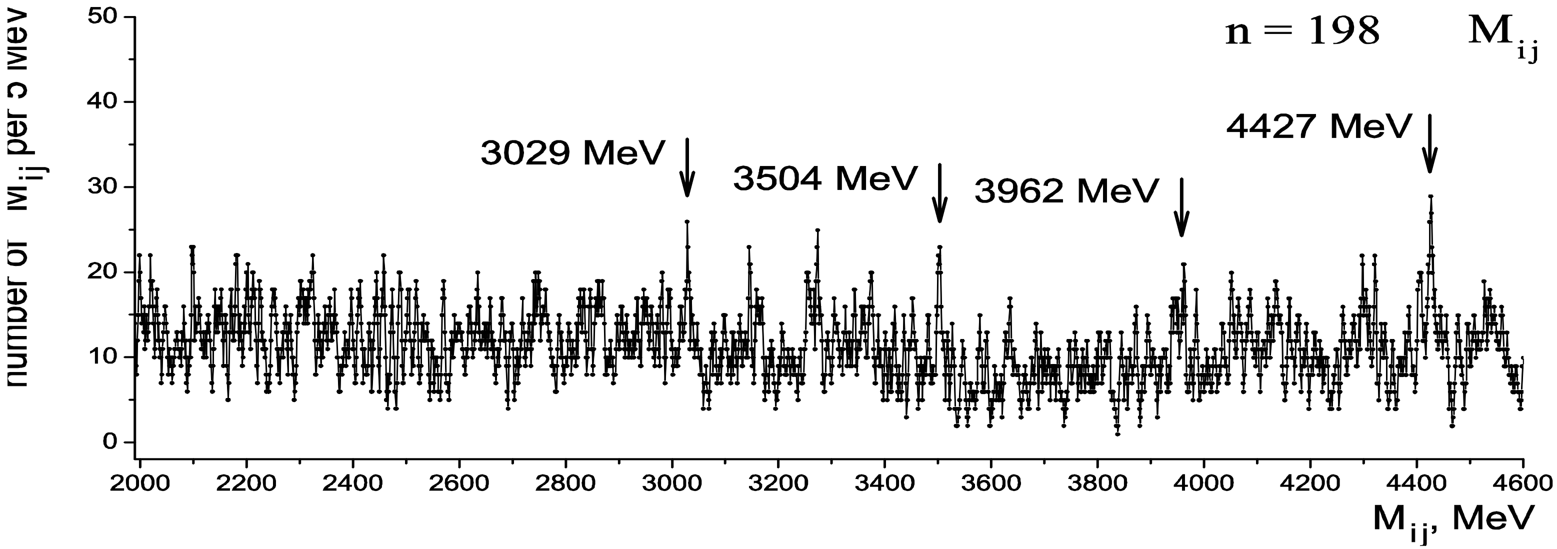


Figure 10b. ΔM distribution of all differences between particle masses from PDG-2020 for the energy region 2000—4600 MeV (averaging interval 5 MeV) . Maxima at 3504 MeV ≈ $\mathbf{8M_q}$ = δ^0 /2, 3962 MeV ≈ $\mathbf{9M_q}$ and 4427 MeV ≈ $\mathbf{10M_q}$

Conclusions

Symmetry motivated relations 1:9:13:16:17 between particle masses and stable nuclear intervals of the few-nucleon-, fine and superfine structures effects are considered here as an indirect check of the ECQM model with the parameter $\alpha/2\pi$ corresponding to the QED correction.

We show that the masses of the fundamental fields $M_Z = m_\mu (\alpha/2\pi)^{-1}$ and $M_H{}^0 = m_e/3(\alpha/2\pi)^{-2}$, as well as the main parameter of the ECQM and NRCQM models, $M_q = m_e (\alpha/2\pi)^{-1}$, are interconnected by symmetry motivated relations and the common QED correction, which can be investigated by neutron resonance spectroscopy.

References

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2. S.I. Sukhoruchkin, *Analysis of particle masses, nuclear data and parameters of constituent quarks*, Nucl. Part. Phys. Proc. 312-317C (2021) 185; *Electron-based Constituent Quark Model,* Nucl. Part. Phys. Proc. 318-323C (2022) 142.

3. S.I. Sukhoruchkin, M.S. Sukhoruchkina, *Study of nonstatistical effects due to tensor forces. Proc. ISINN-19*, Dubna, 2011. JINR E3-2012-30, p. 308.

4. H. Schopper (Ed.), Landoldt-Boernstein New Series, Springer. Vol. **I/26A** (2015).