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GROUPING OF NEUTRON RESONANCE POSITIONS

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1. Introduction

Neutron resonance spectroscopy is a part of nuclear physics based on the Standard Model (SM) as a theory of all interactions. Measurements of neutron cross-sections of heavy nuclei and their analysis at the Institute of Atomic Energy (IAE) and Institute of Theoretical and Experimental Physics (ITEP), carried out in 1950s and later, found out deviations from the statistical model, manifested in unexpected coincidences of neutron resonance positions in different nuclei. In 1950s, I.V. Kurchatov as a director of IAE, have sent to ITEP a communication about this observation of the proximity of neutron resonance positions in compound nuclei: ^{236}U (0.2738 eV), ^{240}Pu (0.296 eV), ^{242}Pu (0.264 eV) and ^{242}Am (0.3051 eV). This simalteneous consideration of the same effect of grouping of the resonance positions at ≈0.3 eV in different nuclei became the starting point for global analysis of nuclear data [1,2].

Two groupings were considered in neutron resonance positions in the energy region of $E_o \leq 50$ eV. The first one, about 0.3 eV, and the second grouping about 5.5 eV. The effect of coincidence of neutron resonance positions in ^{236}U, ^{240}Pu, ^{242}Pu and ^{242}Am at $E_n \approx 0.3$ eV was reported at the First Geneve Conference on the Peaceful Use of Atomic Energy (1955) [3]. The grouping about 5.5 eV was reported in Paris in 1966 year [4].

Spacing in neutron resonance positions is the energy difference (after recoil correction) between the nuclei highly excited states (E_i - E_j, where $i \neq j$). The use of spacing distributions along with distributions of neutron resonance positions (which in turn represent the difference between nuclear excitation energy and neutron separation energy) to study nonstatistical effects is preferable due to the larger number of spacings. In addition, in neutron resonance spectroscopy it is possible to select neutron resonances by reduced neutron width, reflecting the nucleon structure: large neutron widths correspond to a large component of the single-particle wave function.

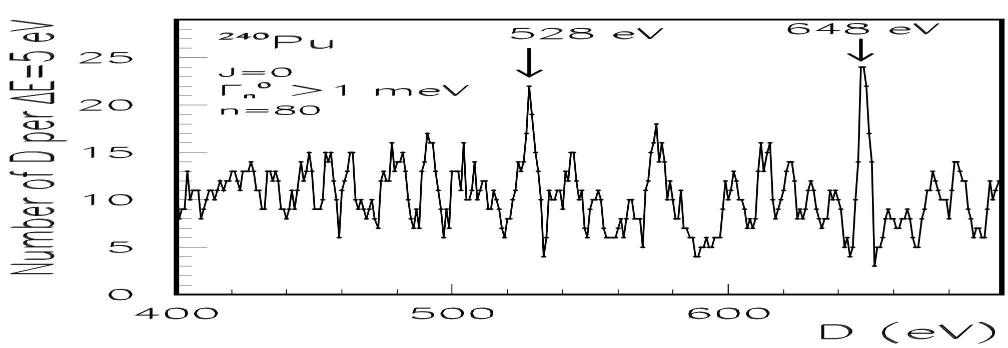

Figure 1: D distribution in 0^+ resonances of ^{240}Pu.

The systematic character of the proximity of resonance positions and spacings in the compound nuclei ^{240,242}Pu and ^{242,244}Am is difficult to check using spacing distributions due to the very small interval considered ($\approx$0.3 eV). However, the resonance at E_n $\approx$0.3 eV in ^{240}Pu can be considered as a part of 0^+ levels spectrum of spacing distribution of this nucleus, where stable intervals of 500-600 eV are observed, see Fig. 1.

The second grouping 5.5 eV in neutron resonance positions was found in 1950s in compound nuclei ^{233}U (5.980 eV), ^{235}U (5.157 eV), ^{237}U (5.45 eV), ^{239}U (6.67 eV). This grouping was preserved in 1966 [4] and later, in the sum distribution of resonance positions of all nuclei, see Fig. 2.

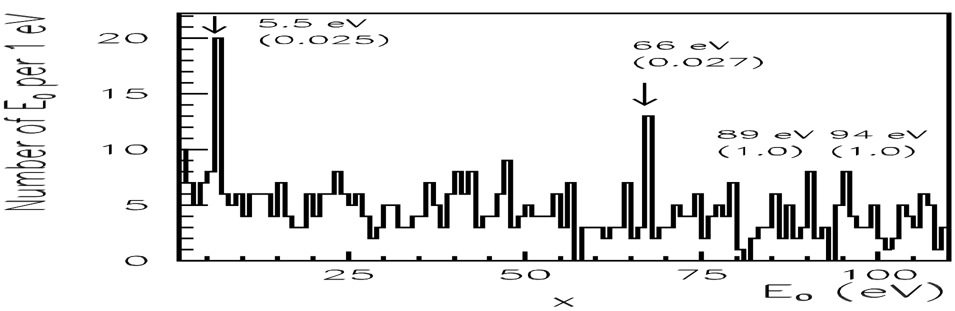

Figure 2: Distribution of neutron resonance positions known in 1966 year. Selection of one strongest resonance (max Γ_n^o) in the interval 10 eV (random probability is given in parentheses).

2. Superfine structure of neutron resonance positions

The maximum at 5.5 eV=$4\varepsilon''$ (where ε''=1.34 eV is the parameter of the superfine structure introduced in [1]) is a stable interval in compound nucleus ^{238}Np spectrum [5]. In Np positions of the doublet of resonances at 1.32 eV and 1.48 eV are close to the maximum (at 1.1 eV) in the spacing distribution (Fig. 7, top, in [5]), while in the distributions for more strong resonances maxima are observed at 4.1 eV=$3\varepsilon''$, 5.6 eV=$4\varepsilon''$ and 16.4 eV=$12\varepsilon''$, as well as at 54.8 eV=$5\delta''$=$40\varepsilon''$ and 87.8 eV, close to 88 eV=$8\delta''$=$64\varepsilon''$ (where δ''=11 eV=2·5.5 eV) (Fig. 7 in [5]).

Many authors, starting from W.W. Havens [6], have paid attention to nonstatistical effects in spacing distributions of different nuclei. Coincidence of positions of neutron resonances in light nuclei was reported in JINR, Dubna, 12-14 June 1964, at the Meeting of Interaction of Neutrons with Nuclei in the energy region 1 eV – 100 keV [7]: "Relationship between the fine structure in nuclear masses and the effect of coincidence of neutron levels of light nuclei". K. Ideno and M. Ohkubo have found stable interval 143 eV in ^{76}As equal to 13×$8\varepsilon''$ [8]. In neighbor heavy compound nuclei ^{233}Th and ^{236}U integer number 13 of the period 5.5 eV was also noticed. A recent analysis of the ^{236}U compound nucleus [9] demonstrate the presence of a stable interval that is multiple of 5.5 eV. For example, in Fig. 6 in [9] in adjacent interval distribution for J=4 ^{236}U resonances for x=44.2 eV an exact ratio 13:4 = 143.4 eV(=5.5 eV×13 × 2) : 44.2ėV(=5.5 eV×4 × 2) is marked.

Thorium isotopes have 90 protons, corresponding to the filled $f_{7/2}$ subshell. It was noted long ago that the spacing distribution of its L=0 resonances is clearly nonstatistical. On the histogram with the averaging parameter 5 eV in Fig. 3 (top), the equidistancy of the 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 an arrow). Fixing all such intervals (x=288 eV) in the spectrum of all s-wave resonances, we obtain maximum at a doubled value of 576 eV. Such an interval corresponds to the distance between strong neutron resonances (maximum at 573 eV in Fig. 3, bottom, with the selection of resonances with a reduced neutron widths greater than 1 meV, deviation from the random level $\approx 3\sigma$). A small maximum at 42 eV on the same distribution (Fig. 3, bottom) corresponds to a 1:13 ratio between strong resonances (between states with a relatively large single-particle component in the wave function).

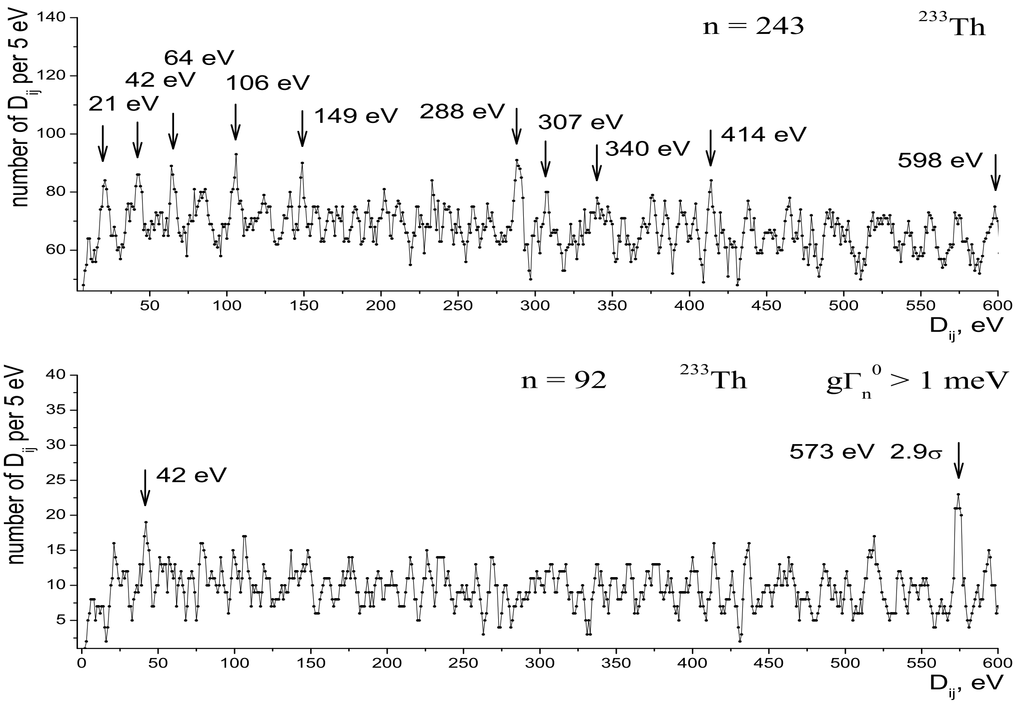

Figure 3: *Top:* Spacing distribution of all L=0 neutron resonances in ^{233}Th. *Bottom:* Spacing distribution of all L=0 strong neutron resonances in ^{233}Th (from [9]).

3. Fine structure of nuclear excitations and binding energies

It was noticed [10] that in ^{141}Ce, the positions of the two strongest resonances ($\mathit{\Gamma}_n^o$ marked with asterisk in Table 1) are in the ratio 9:4=2.25 (2.253, in fact). The same ratio (2.237) exists between the energies of low-lying excitations ^{143}Ce (Table 1, bottom). The triplet of these closely spaced levels (the next E^* is at 633 keV) is the result of the residual interaction between three valence neutrons. One could notice a 1:2 ratio of the values E'_n in ^{141}Ce to E^*in ^{143}Ce (ratio 0.505). E'_n of strong s-resonances in some other N=83 nuclei are related to these E'_n. For example, E'_n in ^{142}Pr is close to that of ^{141}Ce (marked as $8\varepsilon'$=8×1.188 keV), while E'_n in ^{140}La is close to ε' (see Table 1). In the near-magic ^{145}Sm (N=83), the position of the p-wave resonance with the largest Γ_n^1 is close to ε', while the stable spacing of its s-wave and p-wave resonances (n=143, D=3689 eV and n=62, D=2485 eV, see Fig. 5) are close to $3\varepsilon'$=3564 eV and $2\varepsilon'$=2376 eV. Stable intervals D=595 eV=$\varepsilon'/2$ and D=294 eV=$\varepsilon'/4$ were found in resonances ^{134}Cs and ^{128}I.

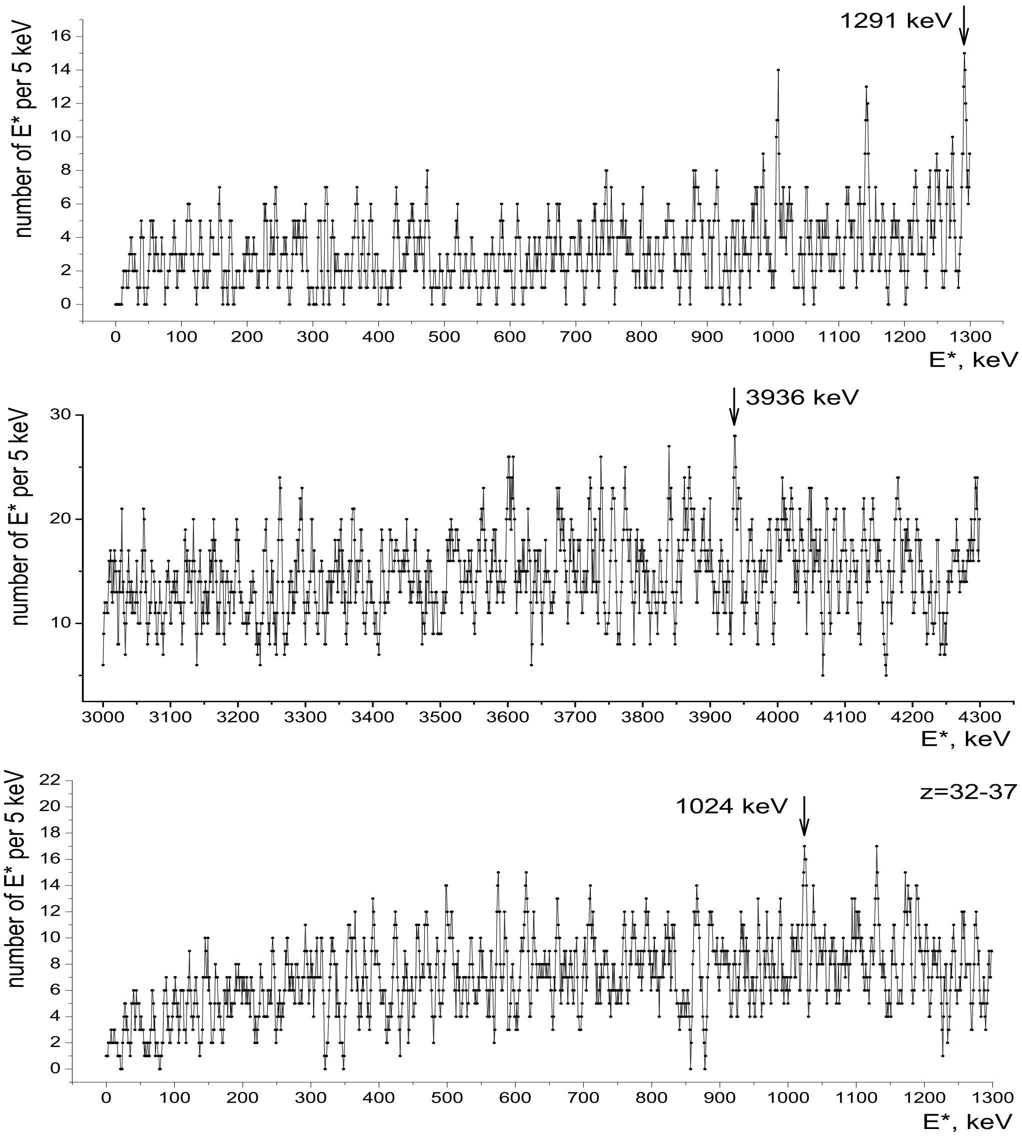

Figure 4: *Top and cetner*: E^*-distribution in nuclei with Z=4-29 for E^*<1300 keV and 3000-4300 keV [9]. Arrows mark δm_N and $4\times8\times13\delta'$=3936 keV (see also Table 2). The equidistant maxima at E^*=1008 keV=$2\times17\delta'+4\times18\delta'$, 1142 keV=$5\times17\delta'$ + $2\times18\delta'$ and 1291 keV=$8\times17\delta'$ are explained in [9]. *Bottom:* The E^*-distribution in all nuclei with Z=32-35. The maximum at 1024 keV=$6\times18\delta'$ is close to ε_o=1022 keV=2m$_e$.

The interest in the number 13 in expressions for intervals of fine and superfine structures is associated with the lepton ratio L=207=13×16-1, which contains this number. The importance of this number 13 can be demonstrated by the new expressin for the mass of τ lepton [11]:

$$m_\tau = 2m_\mu + 2m_\omega \approx 2\cdot13\cdot16m_e - 2m_e + 2\cdot96\cdot16m_e = 2m_{K^*}. \qquad (1)$$

Table 1: (from [5]) Comparison of positions and spacings in light and near-magic nuclei with integer values of the fine structure parameter $\varepsilon' = \delta'/8 = 1.188$ keV. *Top:* Positions E'_n (keV) of strong neutron resonances in light and magic nuclei and periodicity in the spacing distributions in resonances ^{61}Ni (top right). *Center:* Values E_n (keV) in nuclei with N=83=82+1, maxima in spacing distributions ^{141}Ce. *Bottom left:* The positions of strong neutron resonances in isotopes with Z=35-39 are compared with the integer of the period ε'=1.188 keV=9.505 keV/8, found in the positions of strong resonances in Z=57-59, N=83 nuclei (center). *Bottom right:* Excitation energies E^* (keV) of ^{143}Ce. Boxed are values ε'=1.188 keV=9.505 keV/8, δ', $2\delta'$ and $(9/4)\delta'$ discussed in the text.

Nucl.	Ca-Ni	^{61}Ni	^{61}Ni	^{61}Ni	^{61}Ni	^{61}Ni
l_n	l_n=0	D(keV)				
E_n	18.8	4.8	9.3	14.1	19.0	24.7
$k(\varepsilon')$	16	4	8	12	16	20
$k \times \varepsilon'$	19.0	4.8	9.6	14.4	19.0	24.7
Nucl.	^{141}Ce	^{141}Ce	^{142}Pr	^{141}Ce	^{141}Ce	^{141}Ce
J_i^π	$1/2^+$	$1/2^+$	$(5/2^-)$			
Γ_n^o,meV	660*	3060*	160	D	D	D
E_n	9.573	21.570	9.598	21.7	43.1	86.2
E^*,E'_n	9.505	21.418	9.530			
$k(8\varepsilon')$	1	9/4	1	9/4	9/2	9
$k{\times}8\varepsilon'$	9.504	21.384	9.504	21.4	42.5	85
Nucl.	^{140}La	^{80}Br	^{82}Br	^{86}Rb	^{143}Ce	J_o^π=$3/2^-$
J_i^π	3^+	l_n=0	l_n=0	l_n=0	$7/2^-$	$5/2^-$
Γ_n^o,meV	54	72.0	120	159	E^*	E^*
E_n	1.179	1.201	1.209	2.398		
E^*,E'_n	1.170	1.186	1.194	2.370	18.9	42.3
$k(8\varepsilon')$	1/8	1/8	1/8	2/8	2	9/2
$k{\times}8\varepsilon'$	1.188	1.188	1.188	2.376	19.0	42.77

It was found that the clustering of strong resonances in ^{82}Br has a small (0.03) occasional probability of grouping [10]. It is shown in Table 1 that E'_n of the strongest resonances in ^{80}Br, ^{82}Br and ^{86}Rb are close to ε' and $2\varepsilon'$. In ^{182}Ta, E'_n of the two strongest s-resonances are ε' and $\varepsilon'/2$ [5].

In Fig. 4, E^*-distributions in nuclei with Z=4-29 for E^*<1300 keV and 3000-4300 keV are given. Arrows mark 1291 keV, close to 1293.3 keV=δm_N and 3936 keV=$4{\times}8{\times}13\delta'$, where δ'=9.5 keV=8×1.188 keV=$8\varepsilon'$. The maximum at 3936 keV confirms the distinguishing character of the 13th energy interval in nuclear excitations, see Table 2.

Table 2: Excitations (in keV) of light nuclei from ^{33}S to ^{39}Ca at 3936 keV=$32{\times}13\delta'$. Boxed are stable excitations close or multiple to this excitation.

$2J^\pi$	^{33}S	^{38}Cl	^{39}K	^{37}Ar	^{38}Ar	^{39}Ca	D$_{ij}$(^{18}F)	D$_{ij}$(^{20}F)
3^+	0.0	E^*_{exp}	E^*_{exp}	E^*_{exp}	E^*_{exp}	E^*_{exp}	493 keV	490 keV
5^+	1967	1982	2523	1410	2167	2469		984 keV=
3^+	3935	3938	3939	3937	3937	3936	3936/8	3936 keV/4

In Fig. 5, we show that in the D-distributions of neutron resonances in ^{145}Sm for orbital momenta L=0 and L=1 the maxima are located exactly at $3\varepsilon'$ and $2\varepsilon'$.

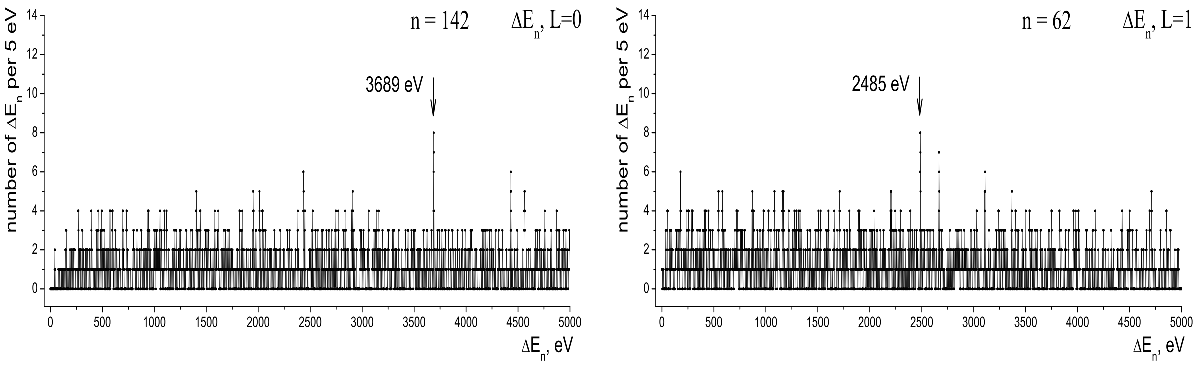

Figure 5: Spacing distributions of neutron resonances in ^{145}Sm (for orbital momenta L=0 and L=1 with maxima at $3\varepsilon'$ and $2\varepsilon'$ (3689 eV/2485 eV=1.48≈3/2, ε'=1.226 keV).

In high energy excitations of nuclei around N=82, many authors (M. Ohkubo, K. Ideno, F. Belyaev [12] and others [13,14]) observed fine structure effects in the spacing distributions of neutron resonances. From the exact ratio 9:4 between the strong resonances in ^{141}Ce (N=82) and the excitation spectra of this and neighboring nuclei, the common period ε'=1.188 keV was derived. The recently observed stable intervals $2\varepsilon'$ and $3\varepsilon'$ (Fig. 5) confirmed the relation $\varepsilon'=\varepsilon_\circ(\alpha/2\pi)^{-1} = 2M_q(\alpha/2\pi)^{-2}$ with QED correction to the electrom mass. This means that the CODATA relations [11,15] confirm all earlier observed "strange unexpected" empirical correlations.

Similar nonstatistical effects were found in the nuclear binding energies [9]. In nuclei around N=82, differing by ΔZ=2, ΔN=4 (or ^{6}He cluster), Values ΔE_B turn to be multiple (k=10) of the parameter $9m_e$=4.6 MeV (see Fig. 6, left). This parameter $9m_e$ is close to the value of d-quark mass (4.67(48) MeV) [15]. Grouping at 147 MeV (equal to 18δ [15]) in nuclei differing by 4^4He-clusters is shown in Fig. 6, right. The discreteness in binding energies was found in many nuclei. For example, the stable interval ΔE_B=106 MeV, close to the mass of muon, corresponds to 13 intervals of the common period δ=16m$_e$.

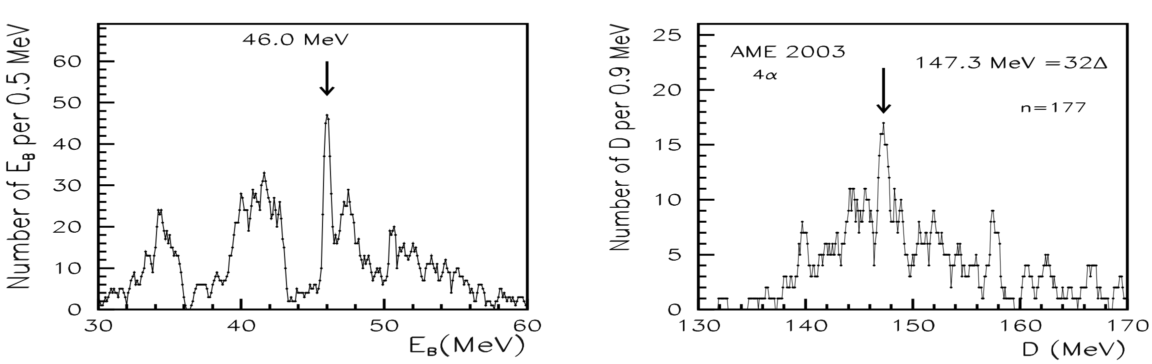

Figure 6: Grouping of ΔE_B at 46.0 MeV in nuclei differing by ^{6}He-cluster (*left*) and differing by 4^4He-clusters (*right*).

3. Discreteness with the parameter $\varepsilon_o = 2m_e$ in nuclear data

Recent data confirm the important role of common relations (with parameter $\alpha/2\pi$) between small stable intervals of the superfine structure (1.34 eV), intervals of the fine structure (1.2 keV), parameters m_e, M_q and scalar boson mass 125 GeV [1,11]. Fine and superfine structures with the parameters $\varepsilon' = 1.2\,\mathrm{keV}$ and $\varepsilon'' = 1.34\,\mathrm{eV}$ observed in neutron resonance spectra together with the stable nuclear excitations $2m_e = 1022\,\mathrm{keV}$ and parameters $2M_q = 882\,\mathrm{MeV}$ and $M_{H^\circ} = 125\,\mathrm{GeV}$ form a sequence of ratios:

$$\alpha/2\pi = 115.9 \cdot 10^{-5} = \varepsilon'' : \varepsilon' = \varepsilon' : 2m_e = m_e : M_q = m_\mu : M_Z = M_q : 3M_{H^\circ}. \quad (2)$$

Table 3: (from [5]) Comparison of the parameter $\alpha/2\pi$=115.96$\cdot 10^{-5}$ with the anomalous magnetic moment of the electron $\Delta\mu_e/\mu_e$ (top line) and with the ratios between the mass/energy values introduced in [1,13,14] (lines No 4-6) and other parameters mentioned in literature.

No.	Parameter	Components or the ratio	Value $\times 10^5$
	$\Delta\mu_e/\mu_e$	$=\alpha/2\pi$-0.328 α^2/π^2	115.965
	$2\delta m_\pi - 2m_e$	(81652(10) keV)/($16m_e$=δ)	132(12)
1	$\delta m_\mu/m_\mu$	($23\times 9m_e$-m_μ)/m_μ	112.1
2	m_μ/M_Z	m_μ/M_Z=91182(2) MeV	115.87(1)
3	$\delta m_n/m_\pi$	(k$\times m_e$-m_n)/m_π=161.649 keV/m_π	115.86
4	$\varepsilon''/\varepsilon'$	1.35(2) eV/1.16(1) keV	116(3)
5	$\varepsilon'/\varepsilon_o$	1.16(1) keV/ε_o=1022 keV	114(1)
6	$(\varepsilon_o/6)/\Delta M_\Delta$		116.02
7	(ΔM_Δ=$M_q/3$)/M_{H°	147 MeV/125 GeV	118
8	δ/δ°	$\delta^\circ = 16M_Z/(L=207)$=7.048 GeV	116.0

It was noted [1] that the radiative correction to the electron mass is similar to the correction to its magnetic moment. This allowed to connect the value m_e with the masses of fundamental scalar and constituent quark [11]. The relation (2) is a continuation (in the high energy region) of the established in 1970s empirical relations (with the same parameter close to $\alpha/2\pi$) between superfine and fine structures in resonance spectra.

Discreteness in particle masses and nuclear data are considered in [11,13-14].

In Table 1 in [15], numbers of fermions in the central field (top, N^{ferm}) are compared with numbers N in a representation $N \cdot \delta$ of the masses m_μ, f_π, $m_{\pi^\pm}$, ΔM_Δ.

Discreteness in E_B, fine structure in E^* at δm_N=1293 keV and 3936 keV (Fig. 4) correspond to N=13 and N=17 in Table 1 in [15].

5. General remarks and conclusions

The discreteness in neutron resonance parameters is the main element of the "data-driven science" approach initiated by I.V. Kurchatov in 1950s, who drew attention to the unexpected coincidence of nuclear resonance positions in different elements. It turned out that this effect was obtained not only in heavy fissile nuclei, but also in other regions of the nuclear chart and depends on the nucleon structure, the stabilizing shell effect, and the influence of vacuum. The global symmetry motivated approach to the method of analyzing nuclear data and particle masses allowed us to confirm the role of the electron mass as the main parameter of the Standard Model as a theory of all interactions.

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