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Fundamental origin of nuclear tuning effects

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Abstract. Relations in values of stable nuclear energy intervals and their coincidence with a half of nucleon Δ-excitation and electromagnetic mass splitting of nucleon, pion and leptons are considered as a common tuning effect in nuclear data and particle masses. Combined study of few-nucleon effects in nuclear binding energies and excitations resulted in determination of common parameters for different shells corresponding to residual nucleon interaction and differences in binding energies of nuclei differing by cluster configuration. Stable intervals in energies of nuclear states ranging from hundreds of MeV to tens of keV are considered as a tuning effect in which the QED radiative correction takes part.

1 Introduction

S. Devons in his review at Ernst Rutherford Jubilee Conference [1] after analysis of first steps of modern atomic physics suggested that using high quality nuclear data one can hope to find manifestation of the nucleon structure. He considered relation between high-energy and nuclear physics in analogy between Rutherford's α-scattering experiment and optical spectra systematics. To check his suggestion we performed analysis [2] of few-nucleon effects at different nuclear shells, simultaneously in nuclear binding energies and excitations. Such common approach was discussed by A. Arima and A. Bohr.

1.1 Nucleon structure and constituent quark masses

Nucleon is formed by three dressed (constituent) quarks with masses of about 410 MeV estimated as $M_q^{\Delta} = m_{\Delta}/3 =$ 1240 MeV/3 (initial masses of d,u-quarks are small). Hadron masses are calculated in the QCD-framework [3–5]. The mass of nonstrange baryons m_N^{init} in constituent quark model ("initial mass" before inclusion of quark interaction) is about $m_N^{init} =$ 1350 MeV $= 3 \times 450$ MeV $= 3M_q$ [5–7]. The value M_q coincides with the interval introduced by R. Sternheimer from relations 441 MeV $= m_{\Sigma}{-}m_N = m_N{-}m_K = m_{\eta}{-}m_{\mu}$ [8,9]. The first interval involves nucleon mass and consists of two parts with a ratio of 1:2 $m_{\Sigma}{-}m_N = m_{\Sigma}{-}m_{\Delta} + m_{\Delta}{-}m_N =$ 147 MeV + 294 MeV. The nucleon Δ-excitation 2×147 MeV is the well-known QCD parameter.

Quark mass $M_d = 436$ MeV close to $M_q = 441$ MeV was used in strange baryon mass calculation [10]. It coincides with P. Kropotkin estimate of Sternheimer's interval [11] as $m_{\Xi}/3 =$ 1324 MeV/3 = 441 MeV (close to $m_N^{init}/3$ [8]). Nucleon parameter $m_N^{strip} = m_N$-σ_N = 940 MeV–60 MeV = 880 MeV known from lattice QCD analysis [12,13] (limit for pion's mass $m_{\pi} = 0$) is close to three Δ-excitations (882 MeV) and sum m_N^{strip} + 294 MeV = 8 × 147 MeV corresponds to three-quark structure (stripped Δ-baryon) with quark mass $M_q'' =$ (4×294 MeV)/3 = 8/9 M_q = 392 MeV introduced by G. Wick [8] from observation of stable mass intervals close to 1/2 of vector ω-meson mass 783 MeV/2 = 391 MeV (meson constituent quark mass).

Constituent quark mass estimates $M_q'' = m_{\omega}/2$, M_q^{Δ}, $M_q = M_{\Xi}/3$ and $M_q' = 3m_{\pi}$ [12] were considered in line with Y. Nambu suggestion [14] that for Standard Model development the analysis of empirical relations is helpful.

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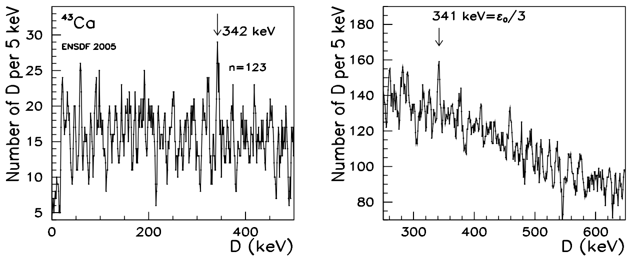

Fig. 1. D-distribution of low-lying ^{42}Ca and neutron resonances in ^{41,43}Ca [2].

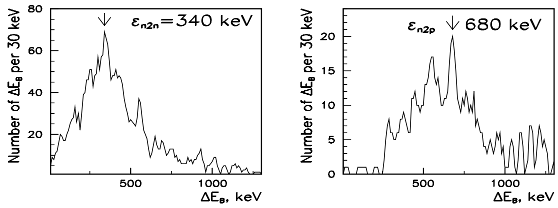

Fig. 2. Distribution of parameters $\varepsilon_{n2n} = \Delta S_n(\Delta N = 2)$ and $\varepsilon_{n2p} = \Delta S_n(\Delta Z = 2)$ in N-odd and odd-odd nuclei [12].

1.2 Tuning effect in particle masses

The involvement of nucleon mass, its excitation and ω-meson mass in accurate correlations [5,12,15] is in agreement with the result by R. Frosch [16] who searched for a periodicity in accurately known 47 particle masses and found the period of $3m_e$ as distinguished. From a closeness of pion's electromagnetic mass splitting δ_{π} to $9m_e$ [17] one can use a doubled value of pion's β-decay ($\delta = 16m_e$) to represent masses of muon (13δ-m_e), pion (17δ+m_e), nucleon ($m_n = (13 + 6 \times 17)\delta$-$m_e$), its Δ-excitation 294 MeV = $2{\cdot}18\delta$, ω-meson mass $6(16\delta{-}1)m_e$ and stable interval in meson masses 409 MeV = 50δ [9].

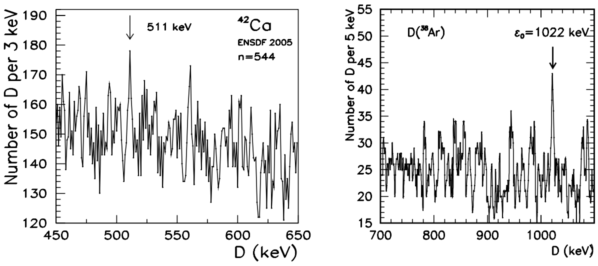

Fig. 3. D-distributions of levels in near-magic ^{42}Ca and ^{38}Ar.

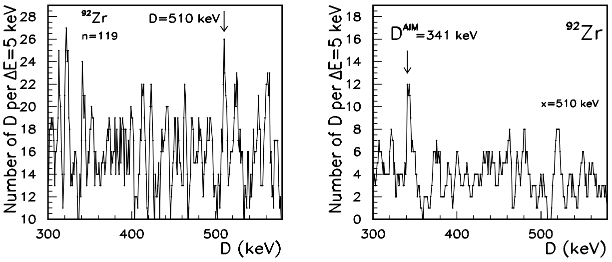

Fig. 4. Spacing distribution in levels of ^{92}Zr (left); D^{AIM}-distribution of intervals adjacent to x = 510 keV = $\varepsilon_o/2$ (right).

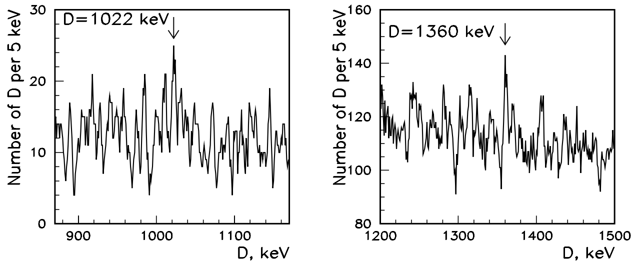

Fig. 5. D-distributions in levels of ^{115}Sn, $D = \varepsilon_o$ and ^{125,127}Te.

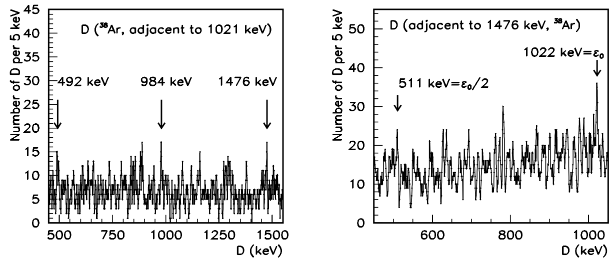

Fig. 6. D^{AIM}-distributions in ^{38}Ar for D = 1021 and 1476 keV.

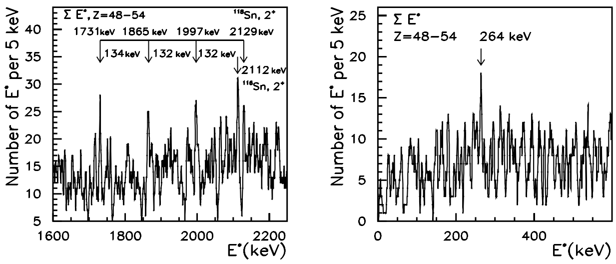

Fig. 7. Sum distributions of excitations of all Z = 48 − 54 nuclei.

To double relation between m_e and Sternheimer–Kropotkin's interval $M_q = 3\varDelta M_\varDelta = 3 \cdot 147$ MeV as $1/32 \times 27$ and QED-correction $\alpha/2\pi$ other relations were added:

1. Ratio δ_π/m_e becomes integer after QED correction.
2. τ lepton mass m_τ = 1777.0(3) Mev [18] coincides with the doubled sum $m_\mu + m_\omega$ of 1776.6(2) MeV.
3. Muon mass relates to Z-boson mass exactly as $\alpha/2\pi$ and lepton ratio m_μ/m_e = 206.77 becomes integer L = 207 = 9 · 23 = 13 · 16-1 after m_e QED correction [12]. It means that M_Z/M_q = 206.8 is close to L. Applying L to M_W = 80.40(3) GeV [18] one find that M_W/L = 388.4(2) MeV deviates from $m_\omega/2$ and is close to $m_\rho/2$ = 775.5(4) MeV/2 = 387.8(2) MeV [18].
4. Top quark mass m_t = 171.4(21) GeV [18] considered by F. Wilchek as a natural fermion-mass estimate [4] relates as 3:2:1 to preliminary mass-effects observed in LEP – Higgs boson mass 115 GeV and mass groping at 58 GeV in L-3 [12]. The value $m_t/3$ = 57.1 GeV relates to M_q as 129(2) close to 8 × 16 = 128.

2 Tuning effect in nuclear excitations

The tuning effect in nuclear data consists in the appearance of stable energy intervals D close (or rational) to electromagnetic mass differences of nucleon $D_o = m_n\text{-}m_p$ = 1293.3 keV [15], lepton $D = m_e$ = 511 keV (or $D = 2m_e = \varepsilon_o$) and pion $\varDelta = 9m_e$. For its study compilations of data on excitations E^* and binding energies E_B for nuclei situated near closed shells were used. For example, a spin-flip effect in ^{10}B corresponds to D = $E^*(1^+, T = 0)$-$E^*(0^+, T = 1)$ = 1021.8(2) keV = $2m_e$ = ε_o and its first negative-parity excitation E^* = 5110.3 keV is equal to $5\varepsilon_o$; 0^+ excitations in ^{18}Ne at E^* = 3576(2) keV and 4590(8) keV are close to 7 and $9m_e$ [**?**], etc. The grouping in E^*-distribution for nuclei with A ≤ 150 at E^* = 1022(2) keV = ε_o discussed in [5, 7] corresponds to three-fold values of E^* = 340 keV in ^{59}Ni, stable interval D = 342 keV in ^{43}Ca low-lying levels (fig. 1 left) and six-fold value of E^* = 168.0(1) keV ≈ $\varepsilon_o/6$ in ^{103}Sn; these nuclei have three neutrons above a core and splitting ($\varDelta J = 1$) are due to residual interaction of nucleons. Standard parameters of residual interaction of the neutron with two nucleons derived from $\varDelta E_B$, namely $\varepsilon_{n2n} = \varDelta S_n(\varDelta N = 2)$ and $\varepsilon_{n2p} = \varDelta S_n(\varDelta N = \mathrm{Z})$ have distributions (fig. 2) with maxima at 340 keV = $\varepsilon_o/3$ and 680 keV = $(2/3)\varepsilon_o$. Interval ε_o is seen directly in E^* (figs. 3–5) and in two- and four-proton separation energies [5, 15].

Neutron resonance data were used for additional check of observed intervals: D = 342 keV in ^{43}Ca corresponds to D = 341 keV = $\varepsilon_o/3$ (fig. 1) in sum resonance spacing distribution in compound ^{41,43}Ca. The nucleus ^{43}Ca itself has $E^* = 2\varepsilon_o$ = 2046 keV ($7/2^- - 3/2^-$). D-distributions in ^{42}Ca and ^{38}Ar (two valence nucleons, fig. 3) have maxima at D = 511 keV = $\varepsilon_o/2$ and 1021 keV = ε_o.

In ^{92}Zr with similar neutron configuration at Z = 40 shell (N = 50 + 2) the maximum at D = 510(2) keV in spacing distribution (fig. 4, left) was studied by Adjacent Interval Method (AIM). We fix all such intervals in ^{92}Zr spectrum and plot the distribution of spacing D^{AIM} between levels forming fixed intervals and all other levels (fig. 4, right). Maximum at 341 keV means that intervals 510-341 keV (ratio 3:2) are interconnected.

In tin isotopes (Z = 50) two-phonon excitations in ^{116,118}Sn ($E^* = 2\varepsilon_o$) can be compared with phonon-like

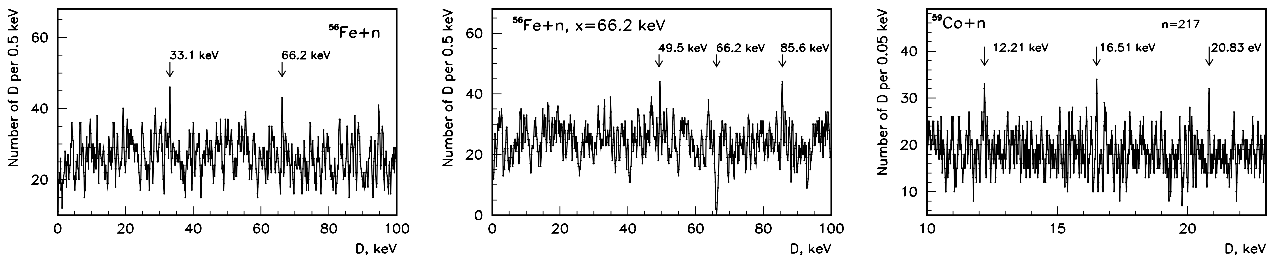

Fig. 8. *D*- and D^{AIM}-distributions in ^{56}Fe neutron resonances (left, center x = $7\delta'$); the same in ^{59}Co (right).

excitation $E^* = \varepsilon_o$ ($\Delta J = 2^+$) in ^{117}Sn ($\Delta J = 2^+$) and stable D = ε_o in ^{115}Sn (fig. 5, left). Stable intervals in ^{125,127}Te ^{127}Te (fig. 5, right) correspond to two-phonon excitation $E^* = (4/3)\varepsilon_o$ in ^{126}Te. The same stable 2^+ phonon in Po-isotopes (also two valence protons) corresponds to stable residual interaction parameter $\varepsilon_{np} = 340$ keV = $\varepsilon_o/3$.

The AIM method was used for a check of interval in D-distributions. For example, by fixing x = 1021 keV in ^{38}Ar (fig. 3) the D^{AIM}-distribution show equidistantly spaced maxima at 492-984-1476 keV (fig. 6, left) and we see $D^{AIM} = 511 - 1022$ keV by fixing $D = 1476$ keV (fig. 6, right). Intervals are expressed as n$\times 2\delta'$, period $2\delta' = 19$ keV, n = 26-27-52-54-78 [2].

In sum distribution of excitations in all nuclei with Z = 48–54 (around tin Z = 50, fig. 7 [2]) a sequence of excitations with the period 133 keV = $7 \times 2\delta'$ (n = 13-14-15-16 and n = 2) was found. Stable interval D = $7\delta'$ = 66 keV and D = 33.1 keV = $(7/2)\delta'$ were found in D-distribution in ^{56}Fe neutron resonances (fig. 8, left). By applying AIM-method and fixing x = 66.2 keV one can see two maxima at 49.5 keV = (3/4)66.2 keV and 85 keV = $9\delta'$ [2]. Stable intervals D = n($7\delta'/32$ = 12.2 keV/3), n = 3, 4, 5 were found in ^{59}Co neutron resonances (see fig. 8, bottom). Period 12.2 keV was noticed earlier in ^{206}Pb by G. Rohr [19] and interval 21.5 keV = $(9/8)2\delta'$ in ^{140}Ce by M. Ohkubo [20]. Intervals of superfine structure $D<\varepsilon' = \delta'/8$ with a period 11 eV = δ'' were studied by K. Ideno and M. Ohkubo [21].

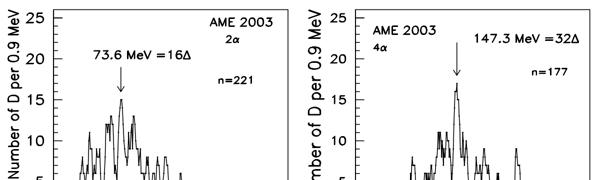

Fig. 9. ΔE_B-distributions in nuclei Z ≤ 26 differing by two and four α, marked $16\Delta = 9\delta$ and $32\Delta = 18\delta$, $\Delta = 9m_e$.

3 Tuning effect in nuclear binding energies

Stability of differences of binding energies ΔE_B in nuclei differing by α-cluster noticed by F. Everling [22] was fitted as $\Delta E_B = (36 \pm 1)\varepsilon_o$ [9]. In figure 9 ΔE_B-distributions in Z ≤ 26 nuclei differing by 2α- and 4α are shown.

Positions of maxima in figure 9 at 73.6 MeV = $2 \times 36\varepsilon_o$ = 9δ and 147.2 MeV = $4 \times 36\varepsilon_o$ = 18δ are exactly 1:2. By using AIM-method and x = ΔE_B = 147.2 MeV = $18\delta'$ in all Z ≤ 26 nuclei (not only Z,N-even) we observe maxima at $\Delta E_B = 9\delta$ = 73.6 MeV and 130.4 MeV = $16\delta - \varepsilon_o/2$ (fig. 10) and using $x = \Delta E_B$ = 73.6 MeV we observe a discreteness with a period Δ = 4.6 MeV (n = 6, 8, 10, fig. 11). Stable ΔE_B = 46.0 MeV (fig. 12, left) and 92.0 MeV (n = 10 and 20), ΔE_B = 50.6 MeV (n = 11) and ΔE_B = 41.4 MeV (n = 9) were found in independent data for heavy nuclei (N = 50–82, N ≤ 50, Z = 79–81) differing by ^{6}He-cluster. In table 1 exact representation of experimental ΔE_B in near-magic nuclei (N = 82) by $10\Delta = 45\varepsilon_o$ is shown. Theoretical values in ETFSI-model deviate strongly from observed ΔE_B.

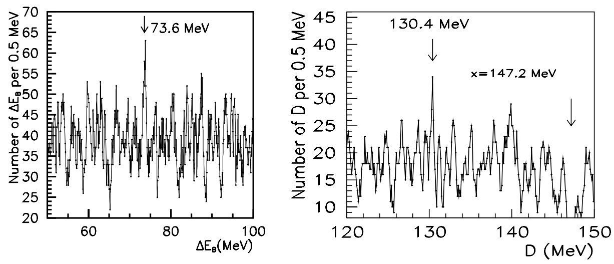

Fig. 10. ΔE_B^{AIM}-distribution in Z ≤ 26 nuclei, x = 147.2 MeV.

Table 1. Comparison of experimental ΔE_B and theoretical estimates in near-magic nuclei (N = 82) with 10Δ = 45990 keV.

	Z = 55		Z = 57		Z = 58			
N	80	$\boxed{82}$	78	80	$\boxed{82}$	78	80	$\boxed{82}$
ΔE_B	45946	45970	46018	45927	46024	46087	45997	45996
diff.	−44	$\boxed{-20}$	28	−63	$\boxed{34}$	97	$\boxed{7}$	$\boxed{6}$
ETFSI	46353	46550	45933	46203	46673	46373	46573	47063
diff., keV	363	563	−57	213	683	383	583	1073

The ΔE_B-distribution for Z ≤ 26 nuclei (fig. 13) has 3 maxima near integers n = 16, 17, 18 of δ; in nuclei differing by 4α (fig. 9) maximum coincides with 18δ. The same stable interval 147.1 MeV = 18δ = 32Δ was found in heavy nuclei differing by $\Delta Z = 8$, $\Delta N = 10$ [5,7]. ΔE_B-distribution for all Z = 65-81 heavy nuclei (fig. 14, left) contains maxima at 147 MeV and 188 MeV and AIM-method permitted to show that ΔE_B = 147.1 MeV = 18δ and 106.1 MeV = 13δ are adjacent (fig. 14, right). Lead isotopes have $\Delta E_B = 5\delta$ (fig. 12, right) for ^{6}He difference.

4 Comparison of tuning effects in hadronic data

Values ΔE_B = 106.1 MeV = 13δ, 130.3 MeV, 140.0 MeV and 147.2 MeV = 18δ are close to muon mass (105.7 MeV),

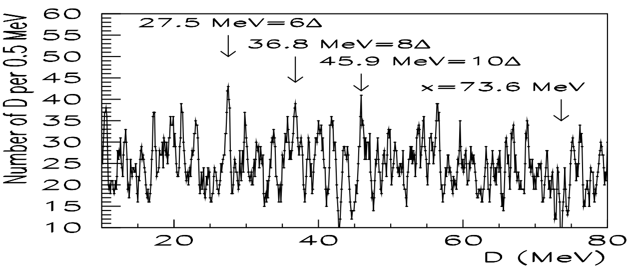

Fig. 11. Distribution of ΔE_B adjacent to x = 73.6 MeV in nuclei with Z ≤ 26 (period Δ = 4.6 MeV is marked, n = 6, 8, 10).

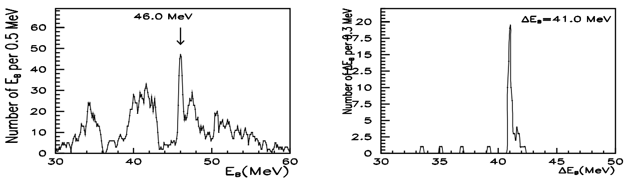

Fig. 12. ΔE_B-distributions in N = 50 − 82 and Z = 82 nuclei differing by ^{6}He-cluster (marked 10Δ = 45ε_o and 40ε_o).

Table 2. Representation of parameters of tuning effect in nuclear data and particle masses by expression (n × $16m_e(\alpha/2\pi)^x)\times m$. Masses M_Z and m_μ (left) and the masses and energy intervals forming the ratio $\alpha/2\pi$ are displayed one under another [5,12,15]. ΔE_B and asterisks mark stable nuclear intervals in binding energies and excitations.

x	m	n = 1	n = 13	n = 16	n = 17	n = 18
−1	1		M_Z = 91.2	M_H = 115		
GeV	3			$\boxed{2m_t = 348}$		
0	1	$16m_e$	$m_\mu + m_e$		$m_\pi - m_e$	$(m_\Delta$-$m_N)/2$
MeV	1	δ	106 = ΔE_B	130 = ΔE_B	140 = ΔE_B	147 = ΔE_B
	3			$m_\omega/2$	$\boxed{420 = M'_q}$	441 = M_q
1	1	9.48*	123*	152*	161*	170*
keV	3		368*	455*	481*	$\boxed{511 = m_e}$
	8	76*	984	1212	1293 = D_o	

$m_\omega/6$ = 130.3 MeV, m_π = 139.6 MeV and a half of nucleon Δ-excitation. It means that particle masses and resulting effects in cluster dynamics have common SM-QCD-origin. In table 2 discussed stable ΔE_B are given together with particle masses and smaller intervals in nuclear excitations with the help of the dimensionless factor $\alpha/2\pi = 1.159 \cdot 10^{-3} \approx 1/(32 \cdot 27)$ considered in [12]. Boxed in Table are three-fold values of 170 keV = $1/3m_e$ = 511 keV/3, m_s = 140 MeV = m_π and M_H = 116 GeV = $2/3m_t$ which form a ratio $1.12 \cdot 10^{-3}$ – QED-radiative correction $\alpha_Z/2\pi = 1.12 \cdot 10^{-3}$ with the parameter α_Z=1/129 for short distance $1/M_Z$ [12,23].

5 Conclusions

The observed discreteness in ΔE_B is similar to the tuning effect in particle masses [2,5,7,12] where masses of muon, pion, nucleon and its Δ-excitation were represented as integers n = 13, 17, 6 × 17 + 13 and 36 of $\delta = 16m_e$ = 8.176 MeV.

Nuclear microscopic models based on QCD as important Standard Model component are needed for description of tunning effects in nuclear data and particle masses. Combining suggestions by S. Devons and Y. Nambu [1,14] one can get fundamental information from tuning effects.

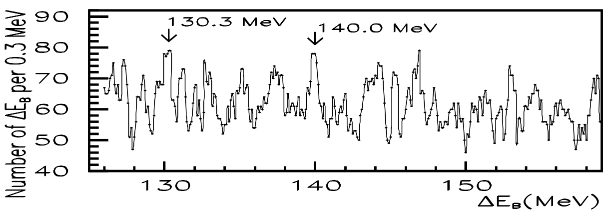

Fig. 13. ΔE_B-distribution in all Z ≤ 26 nuclei; arrows mark maxima at 130.4 MeV = 16δ-ε_o/2 and 140.0 MeV = 17δ + ε_o.

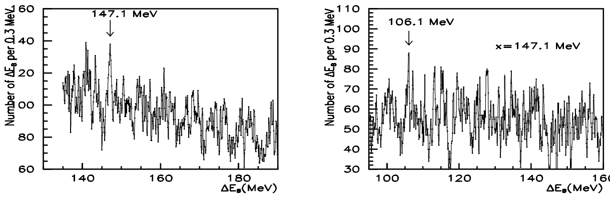

Fig. 14. ΔE_B-distributions in Z = 65-81 nuclei, x = 18δ (right).

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