

Fundamental information from nuclear data analysis

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Abstract.

The observation of a nuclear clustering effect and the stability of parameters of nucleon interactions permit a conclusion about the presence of the tuning effect in nuclear data similar to that in particle masses where integer relations between electromagnetic mass differences of leptons (SM parameters) and masses of nucleons, pions and other particles are found.

1. Introduction

During the Rutherford Jubilee Conference in 1961 it was suggested by S.Devons [1] that “it is a natural temptation to make comparison between the present stage in the study of nuclear structure with the exploration of atomic structure in Rutherford’s time ... Rutherford used the bold, direct approach, what one might designate as the “high-energy approach”... The more subtle “low-energy” investigations (the study of optical spectra) only became a fruitful means ... after Rutherford’s direct approach led to the Bohr theory. Since the nucleons ...are far from simple entities, one may suspect that there are still to be discovered subtle features of complex nuclei which reflect underlying properties of nucleons, and which may even prove difficult to observe in direct study of the elementary particles themselves”. In this contribution, we show that the analysis of accurately measured nuclear excitations and binding energies supports Devon’s suggestion about the presence of a fundamental aspect in nucleon interactions.

Recent understanding of nucleon structure is based on the Standard Model (SM) where the scalar field (Higgs boson with estimated mass $M_H \approx 115$ GeV [2,3] or the measured $M_H = 126$ GeV [4]) is responsible for quark-lepton masses and the masses of vector fields (M_Z, M_W). Light quarks (together with the electron) belong to the lightest SM-family and QCD describes the strong interaction between quarks and the resultant nucleon interactions. Gluon quark-dressing effects [5-7] produce constituent masses out of small initial quark masses of several MeV. Three constituent masses (M_q) combine to form baryon mass and two constituent quark masses (M_q'') form masses of the vector mesons (m_ρ, m_ω). The pion and ρ -meson are important for understanding nucleon structure and their interactions. The pion is a QCD Goldstone mode [6] and the pion exchange between constituent quarks [8] gives the nucleon Δ -excitation ($m_{\Delta^0} - m_n = 294$ MeV = $2\Delta M_\Delta = 2 \times 147$ MeV) corresponding to the spin-flip of quarks.

Pion-exchange dynamics are responsible for the nucleon interaction at long distances (tensor forces) and recent analysis of these dynamics by T.Otsuka [9] explained the systematic trend in excitation energies of single-particle states in Sb-isotopes . Otsuka also predicted regions of the nuclear chart where pion-exchange dynamics might produce a similar effect: i.e. where tensor forces are acting between nucleons with the different orbital motions $j = s + l$ and $j = s - l$. This contribution discusses such effects in nuclear excitation and binding energies.

2. Tuning effect in nuclear excitations

Table 1 shows the above-mentioned linear trend in the excitation energy (E^*) of the $J^\pi=5/2^+$ level in odd-mass, near-magic $^{123-133}\text{Sb}$. Excitations of even-N Sb isotopes ($N=72-82$) reflect the interaction of the valence proton ($1g_{7/2}$) with the number ($n=(N-70)/2$) of neutron pairs in the $1h_{11/2}$ subshell. The excitation energies are observed to be very close to multiples of ~ 161 keV as shown in the bottom line of the table where n is as defined above and δm_N is the excitation energy of the $J^\pi=2^+$ level in ^{116}Sn . Fig. 1, top left shows the energy difference between all pairs of known excited states ($D=E_i^*-E_j^*$, where $i \neq j$) in the two neighbouring isotopes $^{122,124}\text{Sb}$. This distribution also shows a maximum at 160 keV. Stable intervals of $D=162$, 480-492, 642 and 1288 keV were also found in the near-magic nucleus ^{18}F [10] and the bottom figures in Fig. 1 show stable intervals of $D=648$ and 1293 keV (corresponding to $n=4$ and 8 in units 161 keV) in the D -distribution of two near-magic nuclei $^{97,98}\text{Pd}$ ($N=51,52$).

Table 1. Comparison of excitation energies E^* in $Z=51$ nuclei with $n \times (161 \text{ keV} = 1293 \text{ keV}/8)$ [10].

A_Z	^{133}Sb	^{131}Sb	^{129}Sb	^{127}Sb	^{125}Sb	^{123}Sb	^{125}Sb	^{119}Sb	^{113}Sb	^{116}Sn
N	82	80	78	76	74	72		62	64	
$n=(N-70)/2$	6	5	4	3	2	1				
$2J^\pi$	5^+	5^+	5^+	5^+	5^+	5^+	5^+	$3^+, 5^+$	1^+	1^+
$E^*, \text{ keV}$	962.0	798.4	645.2	491.2	332.1	160.3		644	644.0	644.8
$n \frac{\delta m_N}{8}$	969	808	646	484	323	161	646	646	646	1293

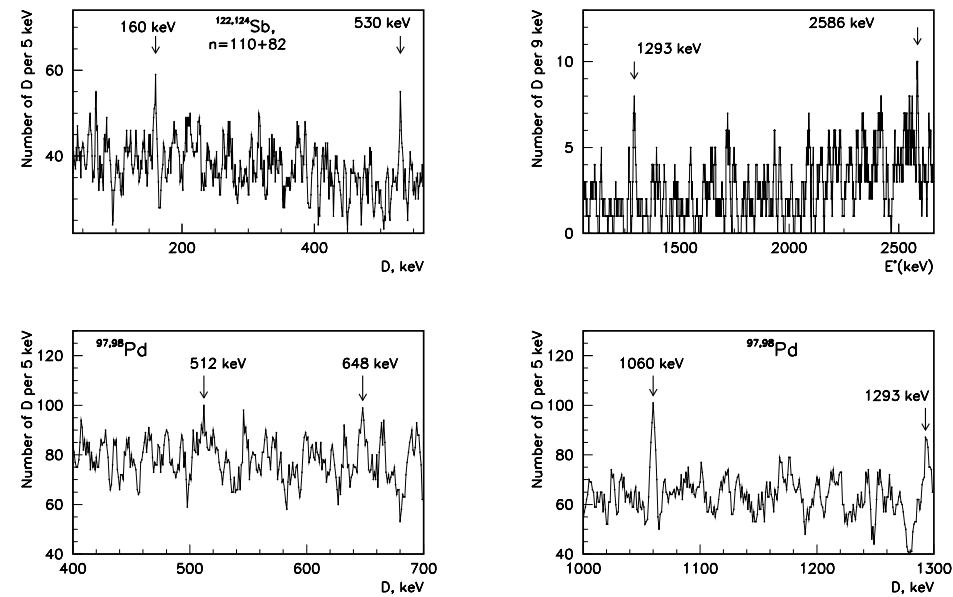


Figure 1. Top: D-distribution in $^{122,124}\text{Sb}$ (left) and in odd-Z $Z=19-29$ nuclei (right).
 Bottom: D-distribution in $^{97,98}\text{Pd}$ with maxima at $512 \text{ keV} = \varepsilon_o/2$ and $648-1293 \text{ keV} = \delta m_N$.

It was further suggested by T.Otsuka [9] that tensor-force effects could be observed in nuclei around calcium ($1d_{3/2}$ and $1f_{7/2}$ subshells) and table 2 shows that the excitation energy of the $J^\pi=3/2^+$ level in ^{41}K (a proton hole and two neutrons compared to ^{40}Ca) coincides with δm_N . The boxed numbers in the table show that in $N=21$ nuclei with one valence neutron, there is a linear trend in E^* with the parameter $\delta m_N/2=646 \text{ keV}=4 \times 161 \text{ keV}$ ($n=12,8,4$ in units 161 keV). Stable excitations in odd-Z nuclei with $Z=19-29$ are seen as maxima at 1293 keV and 2×1293 keV in the D -distribution shown in the top right of Fig.1.

Table 2. Linear trend in excitation energies (E^*) of $N=21$ nuclei.

A_Z	^{41}K	^{41}Ca	($Z=20$)	^{39}Ar	($Z=18$)	^{37}S	($Z=16$)	^{38}S	^{33}Mg	^{32}Si	^{53}Co
N	22	21		21		21		22	21		
E^*	1293.	0.0	[1942.8]	0.0	1267	0	646.2	1292	0.0	159	484
$2J^\pi$	3^+	7^-	7^-	3^-	7^-	3^-	3^-	2^+	(3^+)	(7^-)	(3^-)
$n\frac{\delta m_N}{8}$	1293		1941		1293		646	1293		161	483
n	8		12		8		4	8		1	3
										12	4

It was noticed by C.Detraz [11] that the universal character of 0^+-0^+ β -transitions in many nuclei means that “the nucleus is one specific case, the coldest and most symmetric one, of hadronic matter”. In the case of near-magic ^{10}B this 0^+ state is a member of the $\pi p_{3/2}\nu p_{3/2}$ multiplet. The distance $\varepsilon_o=E^*(0+)-E^*(1+)$ to the second 1^+ state (spin-flip effect) coincides with $2m_e$. Table 3 [10,12] shows that other excitation energies (E^*) in ^{10}B and some near-magic nuclei are rational to $\varepsilon_o=2m_e$. Intervals $n\times 161$ keV and ε_o appear frequently together. e.g D=324, 512 and 1022 keV in ^{55}Co (Fig.2 top), D=480, 511 and 1024 keV in $^{89,90}\text{Y}$ (Fig.2 bottom) and intervals D=962 and 1022 keV in ^{133}Sb were observed with a special Adjacent Interval Method [14].

Table 3. Comparison of excitation E^* (in keV) in light near-magic nuclei with multiples of the splitting $\varepsilon_o=2m_e$ corresponding to the spin-flip effect in ^{10}B [12].

A_Z	^{10}B	^{10}B	^{10}B	^{12}C	($T=2$)	^{16}O	^{18}Ne	^{18}Ne	^{18}Ne	^{38}Ar	^{55}Co	$3/2^-$
J^π	0^+1^+	2^-	3^-	0^+_1	0^+	3^-	0^+_1	0^+_2	2^+		D_{ij}	$5/2^-$
E^*	1021.8(2)	5110	6127	7654	27595	6130	3576	4590	5106	6137	1021	1022
$n(\varepsilon_o)$	5	6	$15/2$	27		6	$7/2$	$9/2$	5	6	1	1
$n \cdot \varepsilon_o$	1022.0	5110	6132	7665	27594	6132	3577	4599	5110	6132	1022	1022
Diff.	0.2(2)	0.3	3	11	1(2)	2	1(2)	9(8)	4(8)	5	1(2)	0(2)

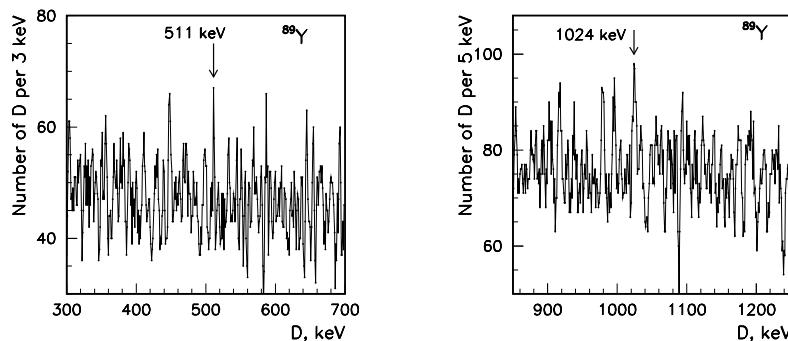
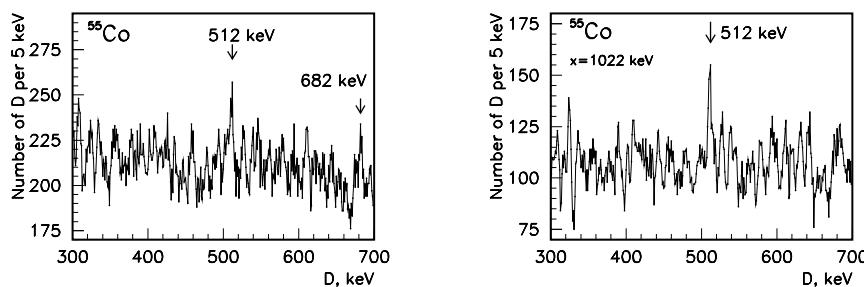


Figure 2. Top:
 D-distribution in ^{55}Co ;
 Adjacent level distribution
 for $D=1022$ keV (see [12]).
 Bottom: D-distribution
 in ^{89}Y with maxima
 at 511 keV $= \varepsilon_o/2$ and
 $1024(2)$ keV $= \varepsilon_o$ [10].

3. Tuning effect in nuclear binding energies

We note that the interval $8 \times 161 \text{ keV} = 1293 \text{ keV} = \delta m_N$ coincides with the nucleon mass splitting $\delta m_N = m_n - m_p = 1293.3 \text{ keV}$. This manifestation of nucleon mass splitting in the measured nuclear data is a direct confirmation of the suggestion by S.Devons of the influence of nucleon structure on observed nuclear data. The manifestation of the mass of the electron (which forms together with quarks a common SM-family) is an important result of nuclear data analysis. The first indication of this manifestation was obtained in [15,16] where the coincidence of the pion mass splitting δm_π with $9m_e = \Delta$ was noticed. The doubled value of the pion β -decay energy $\delta = 16m_e$ was used in analysis of nuclear binding energies and particle masses. The pion mass m_{π^\pm} , its parameter $f_\pi = 130.7(4) \text{ MeV}$ [3], the muon mass and above mentioned value $\Delta M_\Delta = 147 \text{ MeV}$ were found to be close to integer numbers of $\delta = 16m_e$ ($n = 17, 16, 13, 18$).

The stability of binding energies of light nuclei differing with $\Delta Z = \Delta N = 2$ (α) noticed by F.Everling was checked and the clustering effect in 4α was found (Fig.3 left). The interval $\Delta E_B = 147.1 \text{ MeV}$ [13] coinciding with 18δ (Fig.3 right) was found in heavy nuclei differing by $\Delta Z = 8$, $\Delta N = 14$ [17]. Simultaneously the grouping effect in values of ΔE_B in odd-odd nuclei at $3 \times 147 \text{ MeV} = 441 \text{ MeV}$ (Fig.3 centre) and of ΔE_B with the ^6He cluster (Fig.3 bottom) were observed. Long-range correlation with integer numbers of ε_o are shown in Table 4 [12].

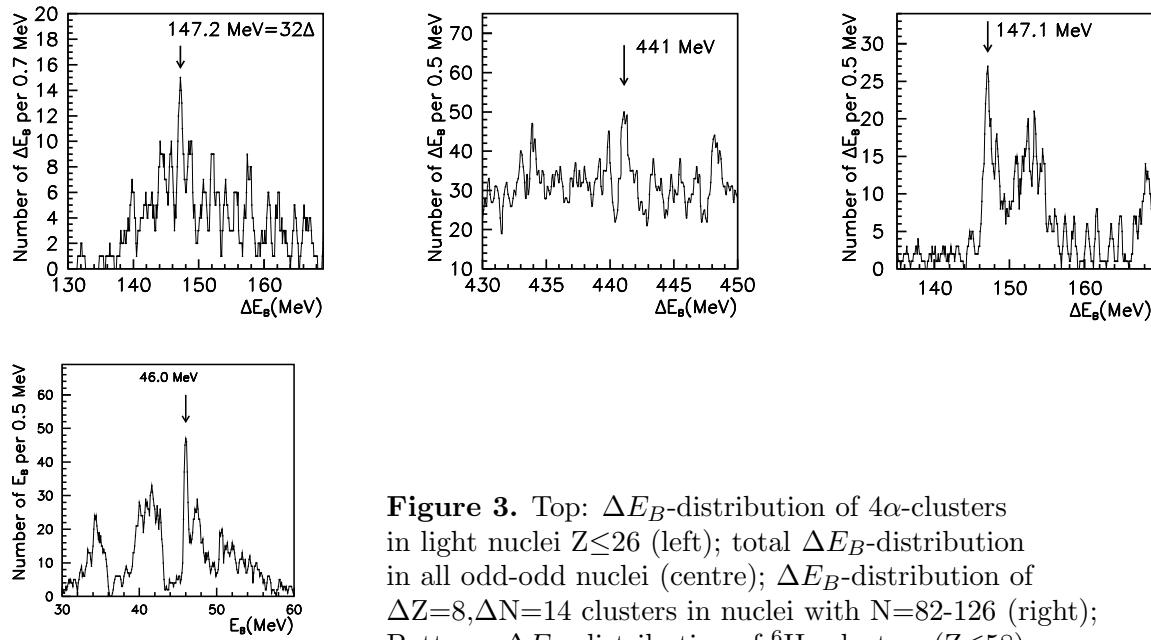


Figure 3. Top: ΔE_B -distribution of 4α -clusters in light nuclei $Z \leq 26$ (left); total ΔE_B -distribution in all odd-odd nuclei (centre); ΔE_B -distribution of $\Delta Z = 8, \Delta N = 14$ clusters in nuclei with $N = 82-126$ (right); Bottom: ΔE_B distribution of ^6He clusters ($Z \leq 58$).

Table 4. Comparison of experimental ΔE_B (in keV) in near-magic nuclei ($N=82$, $N=20$) with $10\Delta = 45\varepsilon_o = 45990 \text{ keV}$ (^6He - cluster) and $32\Delta = 18\delta = 144\varepsilon_o = 147168 \text{ keV}$ (4α -cluster, $\Delta = 9m_e$). Their theoretical estimates in the Finite Range Droplet Model (bottom line) do not show such correlation.

	$Z = 55$ ^{137}Cs	$Z = 57$ ^{135}La	^{137}La	^{139}La	$Z = 58$ ^{136}Ce	^{138}Ce	^{140}Ce	$Z=19$ ^{36}K	^{39}K
N	82	78	80	82	78	80	82	17	20
ΔE_B	45970	46018	45927	46024	46087	45997	45996	147160	147152
Diff.	-20	28	-63	34	97	7	6	-8(2)	-16
FRDM	46340	45950	46820	46970	45960	46850	47160	147450	145950

Stable excitations equal to $\varepsilon_o/6=170(2)$ keV= $m_e/3$ were noticed [12,13] in near-magic, odd-N $^{101,103}\text{Sn}$ while in the discussed Schiffer-Otsuka effect shown in Table 1, the interval 161 keV is observed. Such stable intervals were checked with the data for all existing nuclei [13,17]. Intervals (or periods) $D=161$ keV, 170 keV and 492 keV ($=2\times161$ keV+170 keV) were found in many nuclei. The Z-distribution of nuclei with such systematic effects was obtained [13,17] and maxima in the Z-regions $Z=50-51$ ($\nu h_{11/2}$) and $Z=72-78$ ($\pi h_{11/2}$) were found. A linear dependence of proton separation energies on N was also found. Parameters $\varepsilon_{p2n}=(2/3)\varepsilon_o$ and $\varepsilon_{2n2p}=(4/3)\varepsilon_o$ for $Z=51,78,84$ were derived [13,17].

Nonstatistical effects in neutron resonances of the same nuclei were considered. Maxima at $D=373-745-1501$ and 570 eV in the D-distribution of ^{124}Sb resonances were found to be close to the values of $D=572$ and 749-1495 eV in ^{105}Pd , ^{104}Rh , Th, ^{80}Br , Hf. The ratios between stable intervals in Sb isotopes 373 eV/323 keV= $1.15\cdot10^{-3}$ and 570 eV/490 keV= $1.16\cdot10^{-3}$ are close to $\alpha/2\pi$. One of the exactly measured small splittings in low-lying levels of near-magic nuclei is the interval $D=1.078$ keV between levels at $E^*=1022.394$ and 1021.326 keV in ^{82}Br (E^* close to ε_o). The relative value of this splitting 1.08 keV/1022 keV= $1.06\cdot10^{-3}$ is close to $\alpha/2\pi=1.159\cdot10^{-3}$.

4. Tuning effect in particle masses

It was suggested [16,19] that the QED parameter $\alpha/2\pi=1.159\cdot10^{-3}$ can be used for the comparison of effects of different scales. We start with the coincidence of the QED radiative correction with the ratio between well-known SM parameters: muon mass and Z-boson mass $m_\mu/M_Z=1.159\cdot10^{-3}$ [10,14]. The electron mass is included in such a comparison due to the results obtained with nuclear data and the results of the correlation analysis of particle masses performed in [20] (period of $3m_e$). In Table 5, the relation between particle masses and periods $3m_e$ and $\delta=16m_e$ are shown [12]. The coincidence of the lepton ratio $m_\mu/m_e \approx 13 \cdot 16 \cdot 1$ with the ratios between boson and constituent quarks masses M_Z/M_q , M_W/M_q'' was considered [14].

Boxed in Table 5 and 6 are relations between accurately measured masses of the proton, the nucleon mass difference and the electron mass (from the ratio m_p/m_e). The shift of the neutron mass relative to the integer number of $\delta=16m_e$ ($115\delta - m_e$) is determined with the accuracy of 0.1 keV and is $-161.6=(1/8)\delta m_N$ (the ratio $8\cdot1.0003(2)$ between δm_N and the shift).

The relations between particle masses and nuclear mass/energy intervals [12-14, 16-18] are presented in Table 6. The ratio 3:2:1 between the top quark mass, the estimated value M_H [2,3] and the unconfirmed mass-grouping effect in the L-3 LEP experiment at 58 GeV is included in the upper part. Values which are related as $\alpha/2\pi$ are put in the same vertical column, boxed values $m_\pi - m_e$ and $m_e/3$ are interconnected with the factor $\alpha_Z/2\pi$ for the short distance $1/M_Z$. Confirmation of the recently measured [4] $M_H=126$ GeV= $(\alpha/2\pi)^2 \cdot m_e/3$ could be essential.

Table 5. Comparison of particle masses [3] with periods $3m_e$ and $16m_e=\delta=8176.0$ MeV (N periods), the neutron Δ° -excitation is compared with $2\Delta E_B$; asterisks mark the values considered in [12,20].

Particle	m_i , MeV	$m_i/3m_e$	$N \cdot 16m_e$	N	$N-16m_e$	Comments
μ	105.658367(4)	68.92*	106.2878	13	-0.6294	-0.511-0.118
π^o	134.9766(6)	88.05*	138.9917	17	-4.0174	
π^\pm	139.5702(4)	91.04*		17	+0.57624	+0.511+0.065
p	938.2720(1)	612.05*	940.2380(1)	115	-1.96660	$-m_e-(9/8)\delta m_N$
n	939.5654(1)	612.89*		115	-0.6726(1)	$-m_e-(1/8)\delta m_N$
Σ°	1192.64(2)	777.98	1193.693	146	-1.05(2)	-0.51·2=-1.02
Ξ°	1314.86(20)	857.71	1316.333	161	-1.47(20)	-0.51·3=-1.53
ρ	775.49(34)	505.87	784.8943	96	-9.40(34)	$-9.20 = -2\Delta$
$\Delta^\circ-n$	294.2(2)	191.9	294.3	36		$2\Delta E_B=294.4$

Table 6. Presentation of parameters of tuning effects in particle masses and nuclear binding energies ΔE_B ($X = -1, 0, 1$ in the first column) and in nuclear data ($X = 1, 2$) by the common expression $n \cdot 16m_e(\alpha/2\pi)^X M$ with the QED radiative correction $\alpha/2\pi$, where $\alpha=137^{-1}$. Values $m_\pi - m_e$, $m_e/3$ and the neutron mass shift $N\delta - m_n - m_e$ (all boxed) are related with the parameters $\alpha_Z=129^{-1}$ and $\alpha=137^{-1}$. Stable intervals in excitations (E^* , D_{ij} , $X=1$) and in neutron resonances ($X=2$) are considered as indirect confirmation of intervals and relations in particle masses ($X=-1$) including the mass grouping in the TEVATRON experiment at $\Delta^\circ=4$ GeV. The Higgs boson estimate $M_H=115$ GeV [2,3] and the experimental mass 126 GeV are preliminary.

X	M	n = 1	n = 13	n = 16	n = 17	n = 18
-1	3/2			$m_t=171.2$		
GeV	1	$2\Delta^\circ - 2M_q$	$M_Z=91.2$	$M_H=115$		$M_H=126$
0	1	$16m_e = \delta$	$m_\mu = 105.7$	$(f_\pi=131)$	$m_\pi - m_e$	$m_\Delta - m_n/2 = 147$
MeV	1	$2\Delta - \varepsilon_o$	$106 = \Delta E_B$	$130 = \Delta E_B$	$140 = \Delta E_B$	$147.2 = \Delta E_B$
	3			$M''_q = m_\rho/2$		$M_q = 441 = \Delta E_B$
1	1				$N\delta - m_n - m_e =$	
keV					$= 161.6(1)$	$170 = m_e/3$
	1	9.5	123	152	$161 ({}^{18}\text{F}, \text{Sb})$	$512 (\text{Co}, \text{Pd})$
	4		492		$648 ({}^{97,98}\text{Pd})$	$682(\text{Co})$
	8		984	1212	$1293 (\text{Pd}), \Sigma E^*$	$1360 (\text{Te})$
2	1	11	143	176	$187, 749 ({}^{79}\text{Br})$	D in neutron
eV	4	44	570 (Sb)		$1500 (\text{Sb}, \text{Pd}, \text{Rh})$	resonances

5. Conclusions

It was suggested by Y.Nambu [21] that empirical mass relations can be used for SM development. The universal role of QCD effects responsible for masses of constituent quarks is in agreement with S.Devons suggestion about a fundamental aspect of nuclear data analysis. Performed analysis shows the importance of the pion-exchange dynamics and the QED radiative correction. Tuning effects and relations with scalar masses would be used for SM development.

- [1] Devons S 1961 *Proc. Int. Rutherford Jubilee Conf.*, Manchester (Heywood) 611
- [2] Ellis J 2011 *The infamous boson*: <http://indico2.lal.in2p3.fr/indico/conferenceDisplay.py?confId=1507>
- [3] Particle Data group 2006 *J. Phys. G* **33** 1, Igo-Kemenes P 388, Suzuki M 535.
- [4] Wielers M 2011 *ATLAS Results and Plans*: <https://cgc.physics.miami.edu/Miami2011/Wielers.ppt>
- [5] Bhagwat M S *et al* 2007 *Phys. Rev. C* **76** 045203
- [6] Roberts H L L *et al* 2011 *Phys. Rev. C* **83** 065206
- [7] Landoldt-Boernstein New Series 2009 **vol. I/22A** ed. Schopper H (Springer)
- [8] Glozman L 1990 *Nucl. Phys. A* **629** 121c
- [9] Otsuka T, Suzuki T, Utsuno Y 2008 *Nucl. Phys. A* **805** 127c
- [10] Landoldt-Boernstein New Series 2012 **vol. I/25A** ed. Schopper H (Springer)
- [11] Detraz C 1995 *Nucl. Phys. A* **583** 3.
- [12] Sukhoruchkin S I, Sukhoruchkin D S 2011 *Int. J. Mod. Phys. E* **20** 906
- [13] Sukhoruchkin S I 2011 *Proc. Hadron2011* Muenich, 2011, eConf C110613
- [14] Sukhoruchkin S I 2008 *Int. Rev. Phys. (IREPHY)* **2** 239
- [15] Sukhoruchkin S I 1968 *Proc. 2nd Conf. Neutr. Cross Section*, Washington DC **Vol.2** 923
- [16] Sukhoruchkin S I 1972 *Stat. Properties of Nuclei* ed. Garg G (Plenum Press) 215
- [17] Sukhoruchkin S I *et al.* 2012 *Proc. Int. Sem. Interaction Neutrons with Nuclei ISINN-19* Dubna (JINR publ)
- [18] Sukhoruchkin S I 2007 *Nucl. Phys. A* **782** 37c
- [19] Belokurov V V, Shirkov D V 1991 *The Theory of Particle Interactions* AIP, New York
- [20] Frosch R 1991 *Nuovo Cim.* **104** 913
- [21] Nambu Y 1998 *Nucl. Phys. A* **629** 3c