TUNING EFFECT IN NUCLEAR/NEUTRON DATA II

Sukhoruchkin S. I., Soroko Z. N., Sukhoruchkin D. S.

Petersburg Nuclear Physics Institute 188300 Gatchina

INTRODUCTION

This work is the third part in the series of publications devoted to the analysis of nonstatistical effects in spacing of excited states in nuclei with Z=17-21. In previous parts of the work [1] it was found out that in nuclei situated at $1d2s$ shell an enhancement of tensor force effects exists at the border between $1d_{5/2}$ and $1d_{3/2}$ subshells. Nucleons in these subshells have different spin-orbit orientations j=l+s (>) and j=l-s (<) with a favorable condition for tensor-force action between nucleons in the case (>,<) considered by T.Otsuka and discussed in [2]. We start with D-distributions for ^{41}Ar – nucleus with two proton holes/three neutrons over the core ^{40}Ca. Later we consider $^{39-41}$K: neutron resonance data for ^{40}K are important for the analysis.

In Table 1 discussed earlier three exactly rational to each other excitations in nuclei with N=21,22 are marked with doubled boxes. Within 2-3 keV they coincide with parts of nucleon charge splitting δm_N=1293.3 keV ($1/2\delta m_N$=647 keV, δm_N, $3/2\delta m_N$=1940 keV). First excitation in ^{39}Ar (N=21, marked with asterisk) deviates from δm_N only with 26 keV.

Simultaneously in three neighbour nuclei there is exact equidistancy (ratio 2:1, boxed) between low-lying excitations $2E^*(2^+)=E^*(4^+)$. Such "stabilizing effect of nuclear shell" was noticed earlier in separation energies of near-magic nuclei (at Z,N=82 and Z=N=20).

Table 1. Comparison of E^* (keV) in $^{36-42}$S, $^{38-44}$Ar, $^{40-46}$Ca, $^{42-48}$Ti with parameter δm_N.

^{36}S	N=20		^{38}Ar			^{40}Ca			^{42}Ti		1.72
0^+	0^+	0^+	0^+	2^+	2^+	0^+	0^+	2^+	0^+	2^+	4^+
0.0	3291	3346	0.0	2168	3936	0.0	3526	3904	0.0	1555	2677
^{37}S	N=21		^{39}Ar			^{41}Ca			^{43}Ti		
7^-	3^-	3^+	7^-	3^-	5^-	7^-	3^-	3^-	7^-	3^+	
0.0	646.2	1398	0.0	1267*	2093	0.0	1943	2462	0.0	313	475
^{38}S	N=22	2.19	^{40}Ar		1.98	^{42}Ca			^{44}Ti		2.27
0^+	2^+	4^+	0^+	2^+	4^+	0^+	2^+	4^+	0^+	2^+	4^+
0.0	1292	2826	0.0	1461	2893	0.0	1525	2752	0.0	1083	2454
^{39}S	N=23		^{41}Ar			^{43}Ca			^{45}Ti		
7^-			7^-	5^-	3^-	7^-	5^-	3^-	7^-	3^-	5^-
0.0	1469		0.0	167.3	516	0.0	373	593	0.0	36.5	39.4
^{40}S	N=24	2.12	^{42}Ar		1.998	^{44}Ca		1.97	^{46}Ti		2.26
0^+	2^+	4^+	0^+	2^+	3.4^+	0^+	2^+	4^+	0^+	2^+	4^+
0.0	904	1916	0.0	1208	2414	0.0	1157	2283	0.0	889	2010
^{41}S	N=25		^{43}Ar			^{45}Ca			^{47}Ti		
7^-			5^-	3^-		7^-	5^-	3^-	5^-	7^-	$1,3^-$
0.0	449	904	0.0	201	762	0.0	174	1435	0.0	159	1251
^{42}S	N=26	3.09	^{44}Ar		2.37	^{46}Ca		1.91	^{48}Ti		2.33
0^+	2^+	4^+	0^+	2^+	4^+	0^+	2^+	4^+	0^+	0^+	4^+
0.0	895	2694	0.0	1158	2746	0.0	1346	2575	0.0	983	2296

ANALYSIS OF DATA FOR ^{41}Ar

Excitations in ^{41}Ar and maxima in its D-distribution are given in Table 2. The region D=0-700 keV for two different averaging intervals ΔE=5 keV and 3 keV (top parts of Fig.1) contain maximum at 516 keV coinciding with E^*=516 keV (boxed in Table). Such correlation exists at other excitations: for example, in adjacent interval D^{AIM}-distribution for D=x forming maximum at D=x=4098 keV (bottom part if Fig.1) there are maxima at 2700, 3330, 4156 keV (boxed in Table 1) close to real excitations (stable multiplets).

Table 2 Comparison of E^* (keV) in ^{41}Ar with stable intervals in Spacing (Fig.1 boxed).

$2J^\pi$	7^-	5^-	3^-	3^+	3^-	(9^-)	(11^-)	1^+			1^-
$E^*(^{41}\mathrm{Ar})$	0.0	167.3	516.0	1034.7	1636	1505	1630	1870	1988	2321	2398
D			516	1033				1871	1988		
$2J^\pi$		$1^-,3^-$	3^-	$(9)^+$	3^-	3^-		$1^-,3^-$	1^-	$(1)^-$	1^-
	2568	2701	2733	2891	2949	3010	3122	3293	3327	3388	3433
D	2562	2703					3128		3329		
$2J^\pi$	7^-			3^-					(1^-)		
	3485	3565	3577	3590	3601	3698	3734	3775	3799	3847	3900
D	3470						3734				3906
$2J^\pi$	1^-		3^-	3^-			3^-	$1^-,3^-$			3^-
	3968	4108	4124	4154	4163	4251	4271	4295	4370	4395	4404
D		4098		4156		4254					

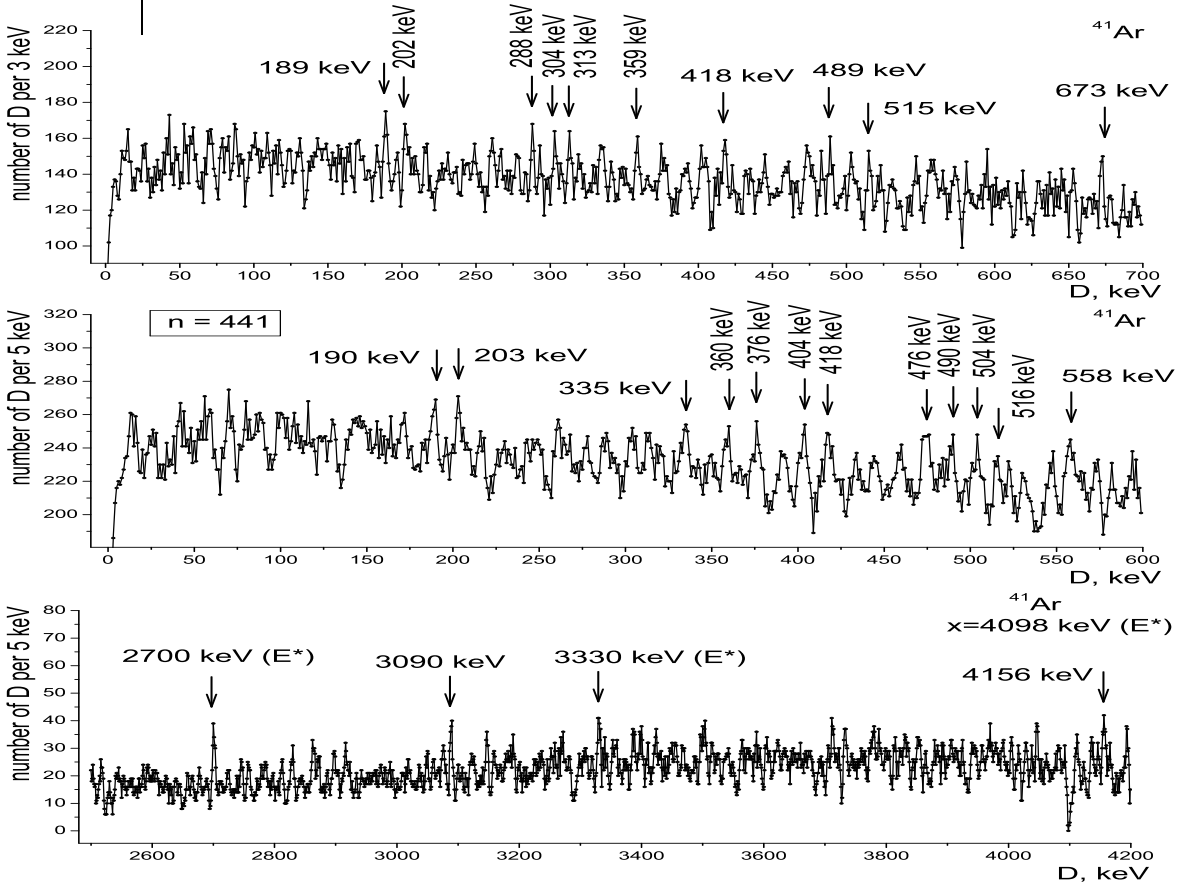

Fig. 1. D-distribution in ^{41}Ar with averaging intervals ΔE=5 keV, 3 keV (top, center). Maximum at 515 keV coincides with E^*. *Bottom:* D^{AIM}-distribution for x=4098 keV.

All other regions of spacing distribution in ^{41}Ar levels are presented in Fig.2. In the high-energy part of the distribution (two bottom sections) the above mentioned effect of the stability of the real excitations can be clearly noticed (six values are boxed in figures). At low excitations (2-nd section of Fig.2) one can notice an exact 2:1 ratio between stable intervals 1284 keV and 644 keV which are close to the above mentioned system of excitation (rational to δm_N) observed in neighbour N=21,22 nuclei (^{41}Ca etc.). Additional conformation of the reality of intervals D=644 keV=$8\Delta^{TF}$=$\delta m_M/2$ was obtained within Adjacent Interval Method of Data Analysis applied to the interval which is equal to the first excitation E^*=167 keV (Fig.3 top).

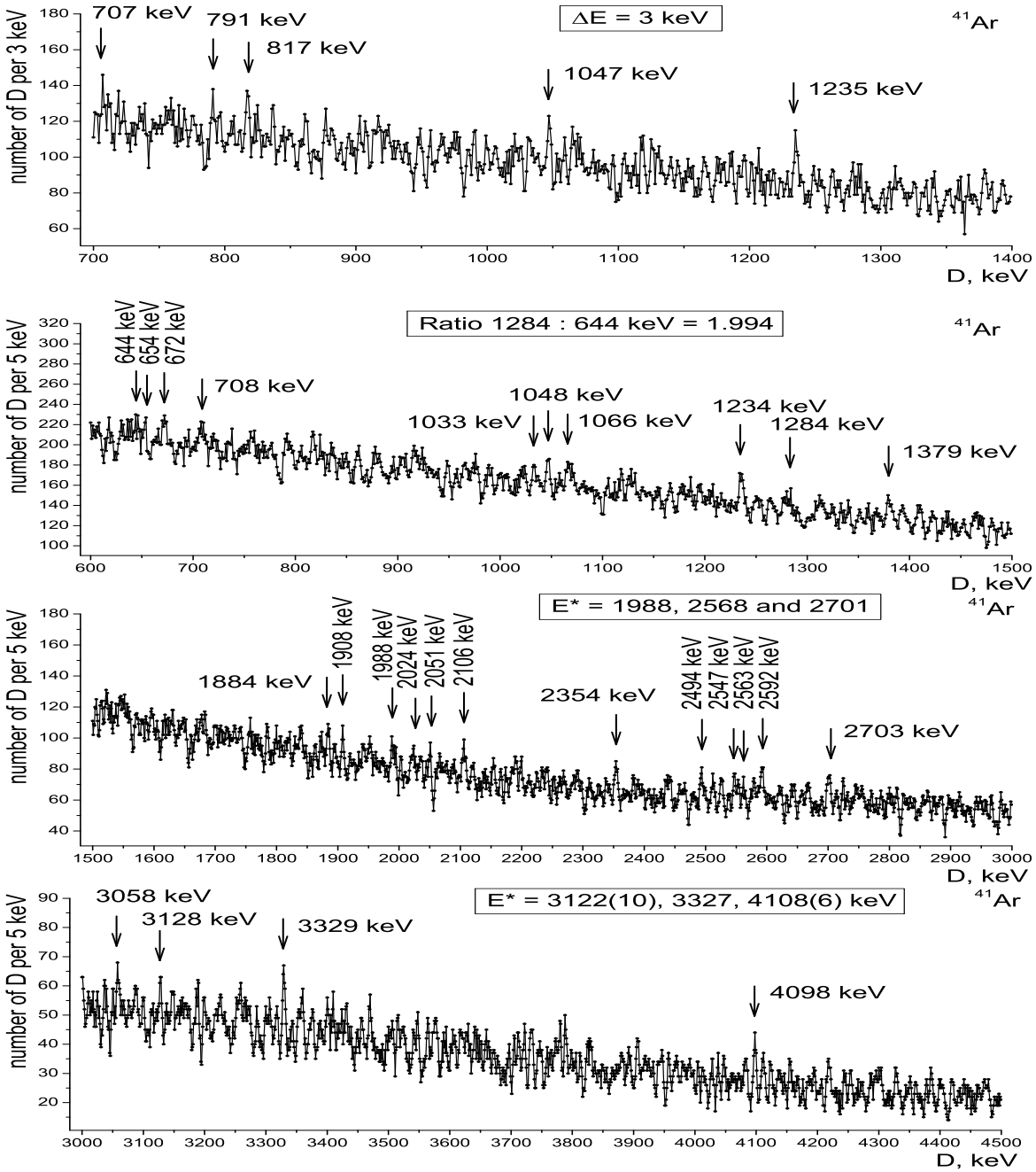

Fig. 2 Spacing distribution in ^{41}Ar for energy region 700 - 4500 keV with averaging intervals ΔE=3 keV (top) and ΔE=5 keV. Boxed are stable intervals discussed in the text.

Adjacent interval distributions D^{AIM} for intervals x=167 keV (Table 2 left) have a maximum at 80 keV=Δ^{TF} besides the interval D=644 keV=$4\Delta^{TF}$ (see top left part of Fig.3). Relation between these intervals (ratio 1:8) is seen naturally also in D^{AIM}-distribution for x=80 keV (2-nd top in Fig 3). Adjacent interval distributions for large x=644 keV and x=1284 keV (Fig.3 two bottom sections) contain also interval D=490 keV which is frequently noticed in spacing distribution of neighbour light nuclei (^{18}F, ^{20}F etc.). This interval was noticed recently by M.Ohkubo in spectrum of ^{41}Ca neutron resonances. Value D=492 keV could be considered as a sum of $2\Delta^{TF}$=$m_N/4$=322 keV and 170 keV=$\varepsilon_o/6$=$m_e/3$. Its doubled value 1986 keV was known as a stable phonon excitation in ^{33}D and its four-fold value coincides with the strongest grouping effect at 3936 keV in sum E^*-distribution of all light nuclei).

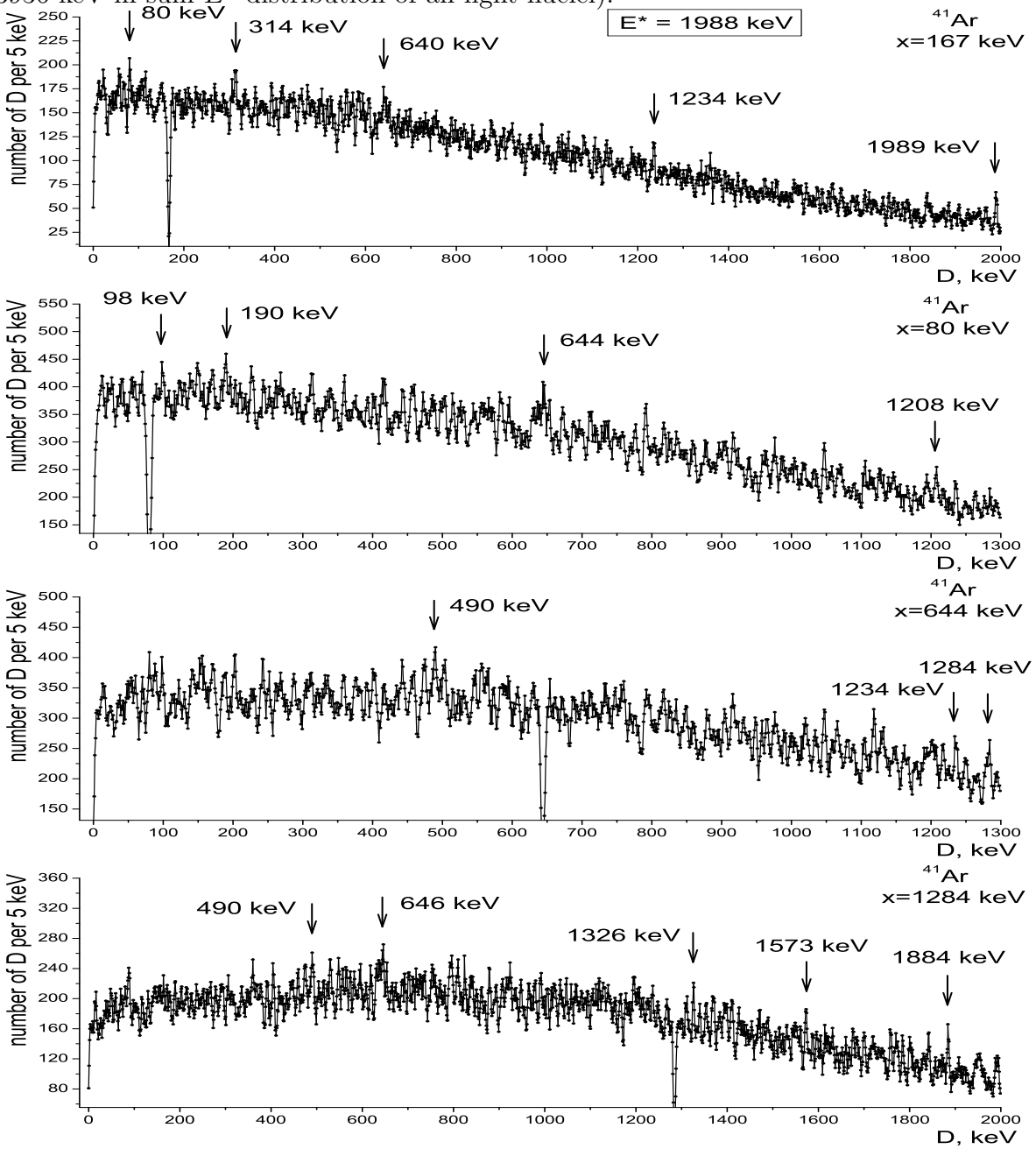

Fig. 3 Adjacent interval distributions in ^{41}Ar for x=176, 80, 644 and 1284 keV. Averaging interval ΔE=5 keV. Marked are stable intervals discussed in the text.

Adjacent interval distributions D^{AIM} for stable intervals D=516 keV coinciding with the second excitation in ^{41}Ar (Table 2, Fig. 1) contains maximum at doubled energy (corresponding distribution for x=1033 keV, Fig.4 center, do not show maximum at 516 keV). Ratio between 2-nd/3-rd excitations (1034.7 keV/516.0 keV=2.005) and between stable intervals (1032/516 keV=2.00) corresponds stable character of excitations close to ε_o.

Stable intervals D=516 keV and D=672 keV close to $\varepsilon_o/2$ and $(2/3)\varepsilon_o$) are forming triplets with intervals D=646 keV and D=1292 keV=δm_N marked with arrows in Fig.4.

Observed in ^{41}Ar long-range correlations with relatively large intervals about 3 MeV are represented with maxima in Fig.5. Interconnection between intervals 674 keV – 3329 keV=E^* (top) and 3329 keV – 3734 keV=E^* (center) could be considered as an indication of the reality of very stable phonon-like excitation. Inclusion in these systems of stable excitation values close to integers of δm_N and ε_o is the main result of the analysis.

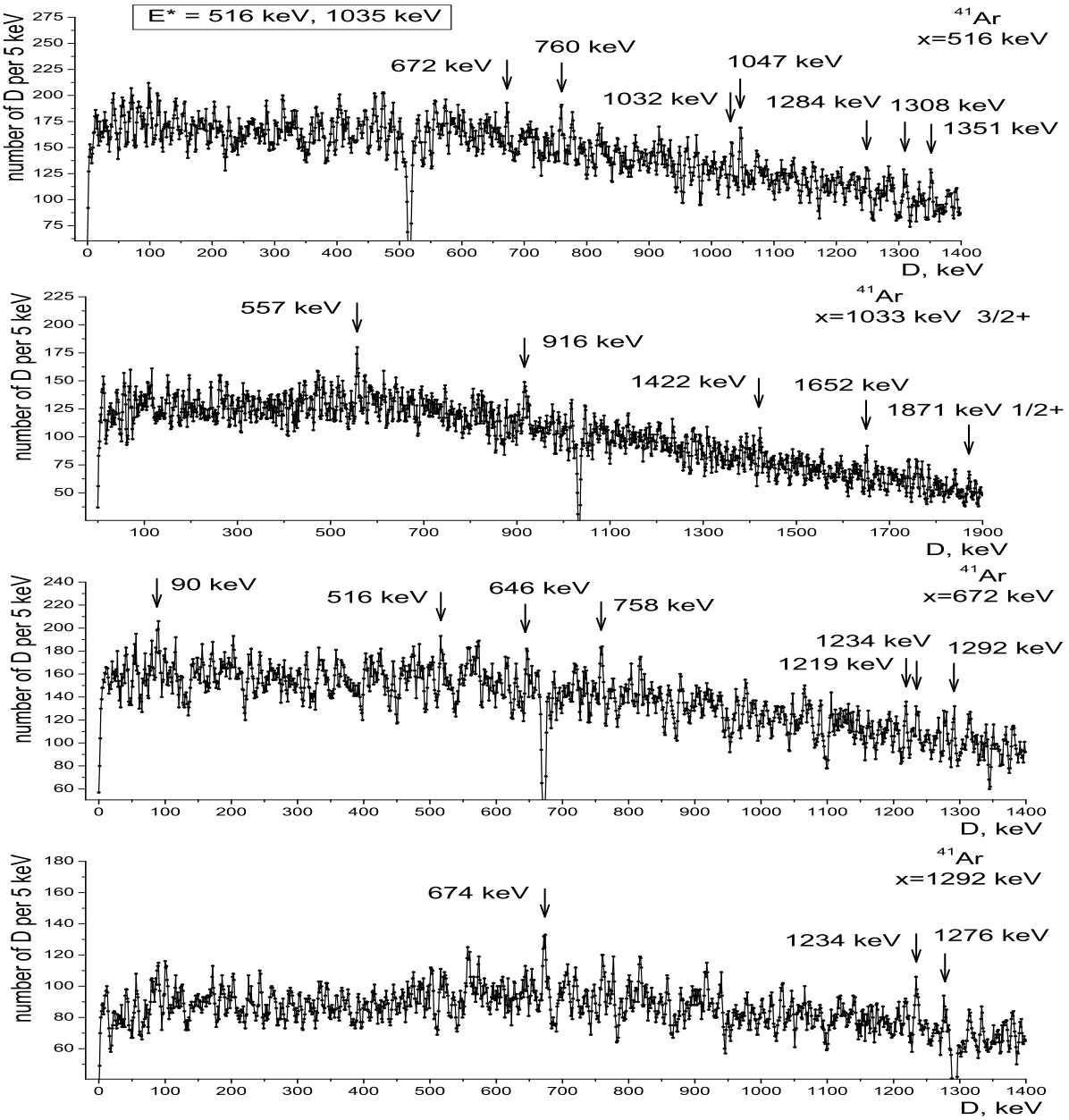

Fig. 4 Adjacent interval distributions in ^{41}Ar for x=516, 1033, 672 and 1292 keV. Averaging interval ΔE=5 keV. Marked are stable intervals discussed in the text.

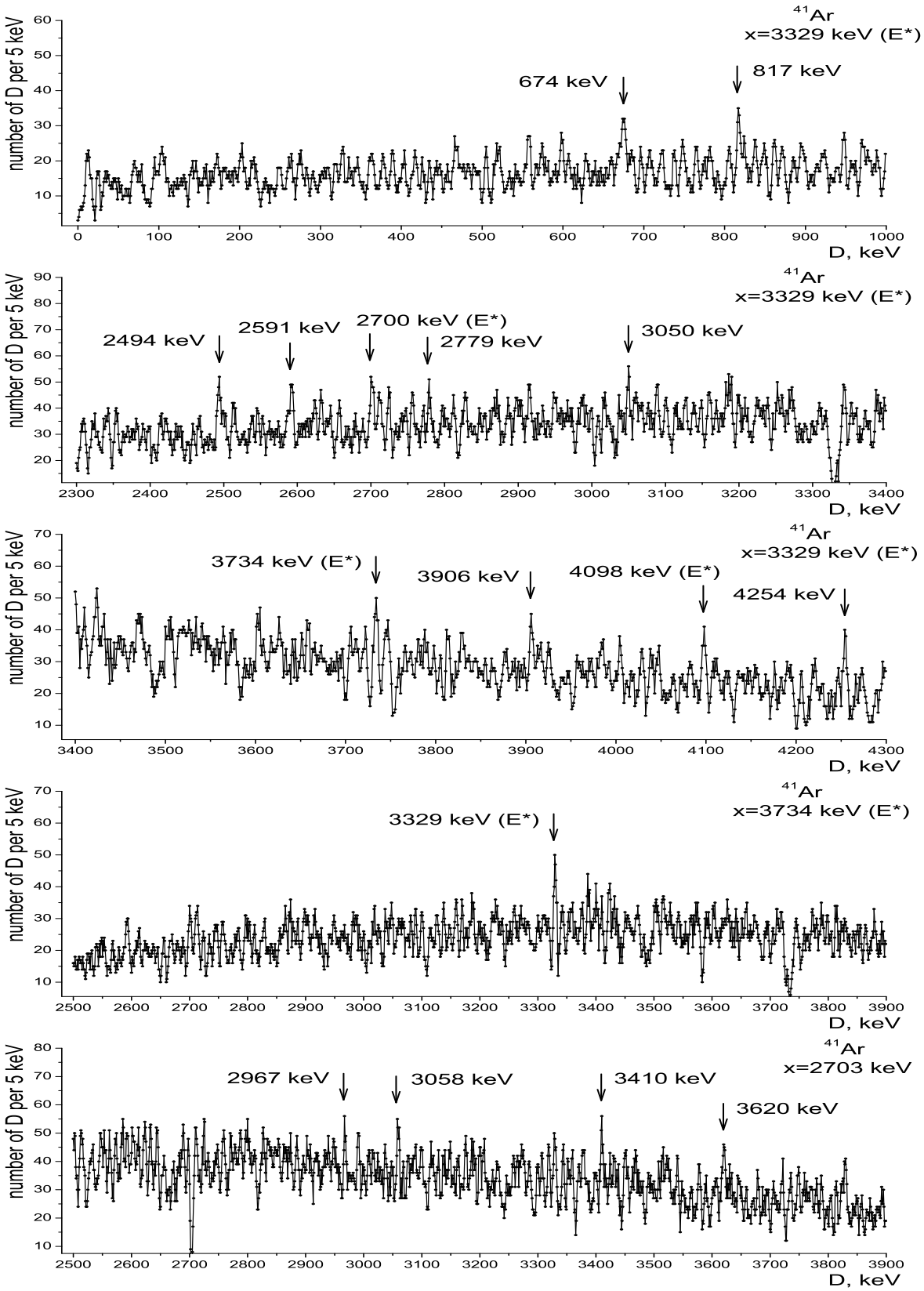

Fig. 5 Adjacent interval distributions in ^{41}Ar for x=3329 keV. Averaging interval ΔE=5 keV. Marked are stable intervals discussed in the text.

ANALYSIS OF SPACING DISTRIBUTIONS IN $^{39-42}$K

Stable interval observed in spacing distributions of near-magic $^{39-42}K$ (Z=20-1) are presented in Fig.6-10. Correspondence between them and excitations is shown in Table 3.

Table 3 Comparison of excitations E^* (keV) in $^{39-42}$K with maxima in D-distributions and parameters δm_N=1293 keV, 3936 keV=8×492 keV and ε_o=1022 keV.

No		1	2	3	4	5	6	7	8	9	10
J^π	3^+	1^+	7^-	3^-	9^-	5^-	3^+	11^-	3^-	1^+	7^-
$E^*(^{39}\mathrm{K})$	0.0	2523	2814	3019	3598	3883	3940	3944	4082	4095	4126
D, E^*							3936	3945	$4\varepsilon_o$		
J^π	4^-	3^-	2^-	5^-	0^+	2^+	2^-	3^-		1^-	3^+
$E^*(^{40}\mathrm{K})$	0.0	29.8	800	891	1644	1959	2047	2070	2076	2104	2260
D							$2\varepsilon_o$				
$2J^\pi$	3^+	1^+	7^-	3^+	3^-	1^+	7^+	5^+	5^+	3^-	5^-
$E^*(^{41}\mathrm{K})$	0.0	980	1294	1560	1582	1593	1577	1698	2144	2167	2317
D			δm_N								
$2J^\pi$	2^-	3^-	4^-	3^-	(2,3)	5^-	2^-	3^-	3^+	4^+	3^-
$E^*(^{42}\mathrm{K})$	0.0	107	258	639	682	699	784	842	1111	1144	1198
D					$(2/3)\varepsilon_o$						

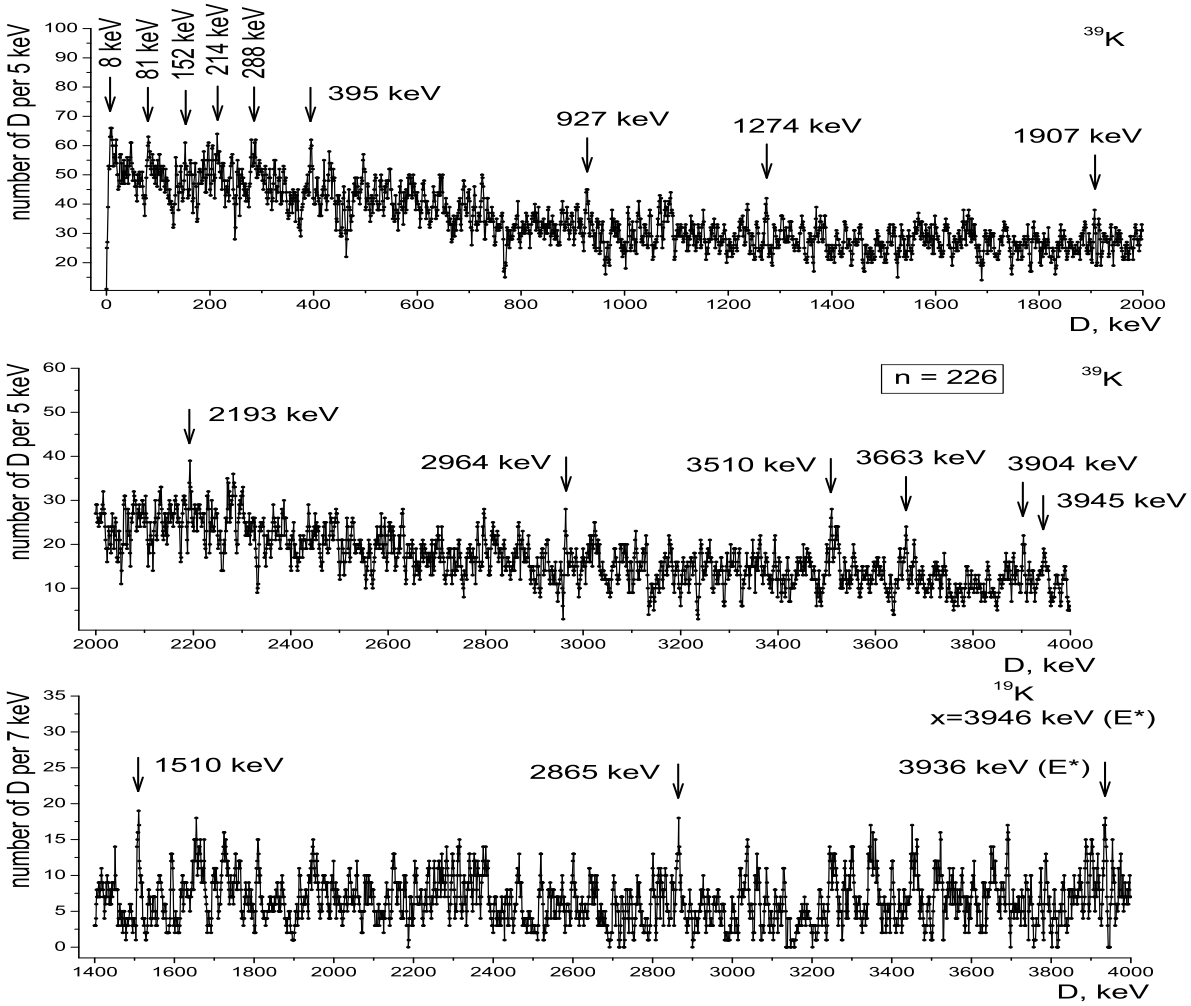

Fig. 6 D-distribution in ^{39}K and adjacent interval distribution for x=3946 keV (ΔE=7 keV). Intervals D=E^*=3936=4×493 keV and D=3945‘keV=E^*=3944 keV are forming doublets.

Excited states of near-magic ^{40}K (one proton hole amd one valence neutron over ^{40}Ca-core) are well known from neutron spectroscopy with ^{39}K target. Discrete maxima in spacing distribution shown in Fig.7 (top left) belong to multiplets with D=242-340-370 keV (top right), D=253-340 keV (2-nd line left, ratio 3:4), D=241-339 keV (right) and D=340-368-985 keV (36-39-8×13) (two bottom lines of Fig.7). Rational 1:3 ratio in positions D=10-28 keV of maxima at the left part of Fig.7 (center, x=368 keV) allows representation of most part of stable intervals as multiple values of a single period of fine structure 28 keV/3=δ'=9.5 keV. Such systematic periodic structures in neutron resonance spacing was known in many light and near-magic isotopes).

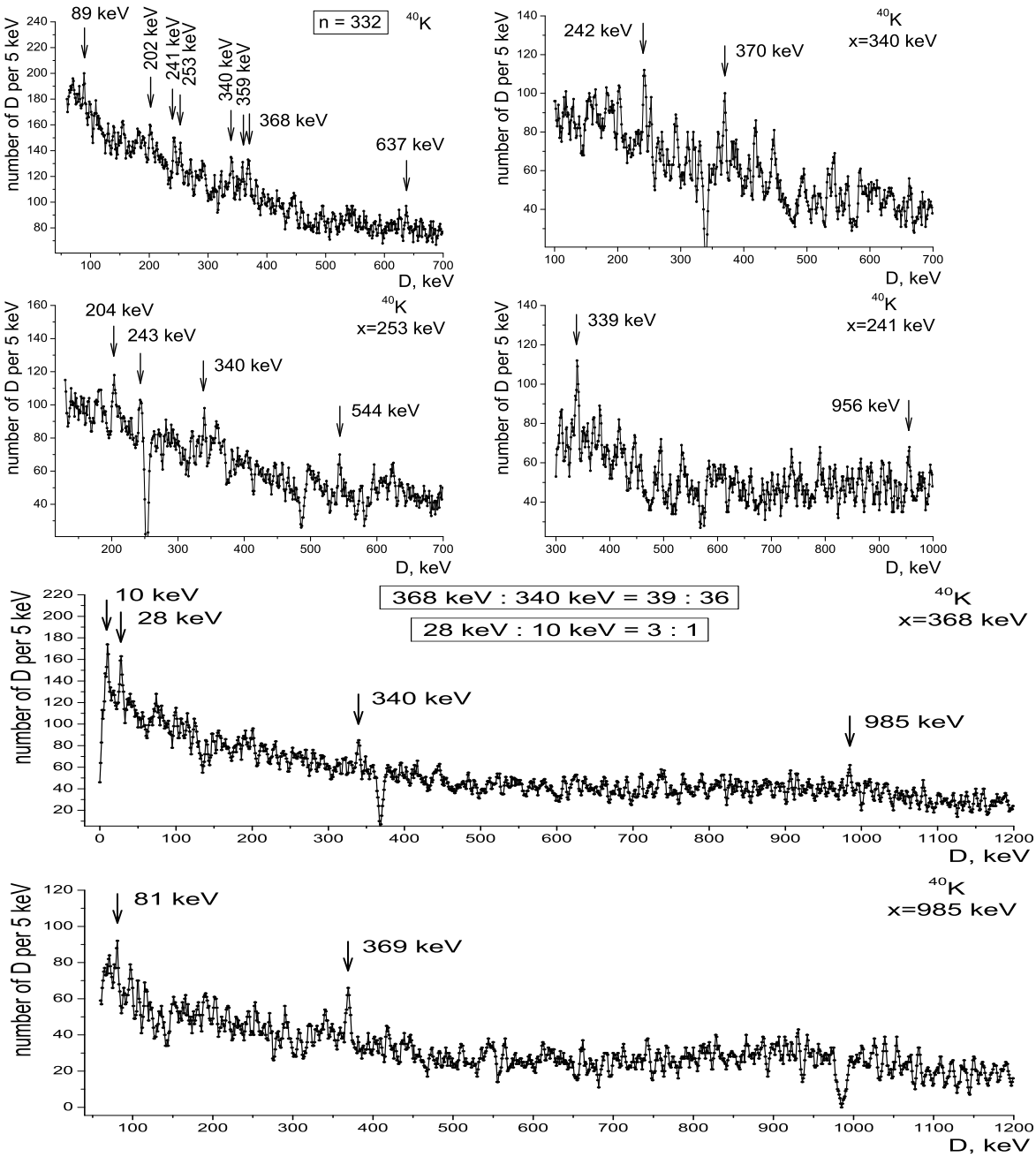

Fig. 7 Spacing distribution in ^{40}K and D^{AIM}-distributions for x=340, 253, 2412, 368, 985 keV.

Similar discreteness with small interval D=86 keV=$9\delta'$ and 683 keV=8·85 keV=$(3/2)\varepsilon_o$ is observed in spacing distribution of levels in ^{41}K (Fig.8 top). Adjacent interval distributions for x=86 keV, 331 keV, 681 keV and 4081 keV=$4\varepsilon_o$ are shown in center part of Fig.8 together with some of rational relation between values of stable intervals. As it was noticed earlier in spectra of lighter nuclei (^{33}S and some other) and in ^{133}Sb, there exists a correlation between the primary interval x of the AIM method of data analysis and the resulted D^{AIM}-distribution. Such example is given in Fig.8 (bottom). Here, with x=738 keV=2×368 keV=2×$39\delta'$ one observes an equidistance (2:4 in units of ε_o). Observed maxima at 681 keV-592 kV (8:7) and 738 keV-493 keV (3:2) in D^{AIM}-distributions shown in Fig.8 (2-nd line) correspond to the same intervals taking part in above mentioned long-range correlation (due to unexpectedly stable character of real excitations in near-magic nuclei).

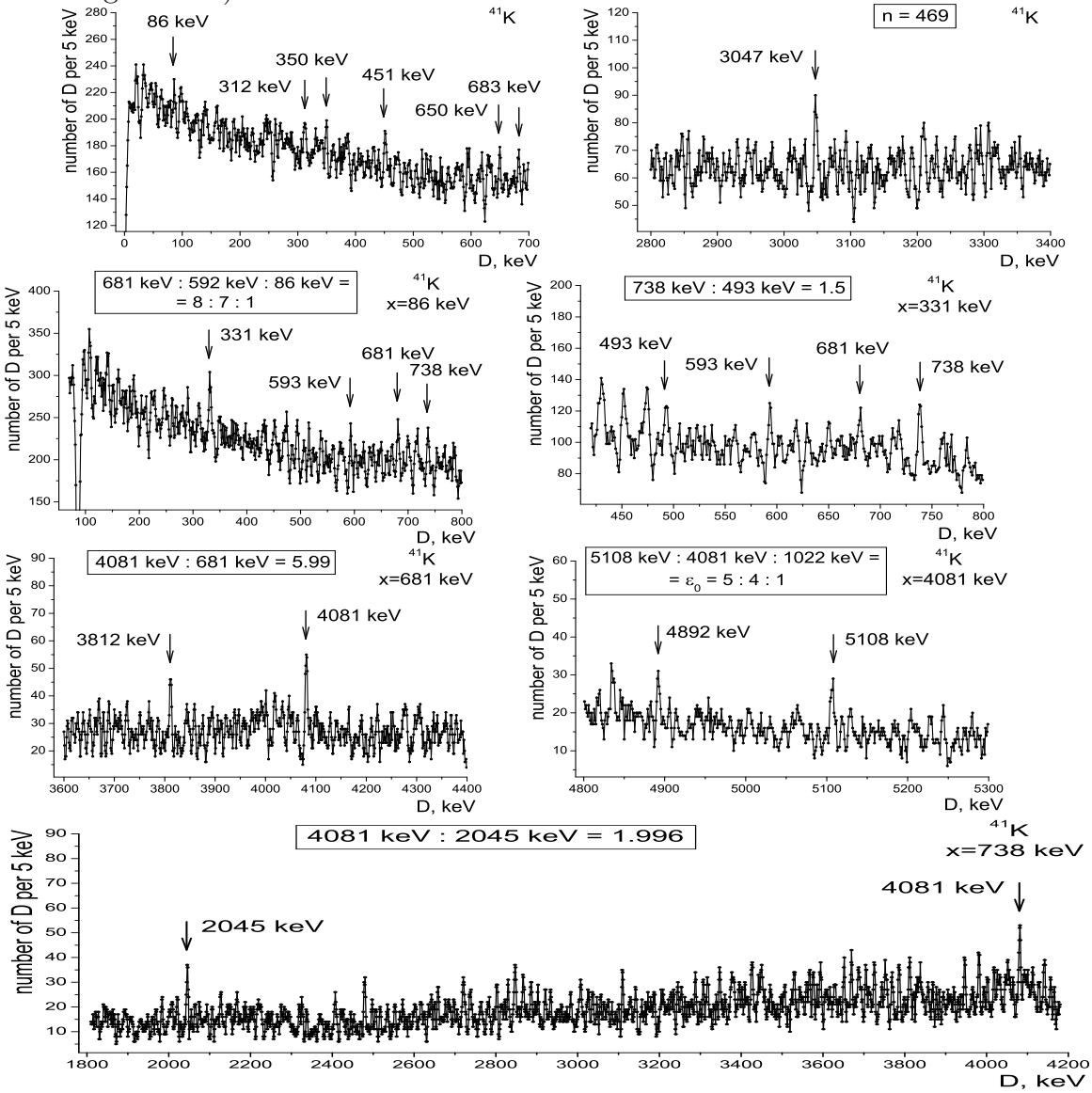

Fig. 8 D-distribution in ^{41}K (top). D^{AIM}-distributions for x=86 keV, 331 keV, 681 keV and 4081 keV (center). D^{AIM}-distribution in ^{41}K for x=738 keV with integer (2:4) relations in stable interval values.

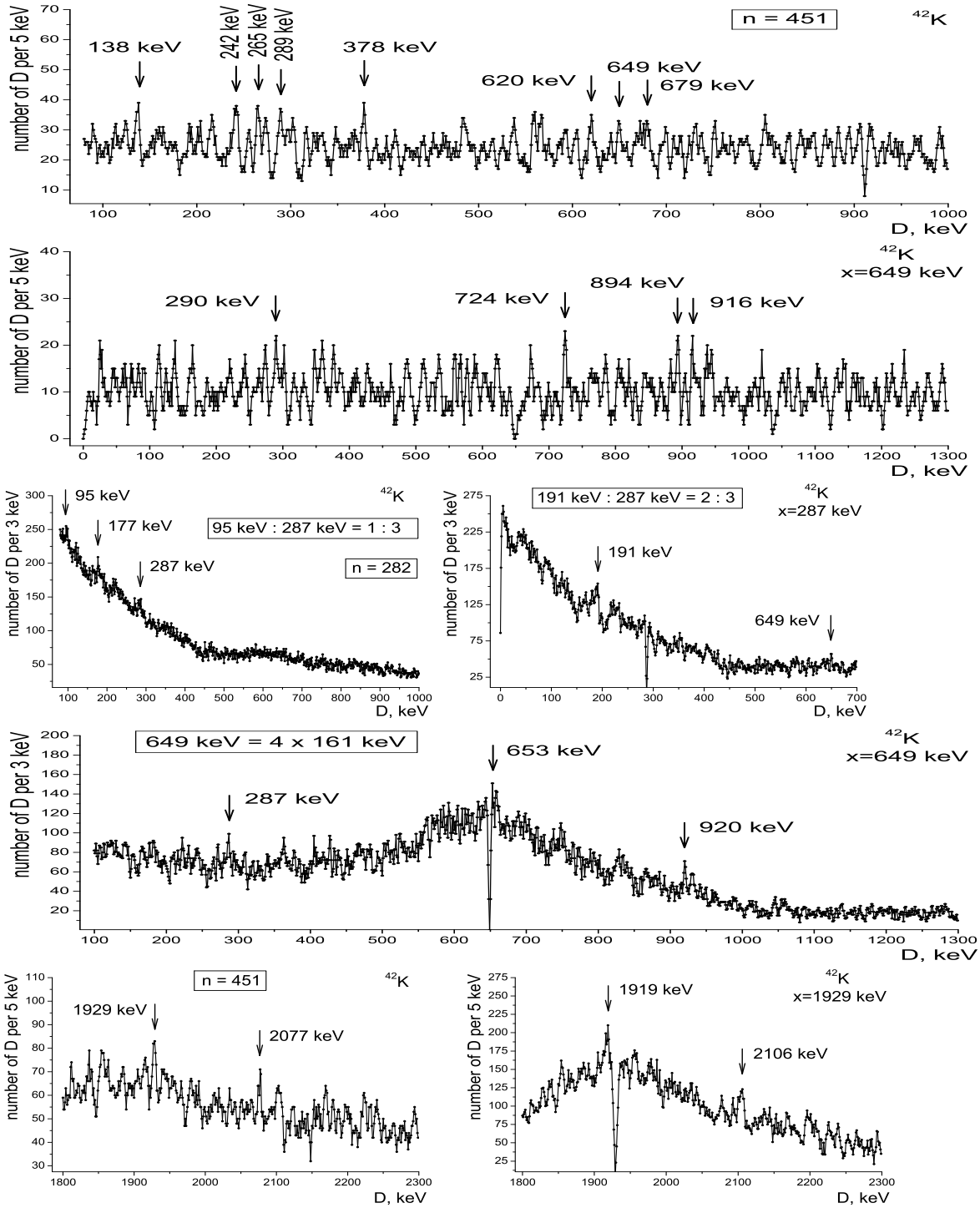

Fig. 9 D-distribution in ^{41}K (top) and ^{42}K (bottom). D^{AIM}-distributions in ^{41}K for x=86,331, 681,4081 and 738 keV (center), D^{AIM}-distributions in ^{42}K for x=1929 keV (bottom right). Spacing distribution in ^{42}K and D^{AIM}-distribution for x=1929 keV (top right).

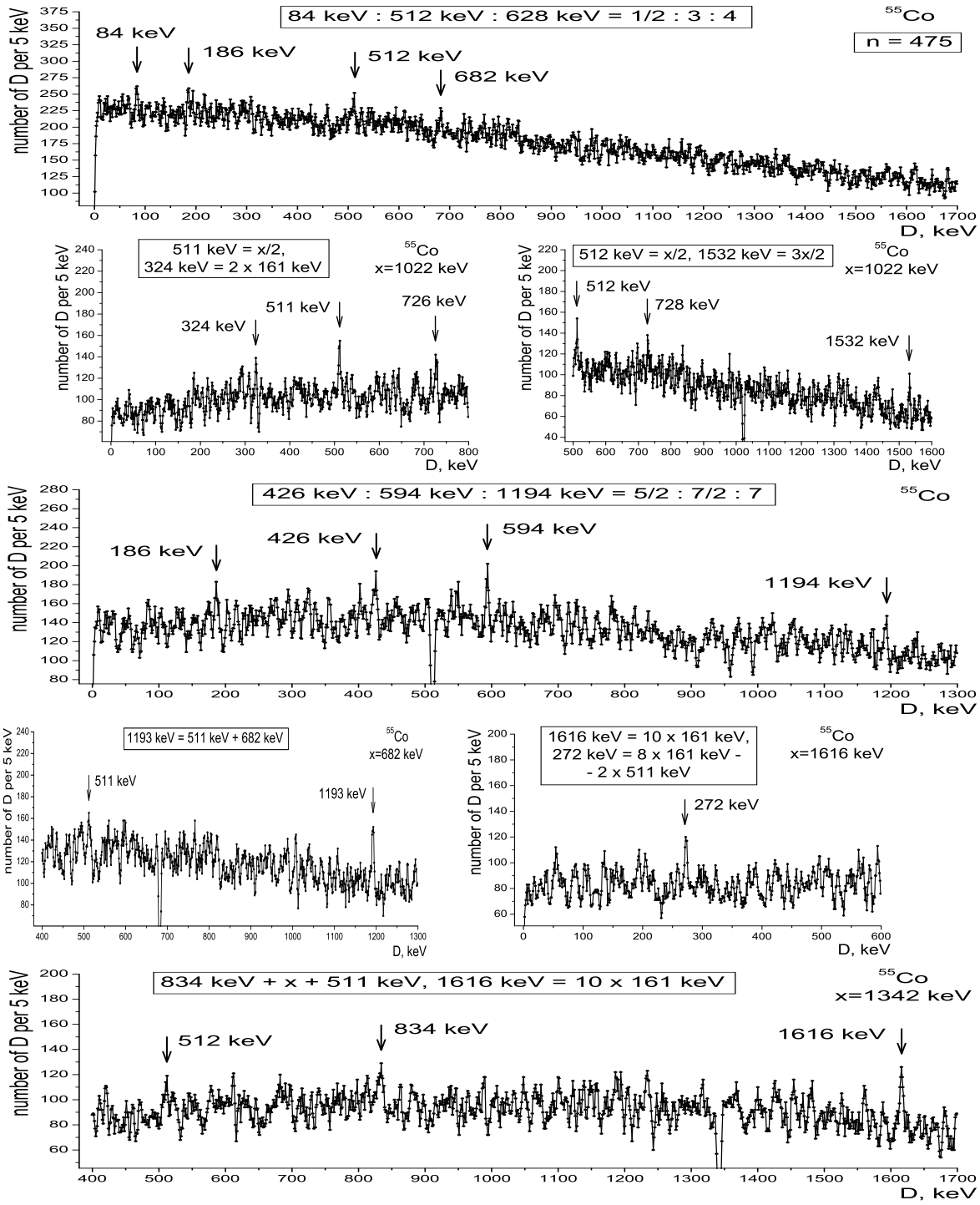

Fig. 10 D-distribution in ^{41}K (top) and ^{42}K (bottom). D^{AIM}-distributions in ^{41}K for x=86,331, 681,4081 and 738 keV, D^{AIM}-distributions in ^{42}K for x=1929 keV).

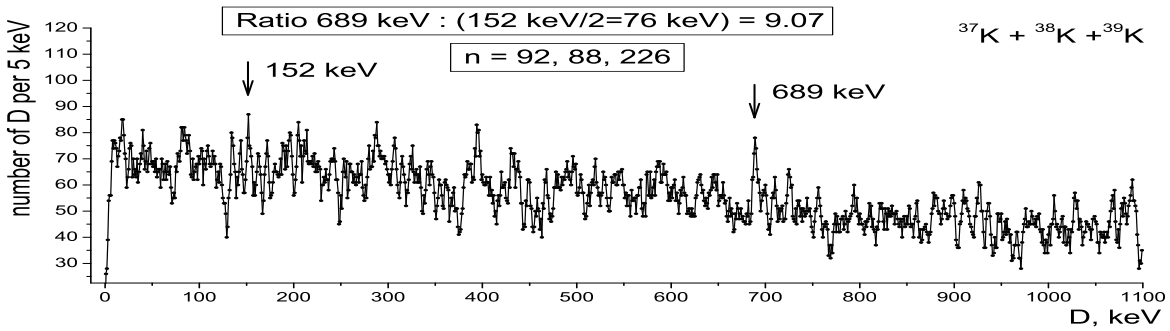

Fig. 11 Spacing distribution in ^{42}K and D^{AIM}-distribution for x=1929 keV (top right). Sum of spacing distributions in ^{37,38,39}K with the maximum close to 683 keV=(2/3)ε_o.

Levels observed as neutron resonances are part of the common total spectrum of excited states of the given nucleus. In case of the ^{42}K we can check the consistency of the results obtained in the independent analysis – of highly-excited and low-lying states: there are 282 resonances and 169 low-lying levels in ^{42}K. Spacing distribution for resonances (Fig.9 top) has maxima at 95 keV, 177 keV=95+82 keV and 287 keV=3×95 keV. Fixed intervals D=x=287 keV are forming triplets with D^{AIM}=191 keV=2×95 keV and D^{AIM}=649 keV close to 4×161 keV=4Δ^{TF} (Fig.9 2-nd line left). By fixating D=x=649 keV one obtains maxima at D^{AIM}=287 keV and D^{AIM}=920 keV (Fig.9 2-nd line right). Spacing distribution in low-lying levels contains many maxima including D=289 keV and 649 keV (Fig.9 last but one) with tripltes x=649 keV and D^{AIM}=290 keV – D^{AIM}=916 keV (Fig.9 bottom). Similar maxima (287-290, 920-916 keV) in both D^{AIM}-distributions for x=649 keV (in low-lying spacing and neutron resonances) show a possibility to use combined spectroscopic data during the study "tuning effect" in nuclear excitations.

ANALYSIS OF SPACING IN EXCITATION OF COBALT ISOTOPES

In the spacing distribution of ^{41}K (Fig.8) we have found the long-range correlation with the parameter ε_o=1022 keV equal to twice the lepton mass splitting m_e and six-fold value of the tensor-force parameter 170 keV determined from first excitations in near-magic ^{101,103}Sn. Similar long-range correlations with the same parameters $n \cdot \varepsilon_o$ and $m \cdot \delta m_N$ were noticed earlier in the nucleus ^{55}Co with the similar proton one-hole configuration Z=27=28-1 as compared with Z=19=20-1 in K isotopes. Correlations with intervals 512-682-1022-1532 keV (Fig.9 top) and 324 keV=2·δm_N/8 (with x=1022 keV, second line) permits a conclusion about systematic character of "tuning effect" in nuclear excitation. It is supported with stable character of parameters of the residual nucleon interaction ε_{NN} and $\varepsilon_{2N,2N}$ at different shells considered earlier.

REFERENCES

1. S.I. Sukhoruchkin *et al.*, Proc. ISINN-22, Dubna 2014, JINR E3-2015-13, pp. 265-301.
2. Landolt-Boernstein New Series, vols. I/25A,B. Springer, 2012; vols. I/25C,D,E, 2013.