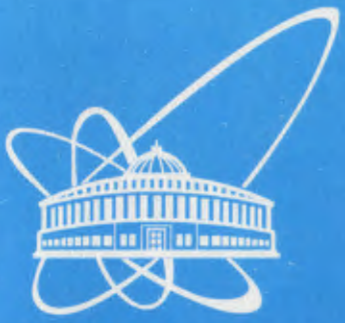

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RESONANCE CAPTURE GAMMA-RAY SPECTROMETRY AT LEAD SLOWING-DOWN NEUTRON SPECTROMETER

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1. Introduction

Since 1955 , when the first Lead Slowing-down Neutron Spectrometer (LSNS) was built [1] , a number of similar devices have been constructed in the world [2 - 8]. All of them were used for neutron cross section measurements of resonance radiative capture or fission reactions. As far as we know , nobody has attempted to investigate the gamma-ray spectra from resonance neutron capture at LSNS facilities. There are some reasons that cause serious difficulties and obstacles in carrying out this investigation. In principle , it is impossible to get from the LSNS a collimated neutron beam on the investigated sample in order to avoid the irradiation of the gamma-ray spectrometer with neutrons , as it is possible in the time-of-flight method.

The neutron flux of intensity requested for the measurement is available only inside of the lead pile, where it is nearly isotropic. For reasonable effectiveness of the capture gamma-ray spectra registration the germanium detector has to be placed very close to the sample inside the pile channel. In this position it will be irradiated with the intensive neutron flux. The neutron radiative capture in the germanium of detector and in its construction materials will cause high background spectrum with numerous peaks that will lead to misidentification in analysis of gamma-ray spectrum from investigated sample. The background spectra illustrating response of germanium detectors to the irradiation with slow and fast neutrons have been investigated in [9] and [10]. The form of these spectra and shape of their peaks depend on the kind of neutron spectrum that irradiates the detector as well as on the type of detector , its construction and surroundings. It is obvious that the background spectrum consists of the prompt and delayed radiation. The former part comes from fast deexcitation of compound nuclei obtained after neutron capture, and the latter one from isomeric states and from photons accompanying beta decay of final nuclei.

In the present paper we propose and test a way of investigation the resonance neutron capture gamma-ray spectra at the LSNS . At some conditions it allows to avoid the considered

difficulty or at least to reduce it considerably. The idea of the method is based on the shielding of the active head of detector from neutrons with a "thick" investigated sample. The sample of proper thickness wrapped around the detector head will absorb neutrons with energies corresponding to sample resonance energies. In these regions of neutron energy that can be chosen by corresponding slowing-down time intervals the detector will register mainly the prompt photons from neutrons captured in the sample . So the ratio of effect to background is much improved. The test of the idea has been performed at the LSNS (which was described in [8]) with the high purity germanium detector and with tantalum sample.

Experiment

The basic features of the LSNS used in our experiment are listed below. It consists of the pulsing neutron generator using $T(d,n)^4He$ reaction and a 65 ton lead pile as a neutron moderator. Deuterons from the Penning pulsed ion source are accelerated up to 180 keV and directed on tritium target placed in the centre of the lead pile. The FWHM of fast neutron burst from tritium target is 3.3 μs. The neutrons are moderated in the lead pile of size : $1.8 \times 1.8 \times 2.1$ m^3. In the pile there are 5 channels: for tritium target chamber , for samples and detectors, and for the monitor of average neutron flux. The horizontal and vertical cross section throughout the centre of pile are shown in Fig. 1. The pile is shielded by 0.5 mm thick cadmium sheets placed 10 cm under its surface and additionally by external layers of polypropylen and boric acid mixture covered once again by additional cadmium sheets. The shielding prevents reentering the neutrons backscattered from surroudings into the pile again , and serves as radiation protection. The frequency of deuteron pulses on the tritium target can be regulated from 200 to 400 Hz. Starting pulses open time analyzers to run measurement cycles and start the pulses of ion source. The time averaged current on the tritium target is about 1 microamper. It

can provide the average neutron yield about 10^7 neutrons per second.

The measurements of time-dependent intensity of neutron radiative capture have been performed using a scintillation counter with CaF_2 scintillator. An example of the measurement result for tantalum sample is shown in Fig. 2.

The calibration of the LSNS has been obtained from measurements of resonance curves for several samples in neutron energy range from 4.28 eV up to 336 eV (Fig. 3). The relation between the average neutron energy and their slowing-down time for above energy region can be described with satisfactory accuracy by formula :

$$E = 177.4 * t^{-2} \ (\mu s^2 \ keV)$$

The neutron energy resolution of the LSNS is about 40 %.

Gamma-ray spectra from neutron radiative capture have been measured by means of the 80 cm^3 Reverse-Electrode Germanium (REGe) detector , with n-type contact on the inside , produced by Canberra. The advantages of this detector are :

i) the good radiation damage resistance for neutron flux,

ii) extremely thin outside ion-implanted contact (0.2 μm), and

iii) thin beryllium window on the front side of the detector head.

The first feature was very important in our experiment because the detector was irradiated by considerable neutron flux , in some cases even with admixture of fast neutrons. The producer informs that the REGe detector may be about 10 times more resistant than conventional Coaxial Ge-detector. The last advantage allows to measure the gamma-ray spectra down to about 5 keV.

The relative neutron density in the pile , needed for estimation of neutron flux , has been measured by helium-3 and boron proportional counters.

The pulses from detectors and counters have been analyzed and recorded by analyzers made in our laboratory. There was the possibility to do the time or pulse-height analysis separately as well as the combined analysis. In the later case the gamma-

ray spectra could be obtained in the chosen slowing-down time intervals (" time windows ") that correspond to neutron energy regions including the investigated neutron resonances.

To test the idea of the measurements of gamma - ray spectra from resonance neutron capture at the LSNS , one has to learn the germanium detector response on its irradiation with neutrons. The basic part of the response spectrum (RS) will come from photons and electrons emitted after neutron capture in germanium isotopes. In our detector the mass of natural germanium in detector is about 400 g.

A number of experimental works devoted to investigation of gamma - ray spectra from thermal and resonance neutron capture in natural germanium and in its separated isotopes have been performed earlier and , in addition to [9 , 10] , presented in [11 - 16]. Nevertheless , one should know the response of particular detector in definite conditions and surroudings. For this purpose , in our experiment the head of REGe detector was set into the 45 cm long horizontal channel at 35 cm inside (Fig. 1). The gamma - ray spectra from this detector were recorded for seven „ time windows " contained in neutron energy interval from 0.2 eV up to 7 keV. Some examples of these spectra are presented in Fig. 4.

In order to observe the effects caused by fast neutrons , the next experiment was carried out with Pu - Be neutron source (5×10^5 s^{-1}) placed inside the channel running across the pile (Fig. 1). The source and REGe detector were separated from each other only by 20 cm thick layer of lead , so a part of fast neutrons reached the detector , too. The obtained spectra are shown in Fig. 5. Some characteristic peaks originated by inelastic scattering of fast neutrons and broadened by recoil energy of nuclei can be observed.

After the neutron irradiation of detector the spectra from neutron induced long-lived radioactivity in detector were measured. They were helpful in the isotopic assignment of spectral peaks. The peaks of isomeric transitions from levels with short lifetime , but longer than period of neutron burst repetition , can be identified by comparison of their spectral intensity in various

time windows. The peak areas for them are proportional to the width of time window interval. As the next step in the testing procedure we chose the tantalum sample. The neutron resonances of tantalum are well known [17]. Gamma-ray spectra from slow neutron capture in this nuclide were investigated in a number of works , e.g. [18 - 22]. The detailed information on transitions from excited states of Ta - 182 compound nucleus can be found in [23].

The REGe head was wrapped in 0.1 mm thick tantalum foil. It was enveloped on its cylindrical side an shielded from the front side , where a thin Be window was installed. Only from dipstick side the head was not shielded by tantalum foil. In two lowest tantalum resonances at 4.28 and 10.36 eV the sample can be considered as thick target for neutrons.

The wrapped detector head was located inside the pile channel as in the previous case. In front of it at the end of the channel an additional tantalum sample in form of a plate of size 9 cm × 9 cm and 1 mm thick was placed.

The low energy gamma - ray spectra obtained with tantalum sample at resonances 4.28 eV and 10.36 eV are shown in Fig. 6. An additional measurement with tantalum sample was carried out with stationery Pu - Be neutron source placed in a channel more distant than in the previous measurement with the REGe detector only. This time , the layer of lead that separated the neutron source from detector was about 60 cm thick. The obtained gamma - ray spectrum is shown in Fig. 8.

Results, analysis and conclusions

The prominent spectral peaks from measurements of the REGe response to neutron irradiation (as it is shown in Figs. 4abc and 5abc) and their suggested origins are listed in the Table I. The more distinct peaks belonging to tantalum from spectra obtained in measurements with the wrapped detector head are presented in the Table II.

As the accuracy of measurement of peak energies in our experiment was 1 - 1.5 keV the energies given in the tables were

corrected in accordance with more precise values from [22] and [23] after the assignment of peaks to definite isotopes and transitions.

Background

The response spectra of the REGe detector to irradiation with slow neutrons , and with neutrons containing fast component are presented in Figs. 4 and 5, respectively. This response is a superposition of spectra emitted by a number of head constituents after radiative capture and inelastic scattering of neutrons or from beta decay of unstable final nuclei followed by photon emission. The registration of monoenergetic electrons from conversion-electron deexcitation of germanium isotopes inside the active part of the head is also possible.

The five germanium isotopes of mass numbers A = 70 , 72 , 73 , 74 , and 76 constitute the considerable part of the head. Except germanium isotopes, there are : aluminium Al-27 as a constituent of the casing , natural indium (A = 113 and 115) as a seal in the hermetic casing cover , copper (A = 63 and 65) in the dipstick cold finger , beryllium in the front part window , fluorin (A = 19) in teflon , and some other components in surroudings like lead in the pile. The considerable number of spectral lines belonging to these constituents have been observed and identified earlier in [9, 10, 24].

At the low energy region of the response spectrum one can find several lines that correspond to isomeric transitions in four germanium isotopes. They are : two-photon cascade transition 23.44 keV (M2) and 174.95 keV (E2) from 20.4 ms isomeric state at 198.37 keV in Ge - 71, analogous transitions 53.44 keV (M2) and 13.27 keV (E2) from 499 ms isomeric state at 66.71 keV in Ge - 73 , isomeric transition 139.7 keV (E3) from 47.7 s state to ground state in Ge - 75 , and transition 159.7 keV (E3) from 52.9 s metastable level to ground state in Ge - 77.

In that spectrum a unique saddle-like shape of combined peaks 53.4 and 66.7 keV is observed (Fig. 4a and 5a). The same effect has also been observed in pulse-height spectra obtained by Weishaupt and Rabenstein [9]. In principle , the 66.7 keV line is not expected to be observed as a result of direct radiative one-photon

transition from 66.71 keV state to the ground one as it is of M4 - type. It is the result of addition of two pulses from photons 53.44 and 13.27 keV emitted in the cascade. This effect occurs when the lifetime of transitional state is comparable to the time constant of electronic amplifier system [25]. In our case the half-life of transitional state at 13.27 keV in Ge - 73 is 2.95 μs [23], while the time constant is about 4 μs. The smooth part of saddle-like figure between its extreme peaks corresponds to the not total addition of pulses from the cascade transitions noticeably separated in time.

Some broadened to higher energy peaks , which can be observed on spectra obtained with Pu - Be neutron source , are originated from inelastic scattering of fast neutrons on germanium nuclei. The broadening comes from recoil energy of the nucleus in inelastic scattering that adds to the energy of the photon from deexcitation (see e.g. [10]). The recoil energy depends on the energy of incident neutron , induced excitation energy and on the angle of scattering. So the spectrum of recoil energy is a continuous one. The evidently broadened lines in spectra from Fig. 5 correspond to energy levels (in keV) : 68.7 ; 353.6 ; 563 ; 595.8 ; 691 ; 834 ; 1039 , and 1204 . Their isotopic assignments are given in the Table I.

The inelastic scattering of fast neutrons occurs also on other constructional materials that are located outside the active part of germanium detector. Then the corresponding peaks from deexcitation are not broadened since the recoil nuclei lose their energy outside the active detector volume , where only the deexcitation photons are registered. In the response spectrum in Fig. 5 one can find such peaks from inelastic scattering on F - 19 (109.9 keV) , which is probably in the composition of teflon , as suggested by Bunting and Kraushaar [10] , and from Al - 27 (843.8 and 1014 keV) which is comprised in the head casing [10], as well as from Pb - 207 (569.8 and 897.7 keV), which surrounds the detector. There are other lead lines from radiative capture (e.g. 1589 keV) on Pb - 207.

In the response spectra a number of lines originated from indium have been found . They come from final products of

neutron radiative capture in In - 115. They are originated from deexcitation of In - 116 , and from Sn - 116 , being daughter nucleus from beta decay of In - 116. These lines have been observed in [24], and earlier by Weishaupt and Rabenstein [9], but have not been seen in the work [10]. The soft indium metal is used in some detectors as a seal to hermetic casing of the detector head.

Among the lines of the above origin , there are ones with half-life longer than several microseconds. For example , the line 162.4 keV from isomeric transition between 289.7 keV (8^-) 2.18 s state and 127.3 keV (5^+) state in In - 116 , and lines 416.8 ; 818.7 (weak) ; 1097, and 1293.4 keV from deexcitation of Sn - 116 levels populated by beta decay of ground and isomeric state of In - 116 are of this kind. Similar case to the latter one, is the line 1778.9 keV, emitted by Si - 28 , created in 2.24 minute beta decay of Al - 28 obtained from neutron radiative capture in Al - 27.

The appearance of the delayed radiation emitted from radioactive nuclei formed by neutron irradiation of the detector , irrespective of its origin , makes some obstacle for the realization of the idea presented in the introduction. In the case of half-life time comparable with the time of repetion of the LSNS , the long-time lines appear in the spectra taken from every slowing-down time interval. Therefore the resonance shielding of the detector head by investigated sample does not eliminate these lines from pulse-height spectra taken from resonance intervals corresponding to those of the shielding sample. The dimensions of the obstacle depend on the number of considered lines and on the overlapping of these lines and those from the investigated sample.

In the case of our detector one can find in the response spectrum the peaks composed of two or more lines belonging to different nuclides. They overlap each other so close that it is impossible to separate them at all in germanium spectrometer with resolution ~ 2 keV. For example , the peak at 60.7 keV can be a superposition of line 60.2 keV from Ge - 75 and line 60.92 keV from In - 116. Next peak at 492.9 keV can come from transition 492.9 keV in Ge - 74 and line 492.5 keV from In - 116.

Another striking example is the peak 608.4 keV that can be an overlapping of lines 608.35 keV from Ge - 74 and 608.36 keV from In - 116 [23]. That obstacle can be removed by measurement of pulse-height spectra in additional time windows outside of those including the resonances of investigated sample (see Fig.6c). The long-time lines will occur in the time windows outside the resonance regions.

Spectra with tantalum sample.

To proceed to the basic question of the paper, let us consider the spectra obtained with tantalum sample. The spectra shown in Figs. 6ab are taken from time intervals corresponding to two lowest tantalum resonances, i.e. 4.28 eV and 10.36 eV, where the result of resonance shielding of the detector head is expected to be the most effective. In these spectra some lines belonging to tantalum are clearly visible. They evidently dominate among others, while the lines of the detector response spectrum seem to be considerably suppressed (compare the lines on the spectra in Figs. 6ab and Fig. 6c). The prominent tantalum lines that correspond to those observed by Van den Cruyce et al. [22] as the strongest ones in the spectrum emitted after thermal neutron capture, are 114.4 keV, 133.9 keV, 173.2 keV, 270.4 keV, 297.1 keV and 402.6 keV. The authors of [22] observed about 550 spectral lines with energies between 44 and 988 keV and with relative intensities changing more than 500 times. In our experiment and with the equipment we used such impressive results could not be achieved, albeit the thorough analysis of enlarged pictures of the obtained spectra allowed to establish the occurrence of much more tantalum peaks, as it can be seen in Fig. 7.

An additional measurement was performed with tantalum sample and Pu-Be neutron source, placed further away than in the measurement without tantalum. Part of the obtained spectrum is presented in Fig.8. This time the influence of fast neutrons on pulse-height spectrum was noticeably reduced or not observed.

As we mentioned above, the main difficulty in the analysis concerning the isotopic and transition assignment is caused by the overlapping of spectral lines from various nuclides and levels. The cases, where the assignment of spectral peak to definite nuclide or to

transition between definite levels is controversial or impossible, are shown in the Table II.

For example, the peak at 114.4 keV can be considered as the result of three transitions in tantalum with energies 114.32 keV (M1), 114.67 keV (M1), and 114.38 keV (M1?). According to Van den Cruyce at all. [22], the most probable assignment is attributed to transition from 114.315 keV level to the ground state with relative intensity 23% , while the relative intensities of remaining transitions are 7.4% and 6.8%, respectively. Another example of peak at energy 139.6 keV can be treated as an overlapping of transitions with energies 139.45 keV (5.3%), and 139.66 keV (1.1%) in tantalum [22] with contribution of isomeric transition 139.7 keV from Ge-75m, and possible admixture of transition 140.5 keV from In-116 [23].

This troublesome situation in analysis of the obtained spectra arises mainly from the very high density of transitions in the excited odd – odd deformed tantalum nucleus, and from rather simple equipment used in the experiment. The choice of tantalum sample for the test resulted from the reason of its neutron resonances and for quite abundant available nuclear spectroscopic data, e.g. in [22,23]. Its form of metallic foil, convenient for the shielding of the detector head without an additional container, was also important.

Taking into account the results of measurements, their analysis and the above consideration, we have come to the following conclusions:

i) the investigation of gamma-ray spectra from resonance neutron capture at the LSNS is feasible by use of shielding of the detector head with investigated sample of proper thickness ($n\sigma x >> 1$),

ii) the investigation requires a small size gamma-ray spectrometer with good radiation damage resistance for neutron irradiation, and considerable amount of sample material needed for shielding the detector.

The main shortcomings of the tested method are: the poor resolution of neutron energy, that seriously limits the number of separated resonances accessible for study, and the requirement of having considerable amount of the sample.

Table I. Prominent spectral peaks from the REGe detector irradiated with neutrons from the LSNS or Pu- Be neutron source inserted into the lead pile. The data on energy and isotope without any additional comment concern the lines from neutron radiative capture.

E_γ (keV)	Suggested origin	E_γ (keV)	Suggested origin
10.4	GeK_α	563	Ge-76, (n,n')
13.27	Ge-73m, 2.95μs	569.85	Pb-207, (n,n')
23.44	Ge-71m, 20.4μs	595.85	Ge-74, from (n,n') and (n,γ) on Ge-73
53.44	Ge-73m, 499ms	608.4	Ge-74, and admix. In-116
60. 7	Ge-75, possible admix. In-116	691	Ge-72, (n,n'), Eoe
66.71	Ge-73m, 499ms	701.5	Ge-74
68.75	Ge-73(n,n') and (n,γ) on Ge-72	708.2	Ge-71
72.3	Pb $K_{\alpha 1}$	798.4	Ge-71
74.8	Pb $K_{\alpha 2}$	834	Ge-72, (n,n')
84.6	Pb $K_{\beta 1}$	843.8	Al-27, (n,n')
96.1	In-116	867.9	Ge-74
109.89	F-19, (n,n')	897,7	Pb-207, (n,n')
139.68	Ge-75m, 47.7s	961	Ge-74
159.7	Ge-77m, 52.9s	999.8	Ge-74
162.4	In-116m, 2.18s	1014	Al-27, (n,n')
174.95	Ge-71	1039.2	Ge-70, (n,n')
185.9	Cu-66, and In-116 ?	1065	Ge-73
198.4	Ge-71m, 20.4ms, sum peak	1089	Ge-74
253.0	Ge-75	1097	Sn-116 from In-116 β^- 54.4m
273.0	In-116	1101.3	Ge-74
297.32	Ge-73	1131.4	Ge-74
325	Ge-71(?) + Ge-73(?)	1139.5	Ge-71
353.6	Ge-73, (n,n')	1204.2	Ge-74, from (n,n') and (n,γ) on Ge-73
391.4	Ge-71	1293.4	Sn-116 from In-116 β^- 14.1s
416.86	Sn-116 from In-116 β^- 54.4m	1464	Ge-74, sum peak
444.8	Ge-75	1471.7	Ge-74
457.0	Ge-75	1509.7	Ge-74
468	Ge-74	1570.2	Ge-74
492.9	Ge-74, possible admix In-116	1589	Pb-208, from (n,γ) on Pb-207
499.88	Ge-71	1697	Ge-74
511	pair annihilation	1778.9	Si-28 from Al-28 β^- 2.24m

Table II. Lines chosen from low-energy spectra obtained from measurements with tantalum sample as belonging to transitions in Ta-182. The spectra were taken at the LSNS from resonances 4.28 and 10.36 eV, and with Pu-Be neutron source in the lead pile.

E_γ (keV)	Suggested assignment to transition in Ta-182 $U_i(I_i^\pi) \rightarrow U_f(I_f^\pi)$	E_γ (keV)	Suggested assignment to transition in Ta-182 $U_i(I_i^\pi) \rightarrow U_f(I_f^\pi)$
95.15	$835.28(3^-) \rightarrow 740.13((2)^-)$	173.2	$443.6(1^-) \rightarrow 270.4(2^-)$
97.83	$97.83(4^-) \rightarrow 0(3^-)$ or admix.	178.6	$292.94(5^-) \rightarrow 114.32(4^-)$
	$817.02(4^-) \rightarrow 719.55((3)^-)$	182.7	$547.10((3)^-) \rightarrow 364.35(4^+)$
99.83	$249.97((3)^+) \rightarrow 150.14(4^+)$	190.33	$592.96((1^+)) \rightarrow 402.62(2^+)$
107.86	$666.15(2^-) \rightarrow 558.28((1)^-)$	195.11	$292.94(5^-) \rightarrow 97.83(4^-)$
114.4	$114.32(4^-) \rightarrow 0(3^-)$ possible admix.	210.54	$701.97(3^-) \rightarrow 491.42(2^-)$ plus
	$558.28((1)^-) \rightarrow 443.61(1^-)$ and		210.9keV unknown background line
	$364.35(4^-) \rightarrow 249.97((3)^+)$		(As-77 from Ge-77(β^-), 11.3h)
118.89	$269.03((5^+)) \rightarrow 150.14(4^+)$	214.21	$364.35(4^+) \rightarrow 150.14(4^+)$
122.7	$782.53((5^-)) \rightarrow 659.86((4)^-)$ and	244.8	$579.43((7^+)) \rightarrow 334.62(7^+)$
	$237.29(5^-) \rightarrow 114.32(4^-)$ and	252.8	$269.03((5^+)) \rightarrow 16.26(5^+)$ plus
	$939.63(5^-) \rightarrow 817.02((4)^-)$		253keV line from Ge-75
	(three unresolved transitions)	260.1	$740.13((2)^-) \rightarrow 480.03(4^-)$
125.13	$960.41((4^-)) \rightarrow 835.28(3^-)$	270.40	$270.40(2^-) \rightarrow 0(3^-)$
133.88	$150.14(4^+) \rightarrow 16.26(5^+)$	297.1	$547.1((3)^-) \rightarrow 249.97((3)^+)$ plus
139.6	$237.29(5^-) \rightarrow 97.83(4^-)$ and		297.3keV line from Ge-73
	$583.27((0^-)) \rightarrow 443.61(1^-)$ plus line	322.5	$592.96((1^+)) \rightarrow 270.40(2^-)$
	139.7 from Ge-75m, IT, 47.7s	346.5	$749.09((2,3)^+) \rightarrow 402.62(2^+)$
146.77	$163.04(6^+) \rightarrow 16.26(5^+)$	360.52	$360.52((3)^-) \rightarrow 0(3^-)$
154.08	$856.05((4)^-) \rightarrow 701.97(3^-)$	373.9	$390.14((4,5,6)^+) \rightarrow 16.26(5^+)$
156.09	$270.40(2^-) \rightarrow 114.32(4^+)$, admix.	377.25	$647.65((2)^-) \rightarrow 249.97((3)^+)$
156.23	$647.65((2)^-) \rightarrow 491.42(2^-)$	382.2	$480.03(4^-) \rightarrow 97.83(4^-)$
159.05	$396.34((6^-)) \rightarrow 237.29(5^-)$ plus	396.95	$547.1((3)^-) \rightarrow 150.14(4^+)$
	admixture of 3 lines + line 159.7	402.62	$402.62(2^+) \rightarrow 0(3^-)$
	from Ge-77m, IT, 52.9m	443.6	$443.61(1^-) \rightarrow 0(3^-)$
167.4	$673.0((6^+)) \rightarrow 505.6(5^+)$	511	annihilation photons

The principal advantages are: the high luminosity of the LSNS that allows to obtain relatively high neutron flux at small yield of neutron source, and rather moderate cost of the LSNS, and its simple servicing. The latter two features allow the smaller centres to perform the experimental study from nuclear spectroscopy.

Finally , we want to notify that on the basis of our measurements of slow neutron capture with germanium and from the literature data obtained by other authors we could propose five new excited levels in germanium isotopes [26].They are given in Table III.

Table III. Proposed new excited levels in Ge-isotopes

Isotope	Level energy (keV)	Possible spin and parity
Ge-71	3024.25	$(1/2, 3/2)^-$
Ge-74	5288.5	$(2^+,3^+)$
Ge-74	5510.3	$(3^-,4^-)$
Ge-75	2068.8	$(1/2^-, 3/2^-)$
Ge-75	2311.2	-

Detailed consideration of their foundation and discussion of the suggestion will be presented in a separate article.

Acknowledgments

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Note : After completion of this paper we learned about the results of studies at the LSNS built in CERN, where the perspective to perform the measurements of neutron radiative capture cross section with radioactive nuclei was demonstrated [The TARC Experiment (PS211) : Neutron – Driven Nuclear Transmutation by Adiabatic Resonance Crossing , CERN 99 – 11, Ed. J. P. Revol, Geneva 1999].

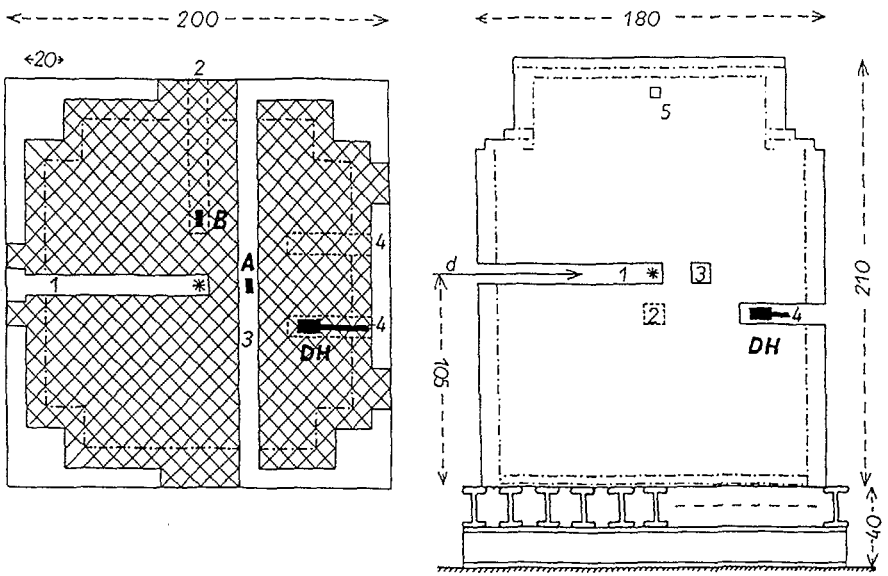


Fig. 1. Horizontal and vertical cross section throughout the lead pile. The broken-dotted lines denote cadmium sheets. Asterisk – location of the tritium target. (DH) – position of the REGe detector head, (A) and (B) – positions of the Pu – Be neutron source.

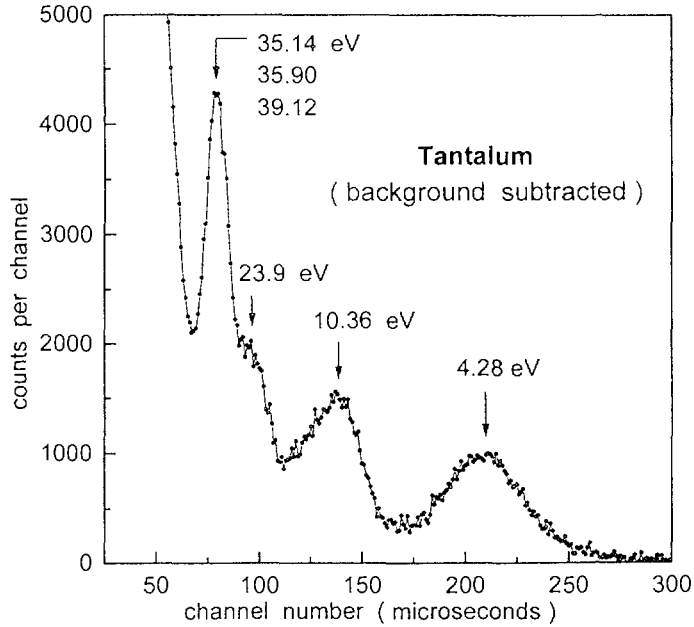


Fig. 2. Number of counts of scintillation counter with CaF_2 scintillator surrounded by tantalum sample as function of slowing-down time.

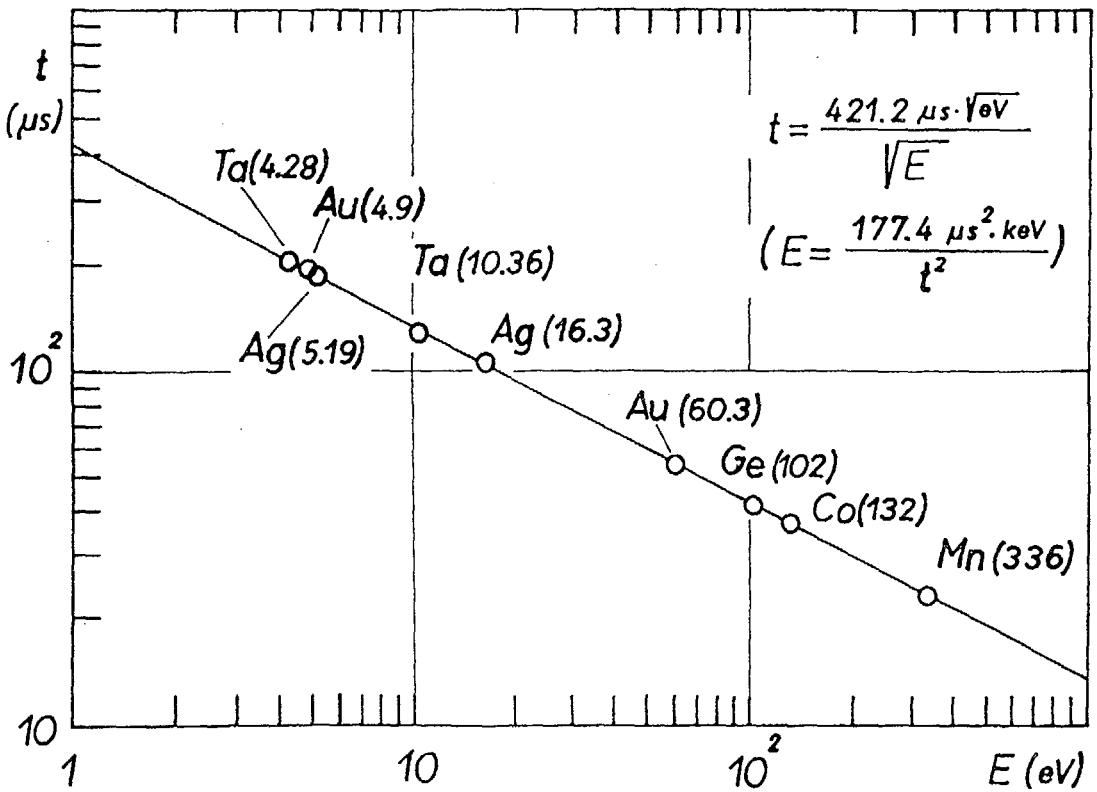


Fig. 3. Calibration curve for the LSNS (slowing-down time versus neutron average energy).

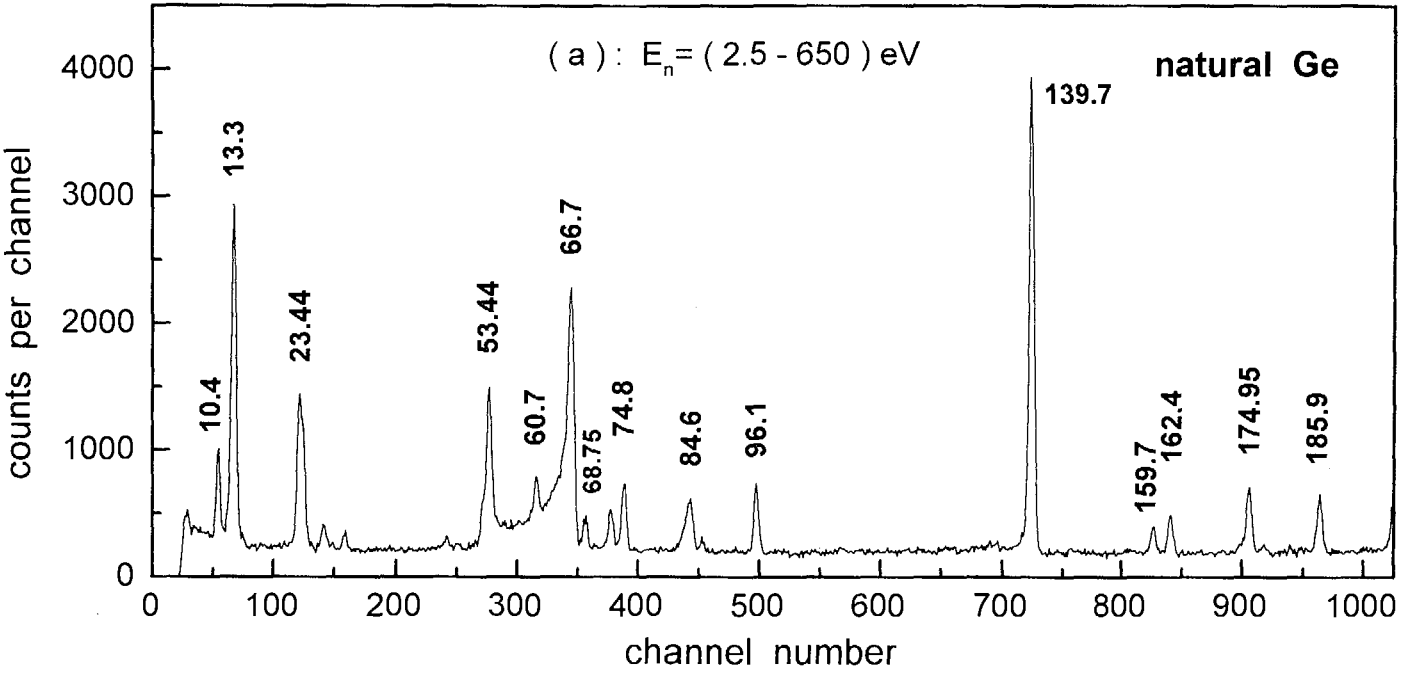

(a) : E_n= (2.5 - 650) eV
natural Ge
counts per channel
channel number
0
1000
2000
3000
4000
0
100
200
300
400
500
600
700
800
900
1000
10.4
13.3
23.44
53.44
60.7
66.7
68.75
74.8
84.6
96.1
139.7
159.7
162.4
174.95
185.9

Fig. 4a

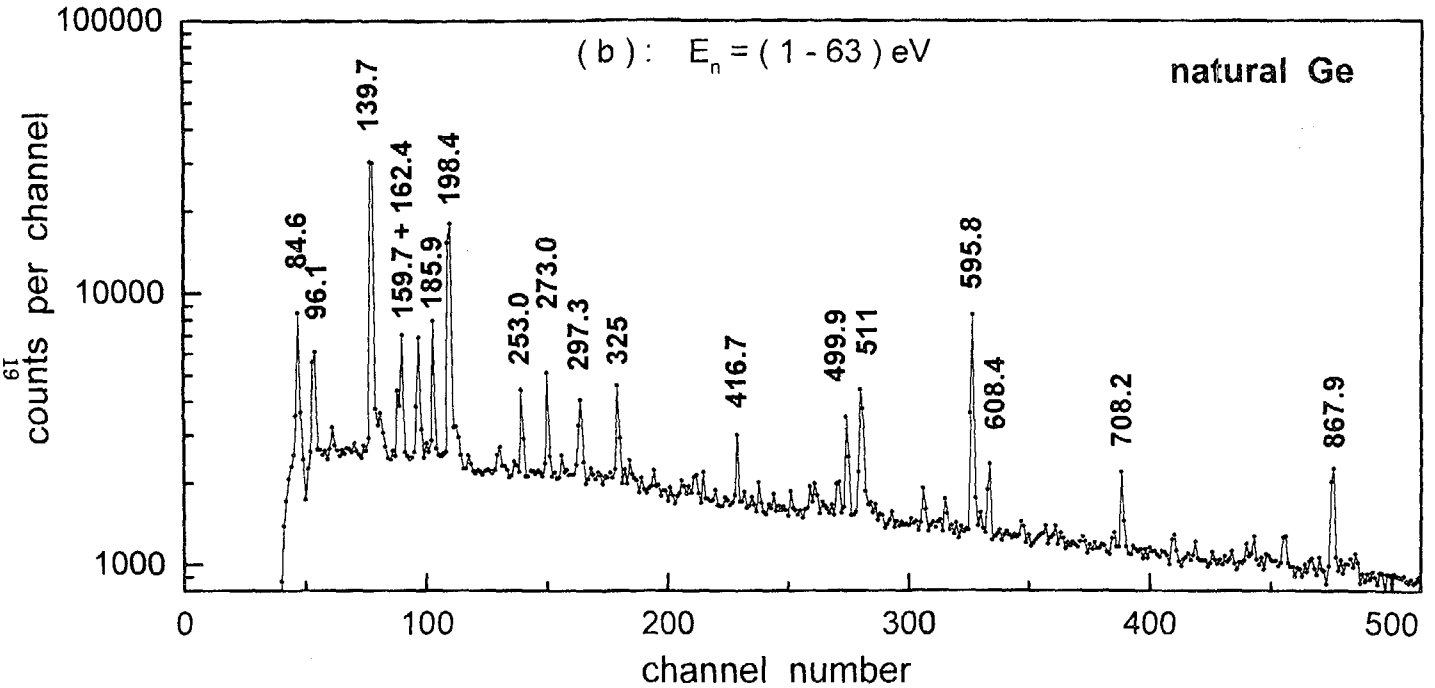

(b) : E$_n$ = (1 - 63) eV
natural Ge
counts per channel
channel number
100000
10000
1000
0
100
200
300
400
500
84.6
96.1
139.7
159.7 + 162.4
185.9
198.4
253.0
273.0
297.3
325
416.7
499.9
511
595.8
608.4
708.2
867.9

Fig. 4b

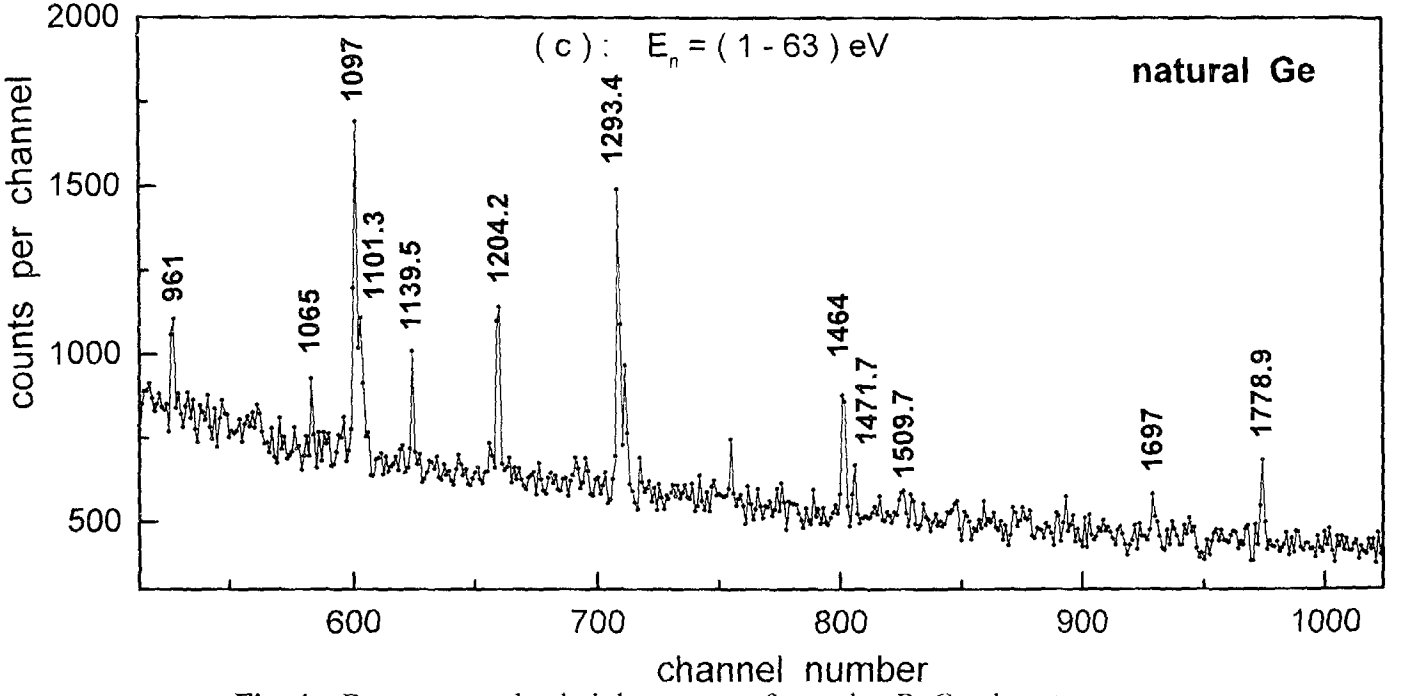


Fig. 4. Response pulse-height spectra from the ReGe detector irradiated with slow neutrons at the LSNS. Energies of lines are given in keV at spectral peaks. Gamma-ray energy intervals are : (a) 8 – 190 keV, (b) 80 – 900 keV, and (c) 900 – 1800 keV.

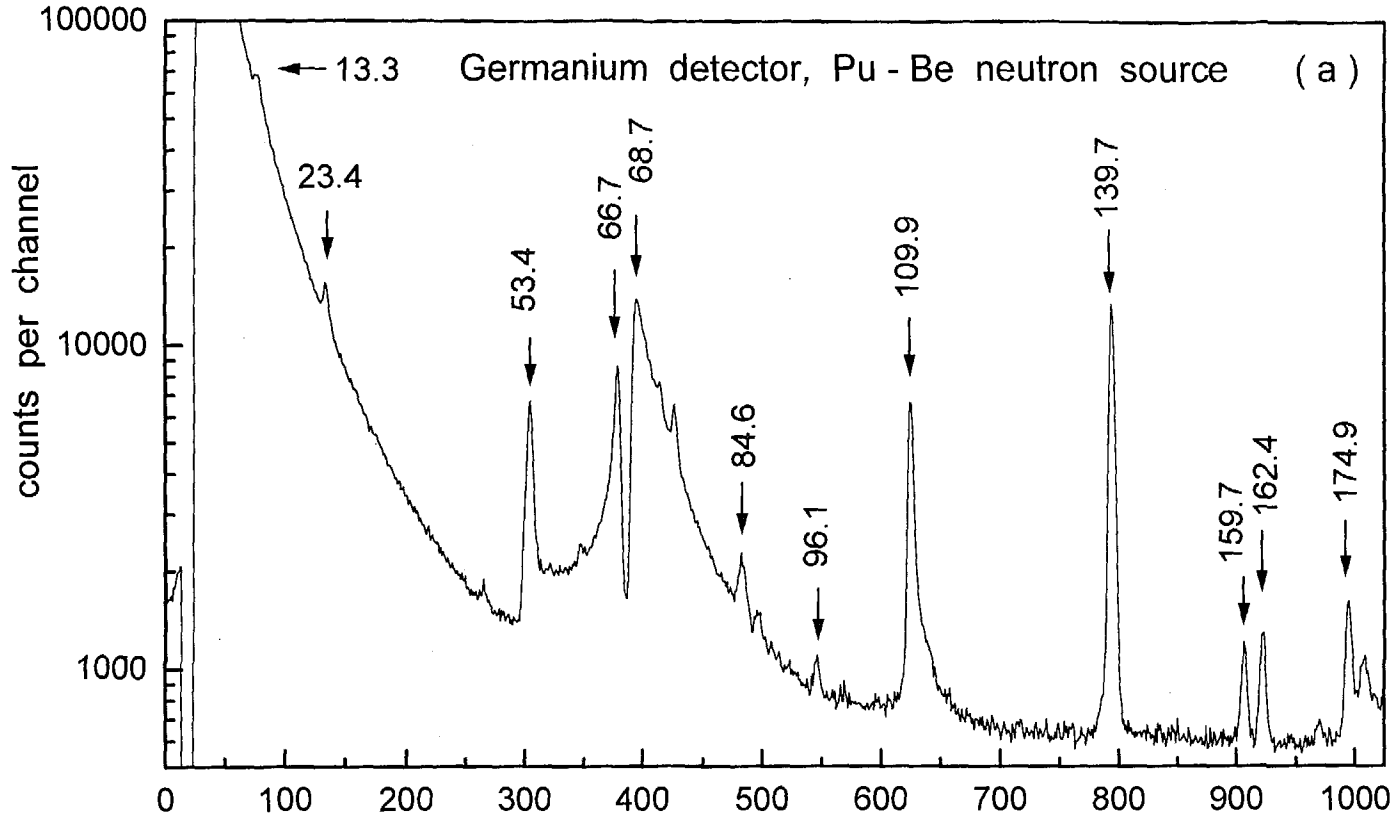
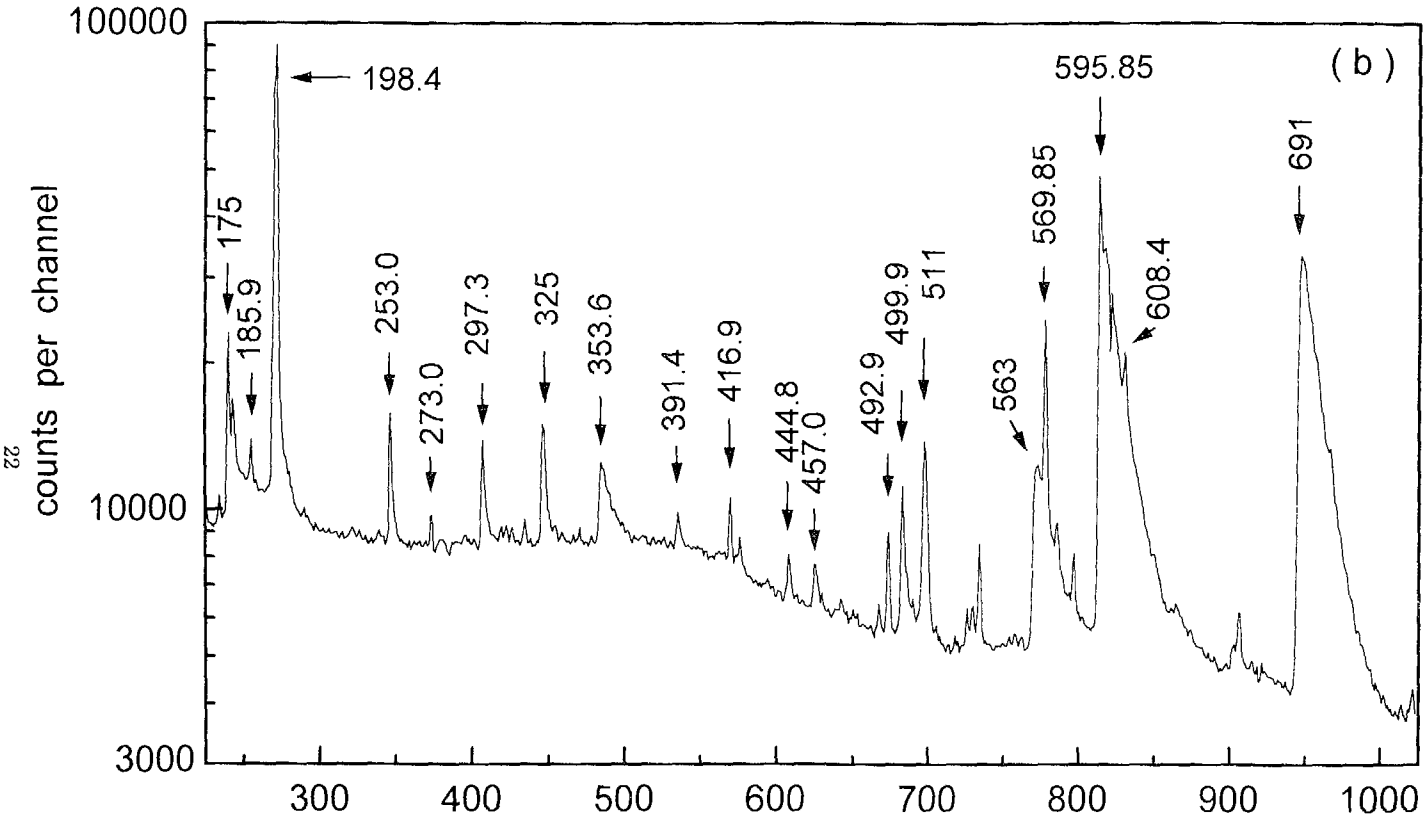

100000
10000
1000
counts per channel
13.3
Germanium detector, Pu - Be neutron source
(a)
23.4
53.4
66.7
68.7
84.6
96.1
109.9
139.7
159.7
162.4
174.9
0
100
200
300
400
500
600
700
800
900
1000
channel number

Fig. 5a


100000
10000
3000
counts per channel
22
198.4
595.85
(b)
691
175
185.9
253.0
273.0
297.3
325
353.6
391.4
416.9
444.8
457.0
492.9
499.9
511
563
569.85
608.4
300
400
500
600
700
800
900
1000
channel number
Fig. 5b

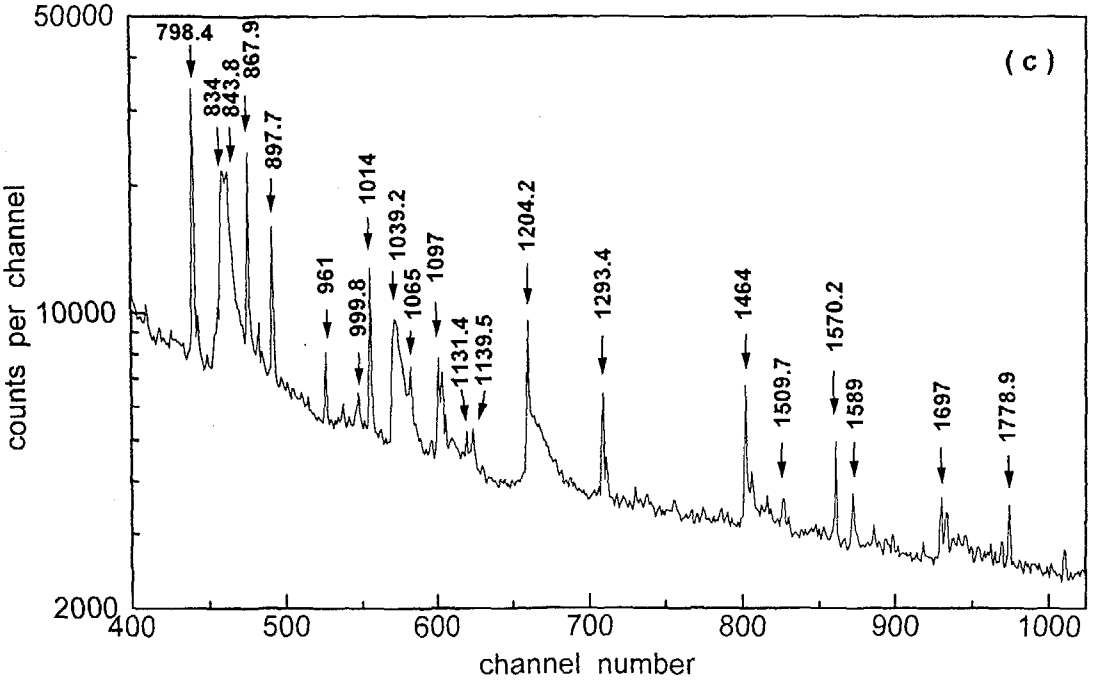


Fig. 5. Response pulse-height spectrum of the REGe detector irradiated with neutrons from Pu – Be neutron source located inside the lead pile in position " A " (Fig. 1). The peaks broadened to higher energy are from inelastic neutron scattering on detector head crystal. Peak energies are in keV.

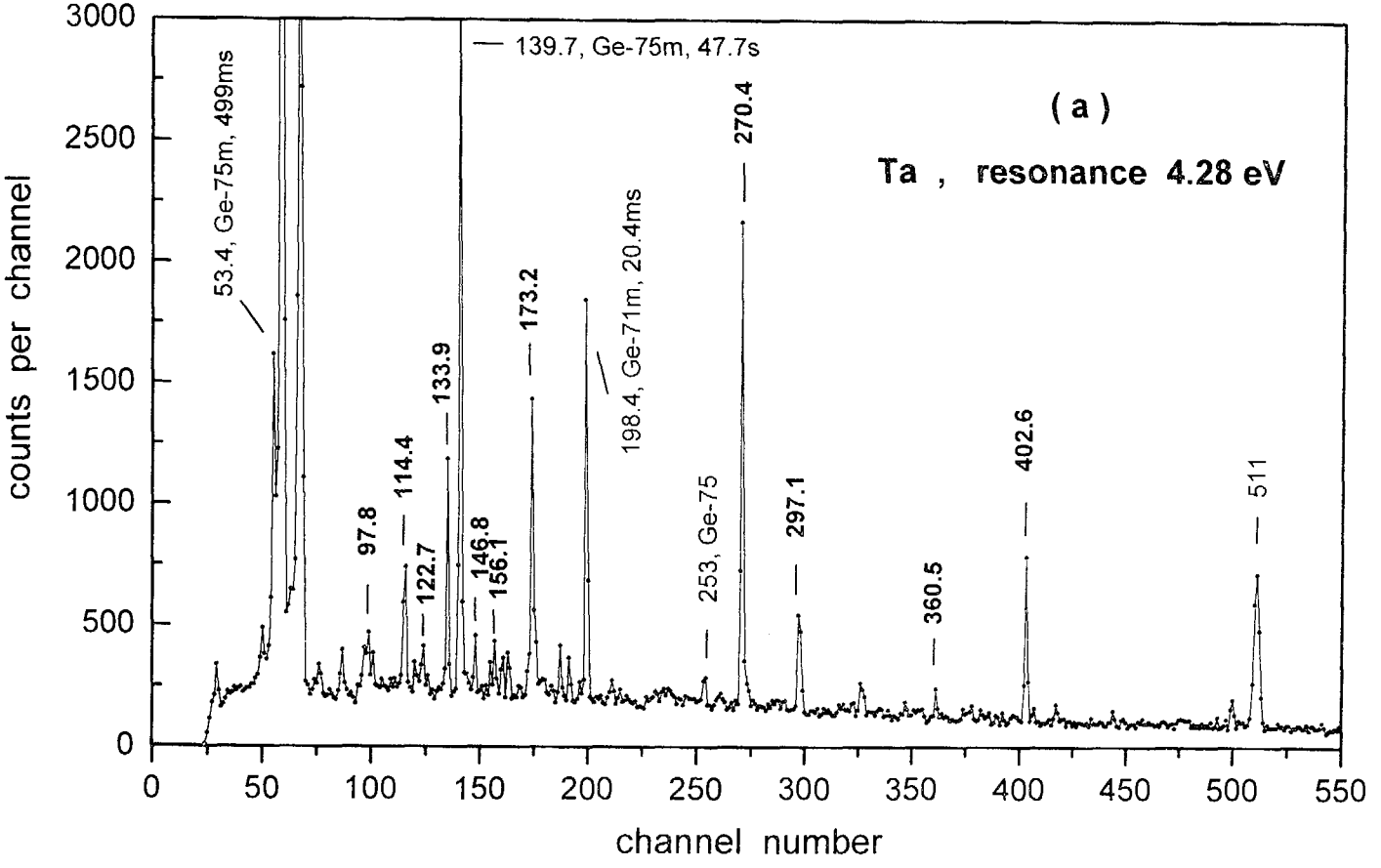

counts per channel
channel number
(a)
Ta , resonance 4.28 eV
53.4, Ge-75m, 499ms
139.7, Ge-75m, 47.7s
97.8
114.4
122.7
133.9
146.8
156.1
173.2
198.4, Ge-71m, 20.4ms
253, Ge-75
270.4
297.1
360.5
402.6
511
0
500
1000
1500
2000
2500
3000
0
50
100
150
200
250
300
350
400
450
500
550

Fig. 6a

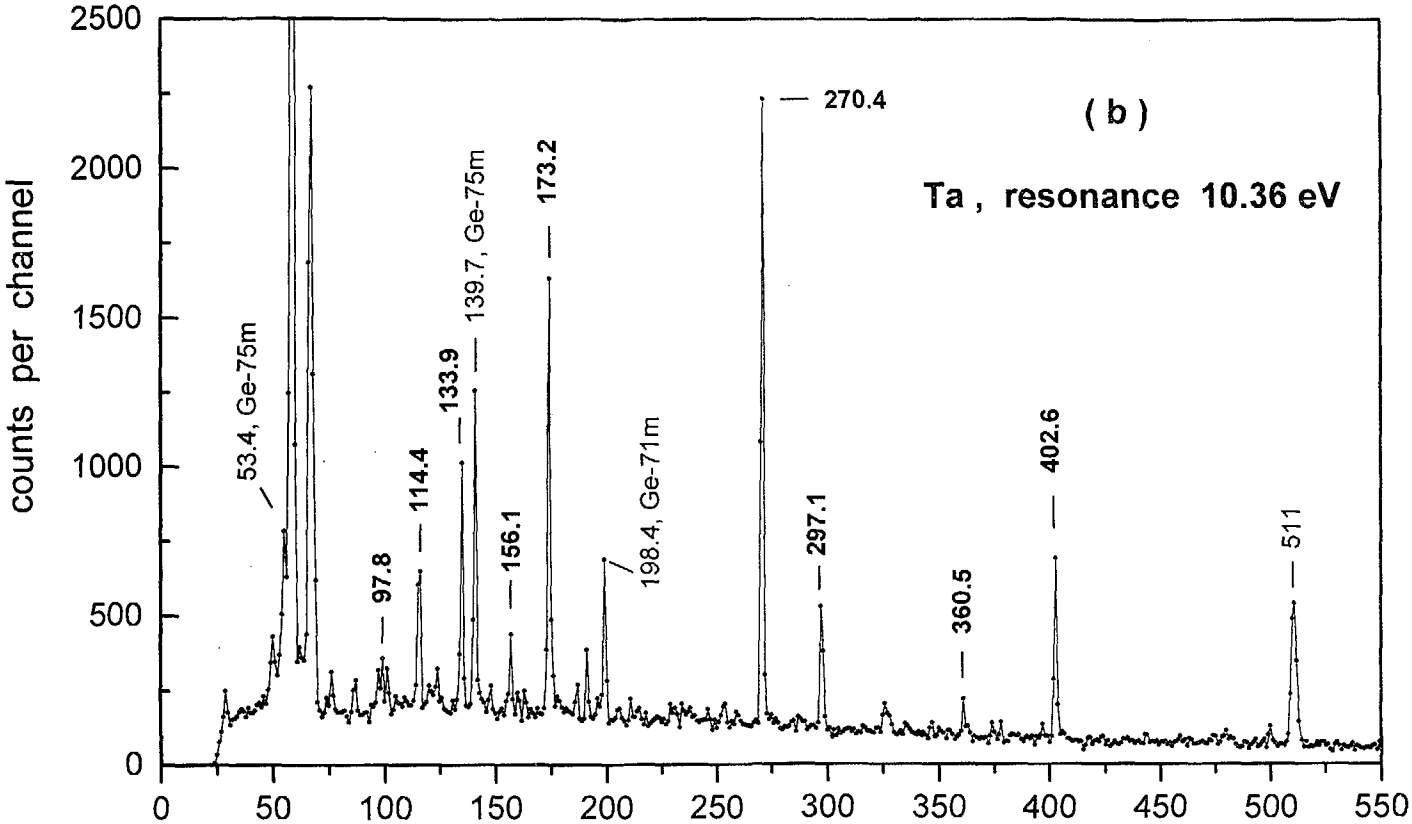

counts per channel
channel number
(b)
Ta , resonance 10.36 eV
53.4, Ge-75m
97.8
114.4
133.9
139.7, Ge-75m
156.1
173.2
198.4, Ge-71m
270.4
297.1
360.5
402.6
511
0
500
1000
1500
2000
2500
0
50
100
150
200
250
300
350
400
450
500
550

Fig. 6b

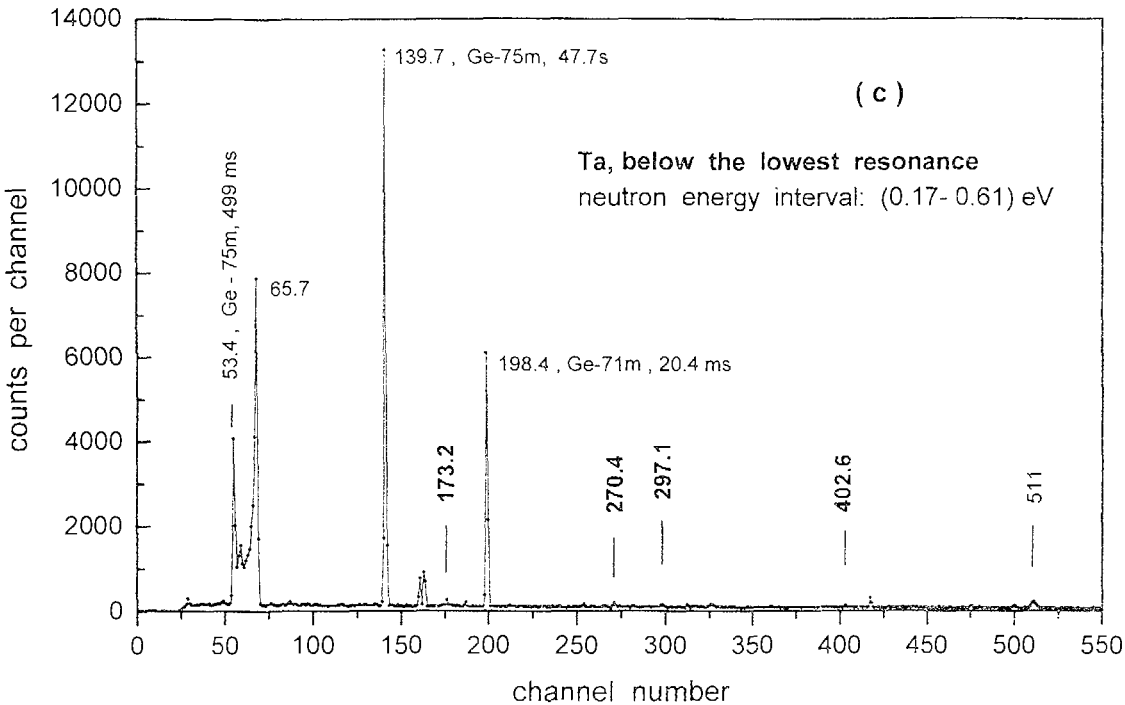


Fig. 6. Low energy pulse-height spectra obtained with tantalum sample wrapped around detector head; (a) – at neutron resonance 4.28 eV, (b) – at 10.36 eV, and (c) – for neutrons with energy below the resonance 4.28 eV.

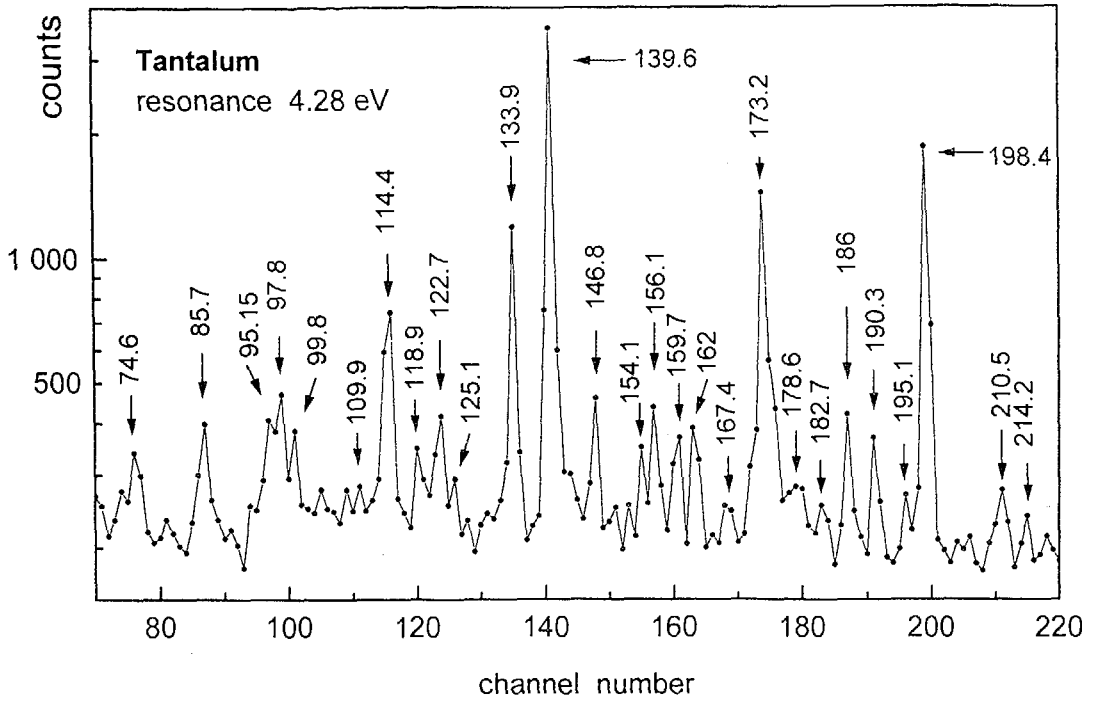


Fig. 7. Enlarged part of spectrum from Fig. 6a (resonance 4.28 eV), presented in " lin – log " scale in order to visualise the occurrence of weak transitions.

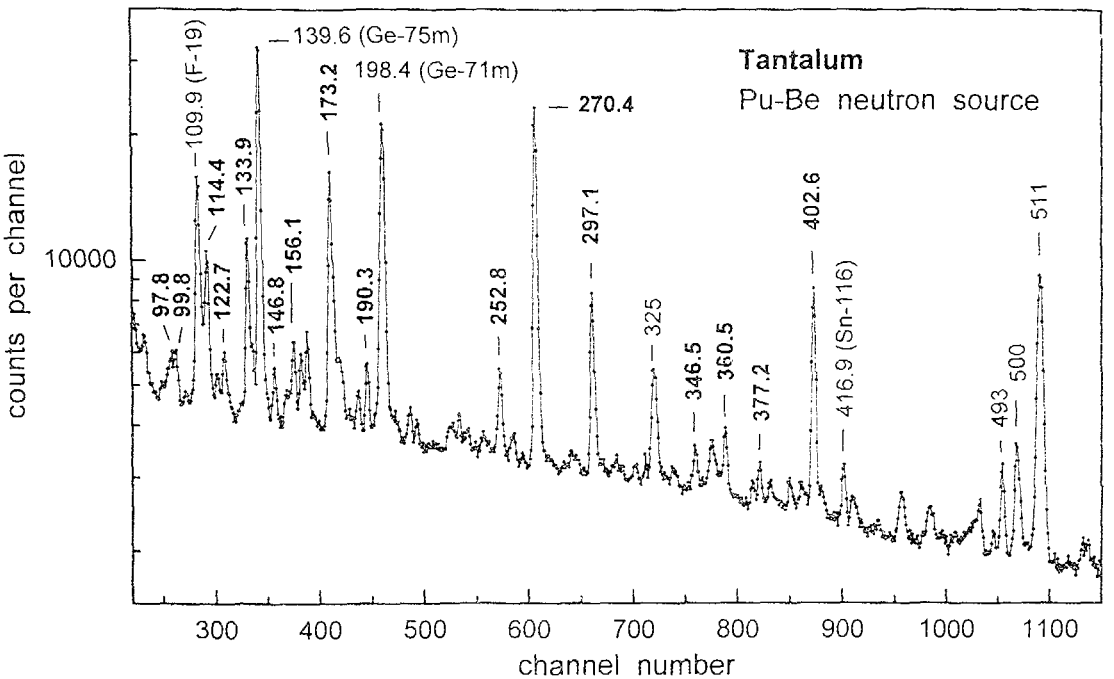


Fig. 8. Part of pulse-height spectrum obtained with tantalum sample and Pu – Be neutron source in position " B " (Fig. 1). Lines denoted by bold type energy values belong to tantalum.

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