DECAY OF NEW ISOTOPES $^{160-163}$Lu

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The new ^{160}Lu ($T_{1/2} = 34.5 \pm 1.5$ sec), ^{161}Lu ($T_{1/2} = 72 \pm 6$ sec), ^{163}Lu ($T_{1/2} = 4.1 \pm 0.2$ min) have been identified as products of spallation reaction of tungsten by 1 GeV protons, using on-line mass-separator "IRIS". The earlier identification of ^{162}Lu isotope, having $T_{1/2} = 86 \pm 5$ sec, has been confirmed. The identification for all four isotopes is based on the analysis of X- and γ-ray spectra, of mass separated samples. Single γ-spectra were measured. Energies and intensities of γ-transitions have been determined. Preliminary decay schemes are proposed.

1. Introduction

The aim of the present work is to identify and to investigate short-lived lutetium isotopes with mass numbers $A = 160$–163. The presented here results concerning Lu isotopes are a part of the investigation program of nuclei laying far from the beta stability line undertaken in the collaboration of the Leningrad Nuclear Physics Institute (LNPI) and Joint Institute for Nuclear Research (JINR). Experiments are realised with the help of the mass-separator "IRIS" installed on-line on 1 GeV proton beam from LNPI synchrocyclotron.

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Preliminary results of these experiments are presented in a short communication [1], together with the results of our earlier investigation of alpha decay, including the identification of new Lu isotopes with $A < 159$ reported in detail in [2, 3].

Daughter nuclei $^{160-163}$Yb obtained from the decay of $^{160-163}$Lu have neutron numbers 90–93. and belong to the nuclei laying close to the transitional region, and from this point of view are interesting for the theory of the structure of the nuclei.

In the contradiction to large amount of experimental data collected for other rare earth elements (see for example [4]), the existing information about Lu isotopes with $A \leqslant 163$ is very poor, and particulary Lu isotopes with mass number 160, 161, 163 have been not yet identified.

^{162}Lu has been identified earlier among the products of (HI, Xn) reaction [5, 6] by observing the decay of two γ-lines (E_γ = 167.0 keV and 320.3 keV) known as the deexcitation of first two excited states in ^{162}Yb [12].

2. *Experimental procedure*

The experiments have been performed on 1 GeV proton beam (about 10^{12} protons/sec on target) from LNPI synchrocyclotron. The beam is transported at about 60 meters to the target room to irradiate a combined "target-ion source" system of mass-separator "IRIS" [7, 8]. The combined "target-ion source" system, based on the surface ionization effect and developed at JINR [10], is a tungsten (or tantalum) cylinder having 5 mm inside diameter and 1 mm thick walls. This cylinder, being for the same time the target and the ionizer, is heated by the electron bombardment up to the temperature of about 3000 K. The radioactive nuclei are produced in spallation reactions W(p, Xn Yp) inside the material of the walls, diffused in to the inside volume of the tube, and are ionized on the inner surface of the hot cylinder. The small orifice in front of the cylinder allowed to extract ions into the optical system of the mass-separator. The high temperature of the ion source gives rise to the diffusion velocity, ionization coefficient, and makes the hold up time for ions shorter. These factors cause high yield and small delay of ions in the ion source. Yields of our ion-source are discussed in [3, 9].

Mass separated ions with two different mass numbers are extracted into two ion tracts, which allowed to run two experiments simultaneously. On one of them, equipped with the tape transport station, ions collected on the tape are transported to two Ge(Li) detectors (0.8 keV and 3.5 keV resolution) for X-ray and γ-ray spectra analysis. The collection and counting time, the transport of the tape, and the record of the spectra on the magnetic tape, are on-line controlled by a small computer M-400. Usually for each sample the eight consecutive 4096 channel spectra are recorded and used for the decay period analysis (first 2048 channels for X-ray spectrum, second 2048 channels for γ-ray spectrum). For each mass number from few tens to few hundreds of such series of spectra are recorded. Summation of corresponding spectra as well as energy, intensity, and decay period calculations are performed on the HP 2116c computer with "Tectronix" graphic display and on EC 1030 computer.

3. *Comments on the identification of the new isotopes*

In the present paper the identification of the new isotopes is based on the following considerations:

a) For any observed mass number A, using the mass-separator, we have the unambiguous mass determination. In each measurement a possible contaminations of the neighbouring masses were additionally checked, in search of the strongest γ-lines belonging to the neighbouring isobars with $A \pm 1$.

b) The identification of the characteristic K_α and K_β Roentgen lines in the spectra determined atomic number Z of new isotope, and the analysis of these spectra in time, gives their preliminary decay period $T_{1/2}$. The analysis of decay period for the new γ-lines in the same spectra, determines their relation to the discussed isotope. Final accepted half-life is based on the decay period of $K_{\alpha 1}$ Roentgen line, and decay periodes of strongest γ-lines ascribed to the investigated isotope.

c) To exclude the possible interpretation of the $^{160,\,162}$Lu isotopes, as high spin isomers of $^{160,\,162}$Yb, the ratio of the intensities of the transitions ($4^+ \to 2^+$) to ($2^+ \to 0^+$) can be discussed. Isomers predominantly should be deexcited by the cascade $6^+ \to 4^+ \to 2^+ \to 0^+$, and the ratio $I_{4^+\to 2^+}/I_{2^+\to 0^+}$ should be close to unity, what is not true in our case.

d) In addition to the arguments discussed above, for the all investigated Lu nuclei the energies of some γ-transitions found in the present work, agree with the energies of γ-transitions deexciting the ground-state bands of the daughter $^{160-163}$Yb [11, 12, 13].

4. *Experimental results*

The ^{163}Lu isotope. For the mass number $A = 163$ the low energy spectrum in the range 20–500 keV has been measured. Eight spectra in the time intervals 2 min or 1.5 min have been measured for the decay time analysis. The whole measuring time being 16 min (8×2 min) was chosen according to the systematics which predict for ^{163}Lu the half-life $\approx$ 3 min. Fig. 1 shows the obtained spectrum on which two ytterbium Roentgen lines $K_{\alpha 1}$ and $K_{\beta 2}$, with the energies 52.4 keV and 61.0 keV are clearly seen. Also the decay curve for the $K_{\alpha 1}$ line is demonstrated. Fig. 2 shows γ-spectrum measured in the energy range 100–1000 keV. Besides γ-lines corresponding to the decay of well known isotopes belonging to the isobar $A = 163$ [14, 15] the number of new γ-lines can be seen. These lines we can ascribe to the new ^{163}Lu, basing on their decay periods and unambiguous mass determination.

The decay curves for the Roentgen lines, and the strongest γ-lines of the ^{163}Lu are shown in Fig. 3d. For the daughter ^{163}Yb, on the decay curve of its γ-line with energy of 234.45 keV the tendency to increase is also demonstrated. From this results we have determined the half-life for ^{163}Lu to be $T_{1/2} = 246 \pm 12$ sec. The energies and relative intensities of γ-lines are listed in Table I.

The ^{162}Lu isotope. For ^{162}Lu the decay time $T_{1/2} = 84 \pm 9$ sec and two γ-lines (167.0 keV and 320.3 keV) are known from papers [5, 6]. In the papers cited above the nuclei produced in the reactions with heavy ions were identified only with the help of the excitation functions. X-ray spectrum (Fig. 4) and γ-ray spectrum (Fig. 5) for the mass number 162 were measured in the same range as for ^{163}Lu. Time intervals were 8×40 sec. On the X-ray spectrum the $K_{\alpha1}$ and $K_{\beta2}$ Roentgen lines corresponding to the decay Lu → Yb

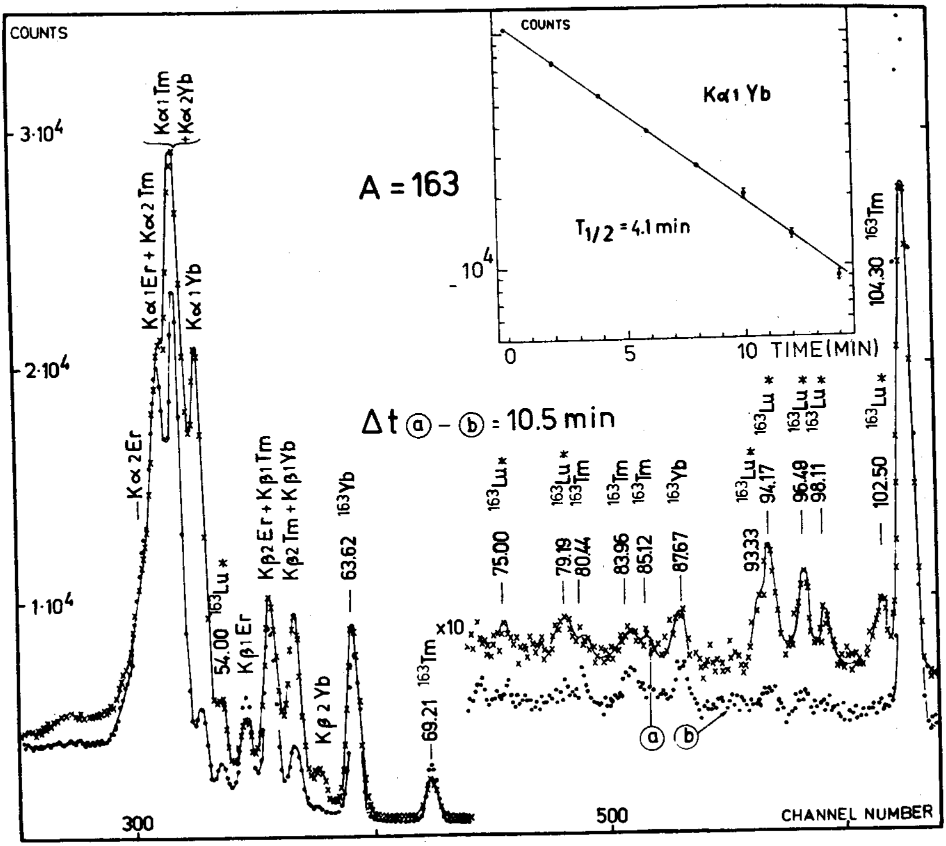

Fig. 1. Low energy part of the γ-ray spectrum for the mass number $A = 163$ in the first and seventh time-interval (8×1.5 min). Decay curve for time-intervals 8×2 min

can be seen. Gamma-lines demonstrated in Fig. 5 belong to ^{162}Yb and ^{162}Tm [16], and the new lines listed in Table II, we have assigned to the decay of ^{162}Lu. The decay curves for the Roentgen lines and the strongest γ-lines are shown in Fig. 3c. The half-life accepted for ^{162}Lu $T_{1/2} = 86\pm5$ sec is in good agreement with the results from [6].

The ^{161}Lu isotope. For the ^{161}Lu isotope the half-life according to the systematics is about 1 minute. The time intervals in the experiment, 8×40 sec has been chosen according to this value. The energy range for the γ-spectrum was 100–300 keV. Fig. 6 shows the X-ray spectrum, and Fig. 7 — the γ-ray spectrum for the mass number $A = 1\ 1$. The $K_{\alpha1}$ and $K_{\beta2}$ Roentgen lines accompanying the Lu → Yb beta-decay are again well pronounced. On γ-spectrum a number of new γ-lines are seen in addition to the known ^{161}Yb

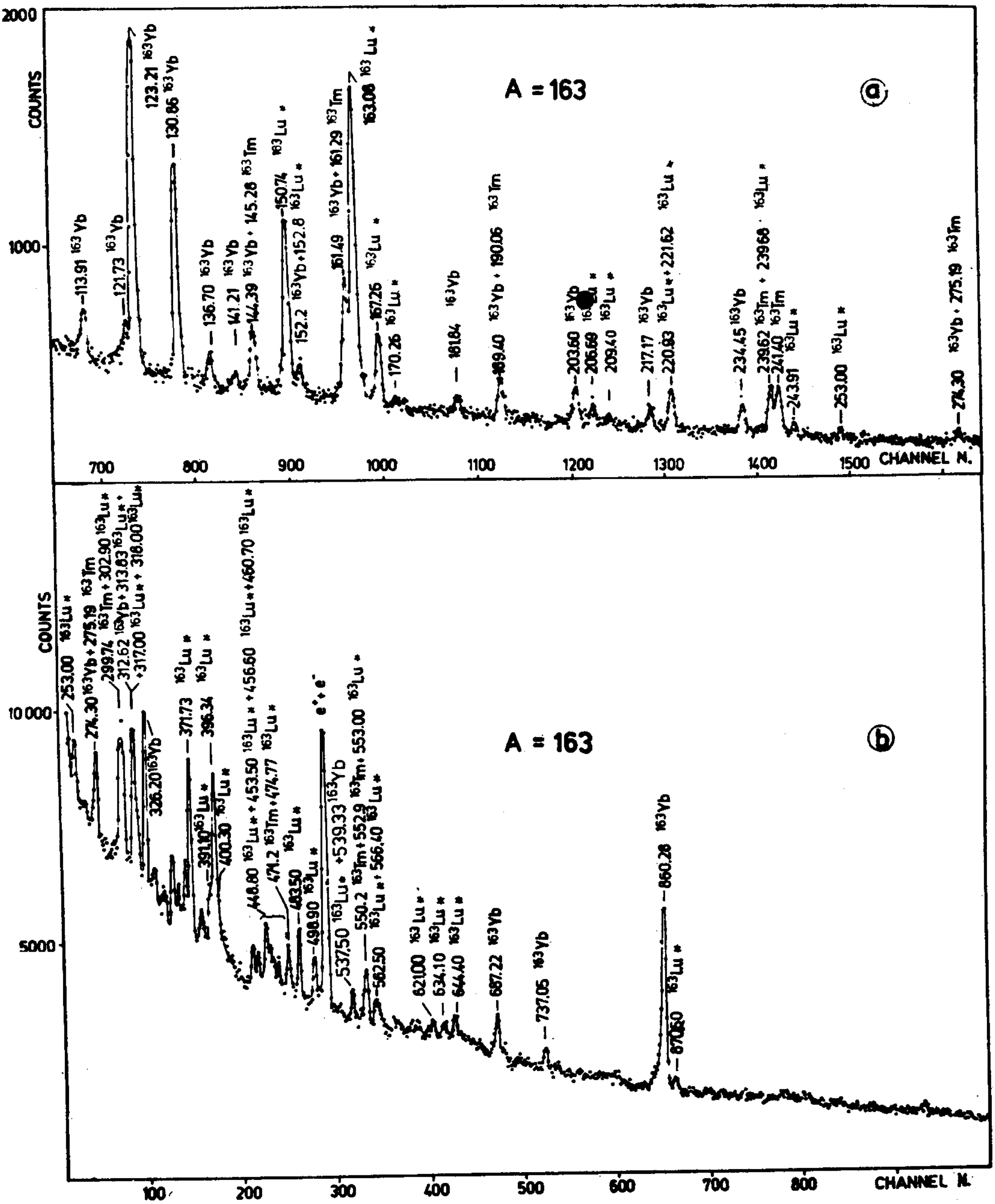

Fig. 2. Gamma-ray spectrum for the mass number $A = 163$ in the energy range 100–1000 keV (first time interval)

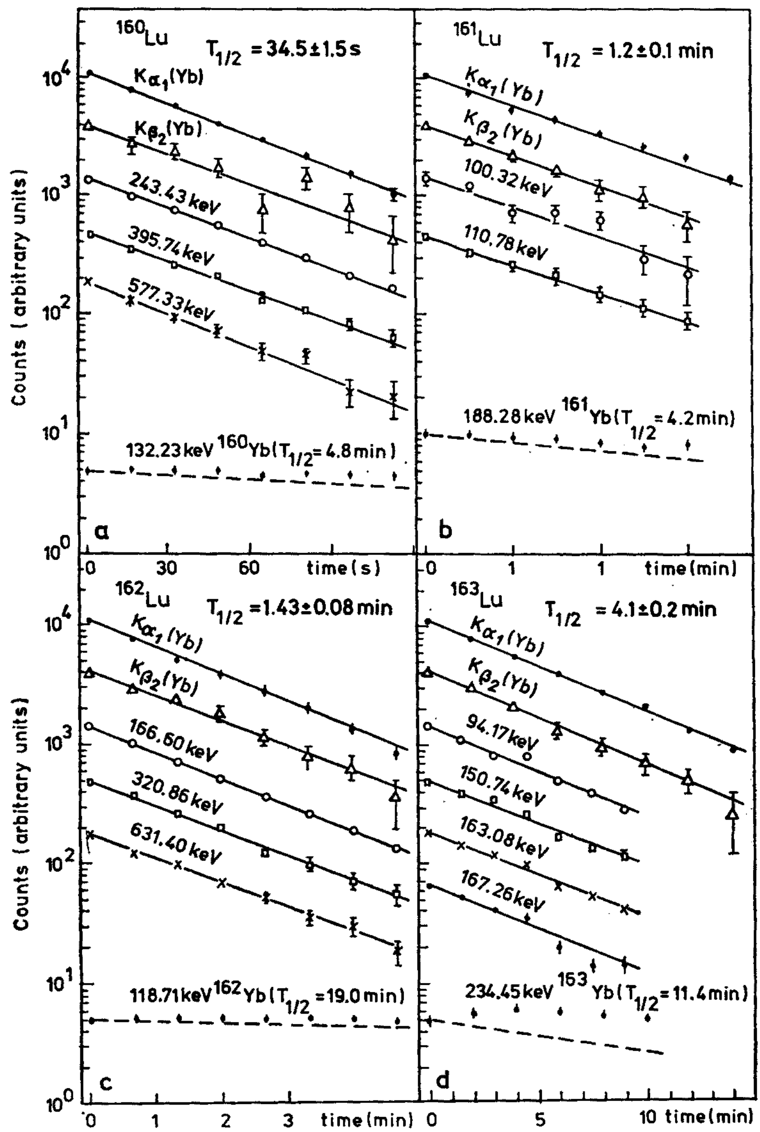

Fig. 3. Decay curves for Roentgen and γ-lines for investigated $^{160-163}$Lu isotopes

TABLE I

Energies and relative intensities of γ-transitions associated with the decay of 4.1 min ^{163}Lu

$E_\gamma \pm \Delta E_\gamma$ (keV)	$I_\gamma \pm \Delta I_\gamma$
54.00±0.10	88.0±8.0
75.00±0.10	2.2±0.7
79.19±0.05	3.8±0.7
93.33±0.10	5.4±1.0
94.17±0.05	12.0±2.0
96.49±0.05	9.6±1.8
98.11±0.05	5.4±1.0
102.50±0.10	7.4±1.5
150.74±0.05	45.0±5.0
152.82±0.10	5.0±1.5
163.08±0.05	100.0±10.0
167.26±0.05	22.0±3.0
170.26±0.10	1.5±0.5
206.69±0.15	8.2±2.0
209.40±0.15	2.6±0.8
220.93±0.10	18.0±4.0
221.62±0.15	12.0±3.0
239.68±0.10	18.5±4.0
243.91±0.15	6.2±1.5
253.00±0.10	7.1±1.5
302.90±0.15	28.0±4.0
313.83±0.15	24.0±3.0
317.00±0.20	11.0±3.0
318.00±0.30	6.0±2.0
371.73±0.10	62.0±10.0
391.10±0.20	20.0±3.0
396.34±0.10	63.0±7.0
400.30±0.20	16.0±2.0
448.80±0.20	30.0±5.0
453.50±0.30	17.0±3.0
456.60±0.40	11.0±3.0
460.70±0.40	16.0±3.0
474.77±0.40	12.0±4.0
483.50±0.20	32.0±6.0
498.90±0.30	15.0±5.0
537.50±0.50	5.0±2.0
553.00±0.30	32.0±5.0
562.50±0.40	16.0±3.0
566.40±0.50	11.0±2.0
621.00±0.50	16.0±4.0
634.10±0.50	14.0±4.0
644.40±0.40	18.0±3.0
870.50±0.40	15.0±4.0

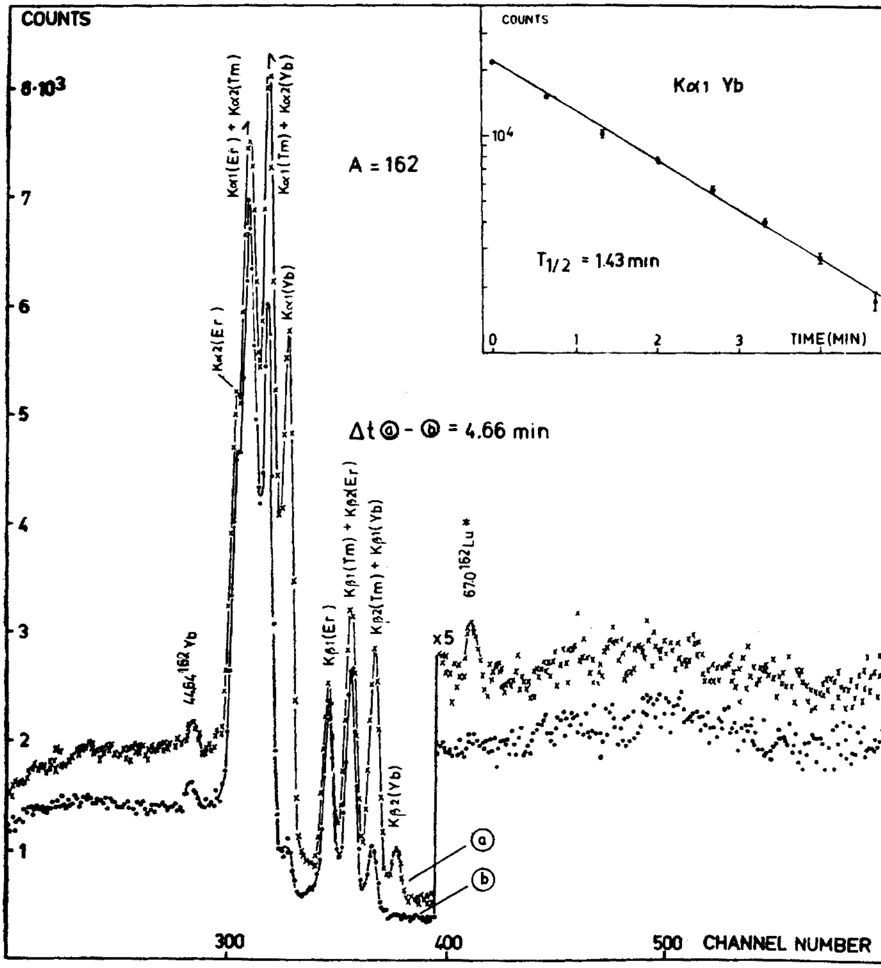

Fig. 4. Low energy part of the γ-ray spectrum for the mass number $A = 162$ in the first and in the last time interval

TABLE II

Energies and relative intensities of γ-transitions associated with the decay of 86 sec ^{162}Lu

$E_\gamma \pm \Delta E_\gamma$ (keV)	$I_\gamma \pm \Delta I_\gamma$
67.00 ± 0.15	1.0 ± 0.3
166.60 ± 0.10	100.0 ± 5.0
320.86 ± 0.10	20.0 ± 2.0
631.40 ± 0.10	28.0 ± 3.0
656.40 ± 0.20	6.7 ± 1.5
825.30 ± 0.20	18.0 ± 2.0
839.80 ± 0.30	7.7 ± 1.5

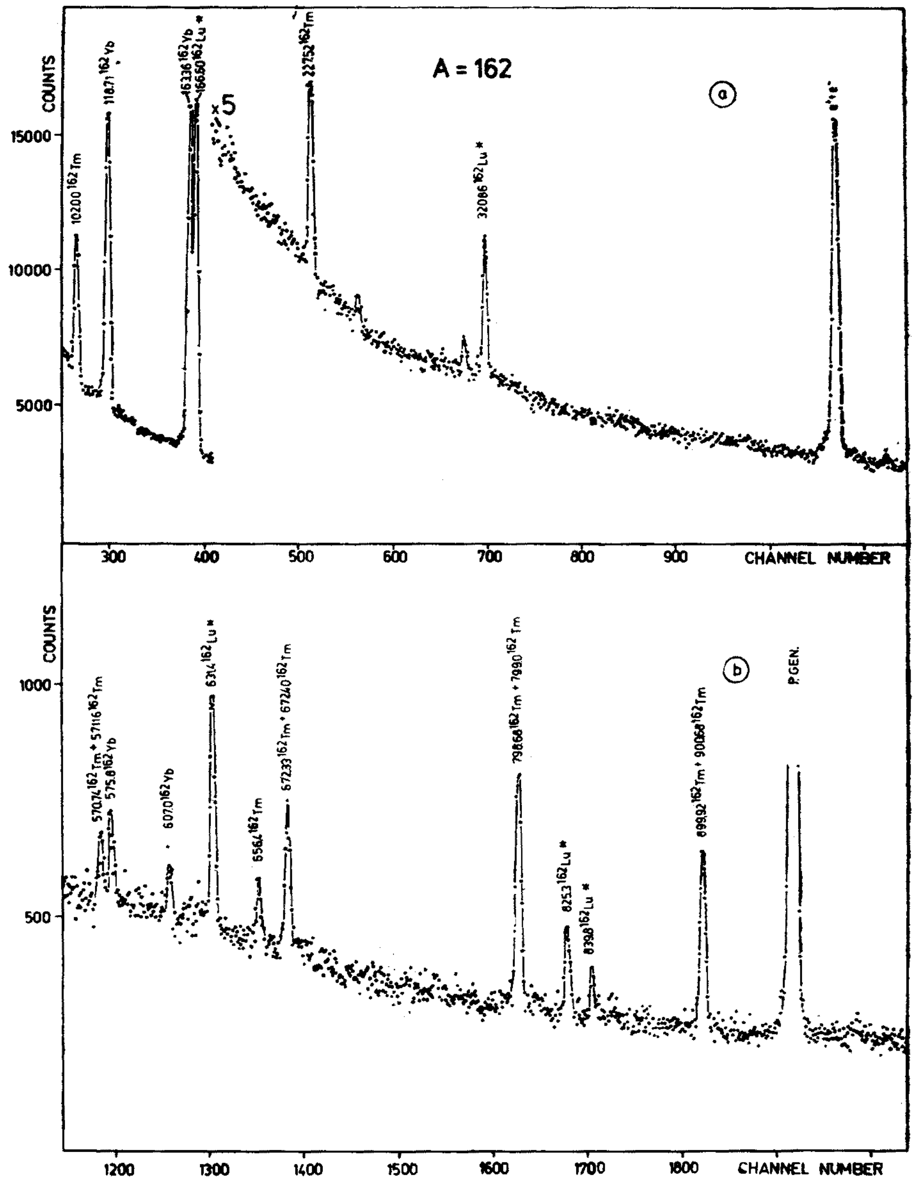

Fig. 5. Gamma ray spectrum for mass number $A = 162$ in the energy range 100–1000 keV (first time interval)

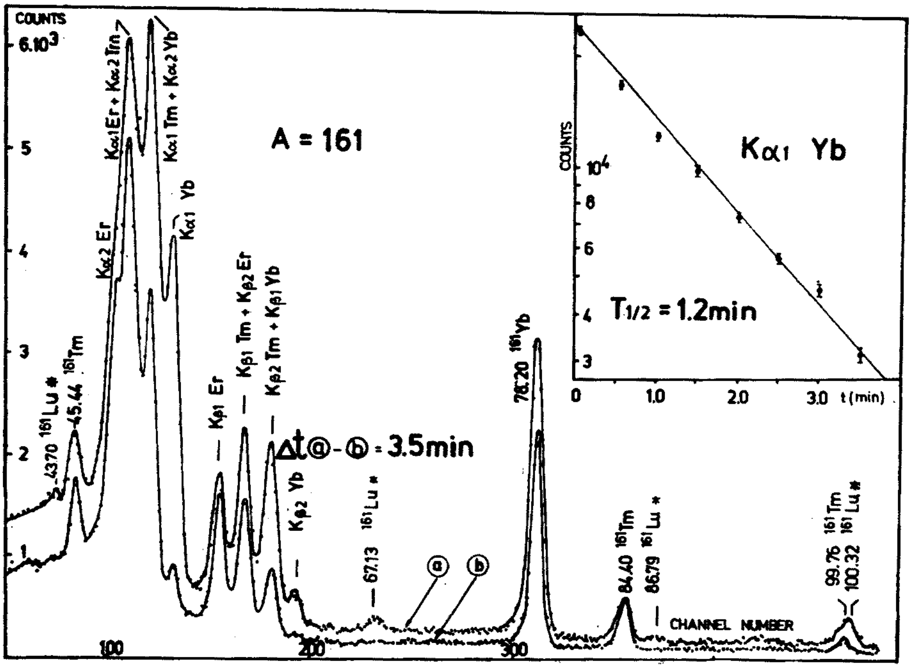

Fig. 6. Low energy part of the γ-ray spectrum for mass number $A = 161$ in the first and in the last time interval

TABLE III

Energies and relative intensities of γ-rays associated with the decay of 72 sec ^{161}Lu

$E_\gamma \pm \Delta E_\gamma$ (keV)	$I_\gamma \pm \Delta I_\gamma$
43.7±0.3	≈70
67.13±0.20	48±5
86.79±0.15	17±4
100.32±0.10	95±9
105.20±0.10	28±5
110.78±0.10	100±9
156.24±0.10	49±5
170.08±0.20	14±4
177.13±0.20	14±4
204.57±0.20	30±6
211.10±0.20	20±10
221.76±0.20	20±4
256.24±0.25	49±8

and ^{161}Tm γ-lines [17, 18]. They have the decay time close to that for the Lu → Yb Roentgen lines. We have ascribed them to the decay of the ^{161}Lu isotope on the basis of the same arguments as for ^{163}Lu. The decay curves for the new ^{161}Lu are shown in Fig. 3b, and

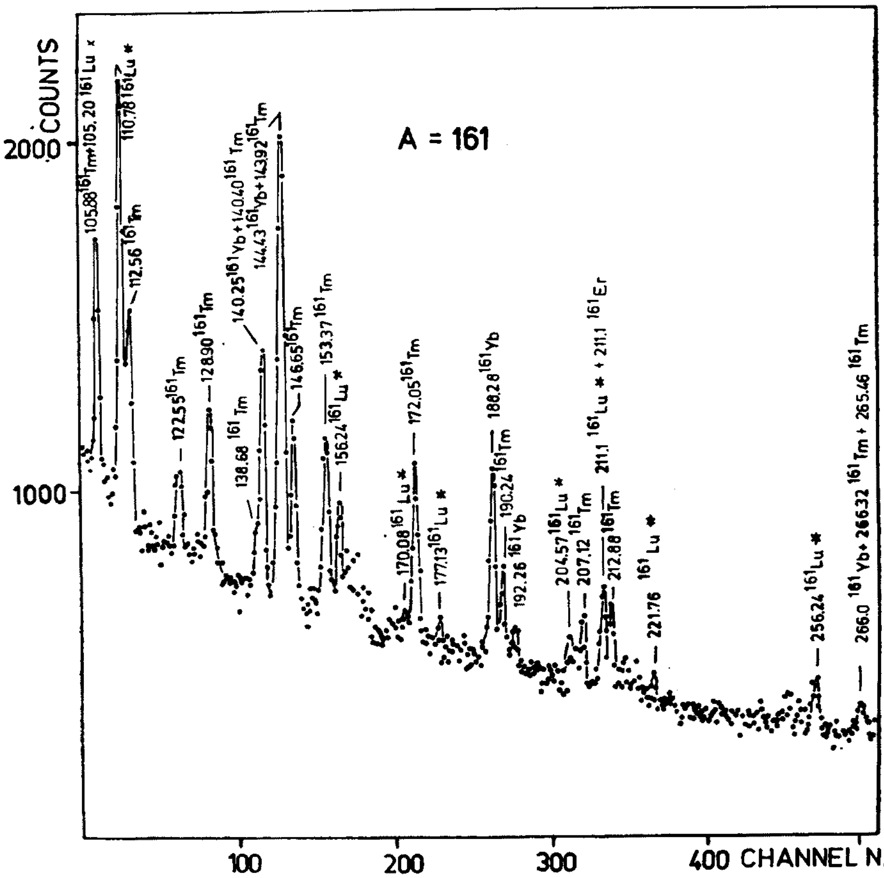

Fig. 7. Gamma-ray spectrum for mass number $A = 161$ in the energy range 100–300 keV

the accepted $T_{1/2}$ is 72 ± 6 sec. Energies and relative intensities of γ-lines are listed in Table III.

The ^{160}Lu isotope. For the mass number $A = 160$ the spectra are measured for the same energy range as for ^{163}Lu. Time intervals have been chosen 8×15 sec according to the half-life $T_{1/2} \approx 30$ sec expected from the systematics. On the X-ray spectrum in Fig. 8 short living Roentgen $K_{\alpha 1}$ and $K_{\beta 2}$ lines associated with the beta-decay of Lu are seen. The 8 γ-lines (see Table IV) in the γ-ray spectrum (Fig. 9) decay with the half-lives close to those of the Roentgen lines and we have assigned them to the decay of the new ^{160}Lu isotope. Other γ-lines seen on this figure belong to daughter isotopes mainly ^{160}Yb and ^{160}Tm [16, 19]. The accepted half-life for the ^{160}Lu is $T_{1/2} = 34.5 \pm 1.5$ sec (see Fig. 3a).

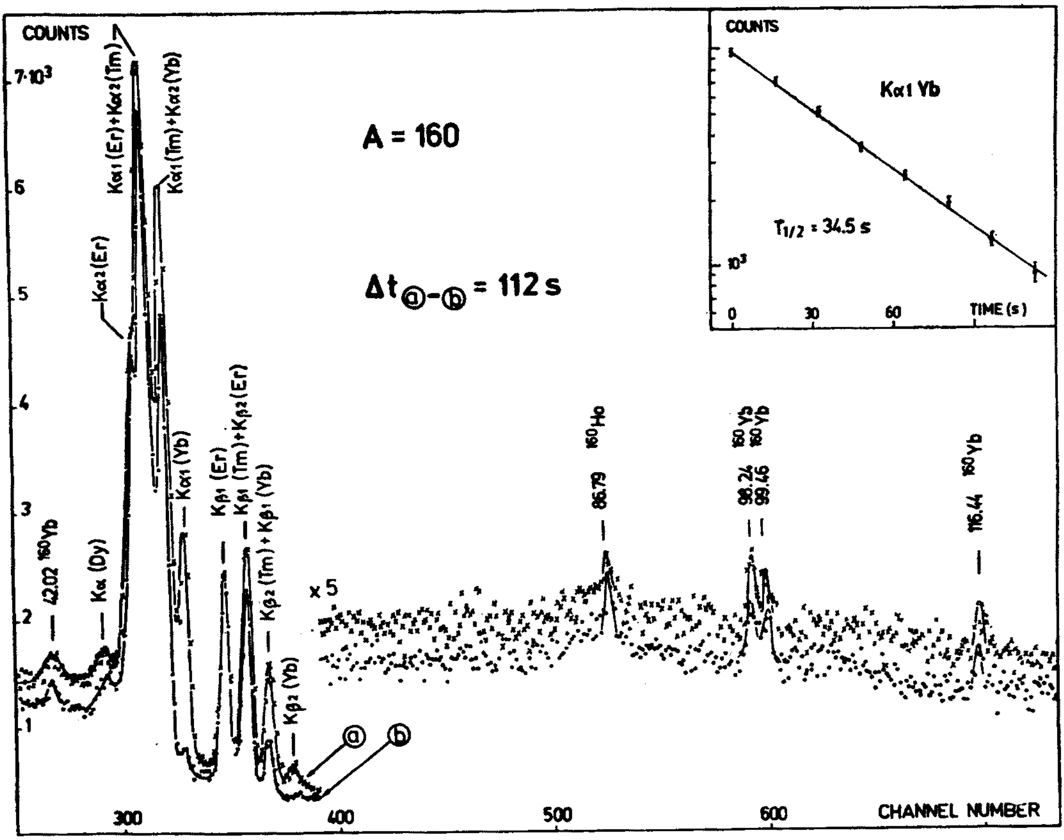

Fig. 8. Low energy part of the spectrum for the mass number $A = 160$ in the first and in the last time interval

TABLE IV

Energies and relative intensities of γ-rays associated with the decay of 34.5 sec ^{160}Lu

$E_\gamma \pm \Delta E_\gamma$ (keV)	$I_\gamma \pm \Delta I_\gamma$
243.43 ± 0.10	100.0 ± 5.0
375.65 ± 0.20	7.8 ± 1.7
395.74 ± 0.15	30.0 ± 2.0
577.33 ± 0.20	13.0 ± 1.5
704.38 ± 0.20	6.1 ± 1.5
738.22 ± 0.20	6.6 ± 1.5
820.12 ± 0.30	9.0 ± 1.5
870.67 ± 0.40	8.6 ± 1.5

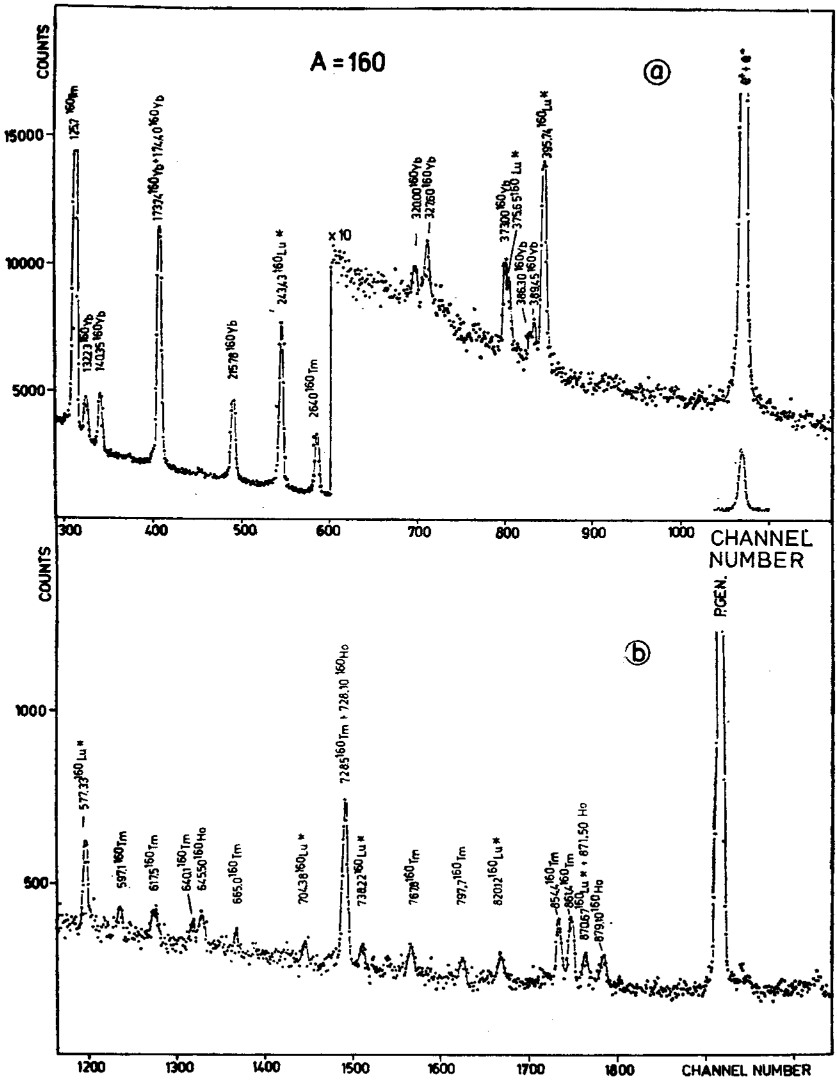

Fig. 9. Gamma-ray spectrum for the mass number $A = 160$ in the energy range 100–1000 keV

5. Discussion

In Table V the data on the new isotopes ^{160}Lu, ^{161}Lu, ^{163}Lu and data on the ^{162}Lu are collected. Half-lives obtained for the decay of these isotopes are in good agreement with the theoretical predictions by Takahashi et al. [20].

On the basis of the presented results, and the data obtained from the studies of excited levels in Yb nuclei, one can try to construct rough decay schemes for the investigated Lu isotopes. For even nuclei $^{160,\,162}Lu$ the preliminary decay schemes shown on Fig. 10 are in agreement with [11, 12].

TABLE V

Summary of data on $^{160-163}$Lu isotopes

Nucleus	Type of radiation	Accepted exp. $T_{1/2}$ (sec)	Predicted [20] theor. $T_{1/2}$ (sec)	Remarks
^{160}Lu	X: $K_{\alpha 1}$, $K_{\beta 2}$ γ: 8 transitions	34.5±1.5	30	first identification
^{161}Lu	X: $K_{\alpha 1}$, $K_{\beta 2}$ γ: 13 transitions	72±6	80	first identification
^{162}Lu	X: $K_{\alpha 1}$, $K_{\beta 2}$ γ: 7 transitions	86±5	80	84±9 sec [6]
^{163}Lu	X: $K_{\alpha 1}$, $K_{\beta 2}$ γ: 43 transitions	246±12	180	first identification

For the odd isotopes $^{161, 163}$Lu the preliminary decay schemes proposed only on the basis of energy and intensity balances are demonstrated in Fig. 11.

Since the γ-spectrum for ^{161}Lu was measured only below 300 keV the proposed excited states in ^{161}Yb do not include excited levels above the energy of 400 keV. The energies of first and second excited states agree with the energies obtained in the "in-beam"

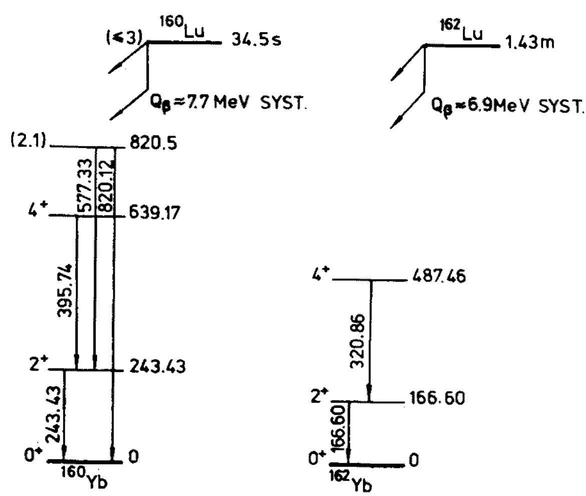

Fig. 10. Preliminary decay schemes for even ^{160}Lu and ^{162}Lu nuclei

studies of rotational bands in ^{161}Yb [13]. The most probable assignment of Nilsson orbital to the 91-th neutron in the ground state of ^{161}Yb is 3/2⁻ [532] or 3/2⁻ [521].

The decay scheme for ^{163}Lu was constructed considering only the levels, based on three or more γ-transitions, according to the energy balance. Taking this into account, some strong γ-transitions (for example 163.08(100), 313.83(24), 391.10(20), 448.8(30),

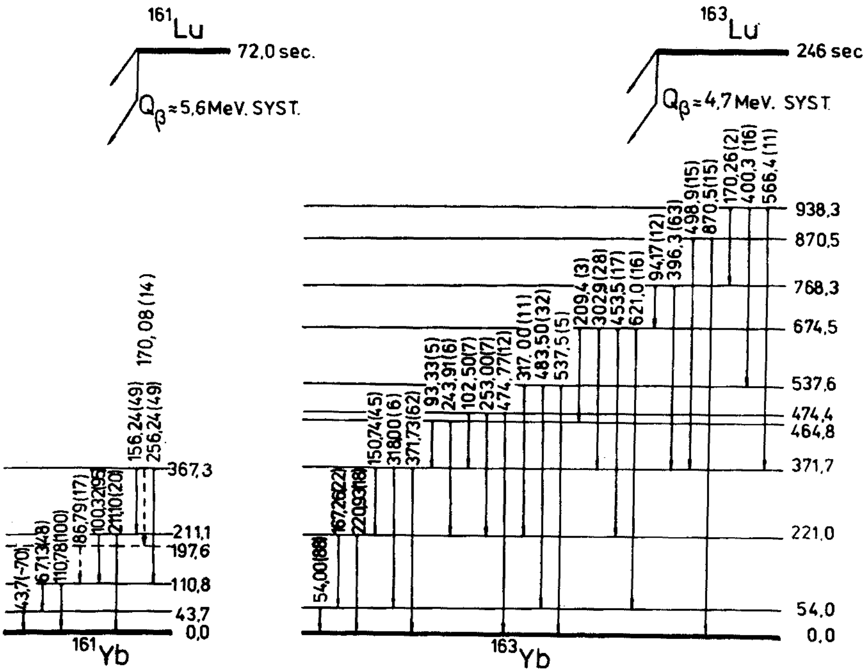

Fig. 11. Preliminary decay schemes for odd ^{161}Lu and ^{163}Lu isotopes

553.0(32), ...) have been not included into the tentative decay scheme proposed in Fig. 11. The first excited state at the energy of 54.0 keV agrees with that proposed in reference [13]. According to the analysis of the ground state rotational band in ^{163}Yb, studied "in-beam" in [13], the assignment of Nilsson orbital associated with the 93th neutron in the ground state of ^{163}Yb nucleus is 3/2$^-$ [521].

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