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1. Introduction

Already in 1961 Sheline et al.[1] postulated a new region of deformation containing the strongly neutron-deficient nucleides with $Z > 54$, $N < 78$. In the meantime, many experimental data have been accumulated which proved this assumption to be true. Most convincing are those experiments in which the ground-state rotational bands of even-even nuclei of this region were observed[2,3]. A further argument in favor of the proposed deformation is the lifetime of the first excited 2^+ state of such nuclei[2,4]. There are, however, also arguments against the assumption of a stable deformation because the observed ground-state rotational bands do not observe the $I(I+1)$ rule characteristic for a well-behaved deformed nucleus, and the enhancement of the quadrupole transitions could be caused by a dynamic instead of a static quadrupole moment. In any case, one has to assume that the nuclei in question are much softer than those in the classical regions of deformation. One has, therefore, to take into account strong rotation-vibrational coupling in order to explain their spectra. Furthermore, in the new region of deformation one expects competition between positive (prolate) and negative (oblate) deformation. Already Kumar and Baranger[5] pointed out that in this region oblate deformation should be more stable than prolate deformation. Recent calculations by Soloviev's group[6,7] confirmed this but showed at the same time that the binding energy difference between the minimum at positive and negative deformation is rather small ($\lesssim 0.5$ MeV), and that the nuclei are very soft against γ-deformation. This is a further argument to assume a strong coupling of the rotational motion not only to the β-vibration but also to the γ-vibrational mode. By observing the rotational or quasirotational ground-state bands of even nuclei one cannot discriminate between oblate and prolate deformations. This is, however, possible if one is able to identify definite Nilsson orbitals in odd-mass nuclei of this region, because the one-quasiparticle level schemes are completely different for oblate and prolate shape of the same nucleide. It is difficult to apply to this end the ordinary methods of nuclear spectroscopy because of the short half-life and the large decay energy (leading to very complex spectra) of the interesting nucleides. Therefore, very little is known so far about the level schemes and even the ground state spins of these very neutron-deficient odd-mass nuclei.

The identification of an isomeric state can be of help in this respect because it may have a simple decay scheme which can be studied separately. Sometimes the very existence of an isomeric state may be used as an argument in favor of a definite deformation of the nucleus in question. So, the detection of isomeric states in ^{129}Ba by Li et al./8/ and in ^{125,127}Ba by D'Auria et al./9/ was interpreted as an indication for oblate deformation of these nuclei. In this paper we describe experiments which led to the observation and identification of an isomeric state in ^{129}La, giving strong evidence for a stable oblate deformation of that nucleus+).

+) Part of the experimental data and their interpretation were already published as a Short Communication to the Dubna Symposium/10/. In an earlier, preliminary report/11/ the isomeric activity was erroneously ascribed to ^{128}La.

2. Production and Identification of ^{129m}La

The experiments were conducted initially at the external beam of the cyclotron for heavy ions U-150 and later on continued at the beam of the cyclotron U-300 using essentially the same experimental setup. The energy of the bombarding ions was determined by calibrated Al foils introduced into the beam about 50 cm in front of the target. After transversing the target (ordinarily a few mg/cm^2) the beam was stopped in a Faraday cup. To observe short-lived activities the beam was pulsed by modulating the hf voltage on the dees. Between beam pulses, the induced activities were observed using a suitably timed multichannel analyzer. Gamma-ray spectra were taken with a NaJ(Tl) scintillation spectrometer or with a Ge(Li) spectrometer. The geometrical arrangement of target chamber and detector on the beam line is shown in fig.1. Using this arrangement, a new activity with a half-life $T_{1/2}$=(0.56 $\pm$ 0.05) sec was found in bombarding an Antimony target with Carbon ions. Ordinarily, the measurements were made with natural Sb targets prepared by evaporation on Al foils. Bombardment of an enriched target (^{121}Sb, 99.6%) showed, however, that the isotope ^{121}Sb is responsible for the observed reaction. The same activity was produced bombarding enriched targets of ^{118}Sn, ^{119}Sn and ^{120}Sn with ^{14}N ions. The measured excitation functions were of the typical form for neutron evaporation. To exclude with certainty the possibility that the activity was formed by charged-particle evaporation (i.e. by (H.I., pxn)-or (H.I., α xn)-processes) several cross-bombardments were undertaken. In table I the target-ion combinations are listed which were used to determine the atomic and mass number of the new activity. In table 2 are given the cross-bombardments and the possible charged-particle evaporation reactions which can be excluded by the negative outcome of these runs. These experiments led to the conclusion that the 0.56 sec activity is formed via (H.I., xn)-reactions and belongs, therefore, to an isotope of Lanthanum. Later on, this was confirmed by the precise measurement of conversion electrons (see below).

To determine the mass number of the La isotope one has to analyze excitation functions. For (H.I., xn)-reactions one may guess the number x of evaporated neutrons from the empirical relation due to Simonoff and Alexander/12/

$$\frac{E_{exo} - \sum_{i=1}^{x} B_{ni}}{x} = \frac{\epsilon_x}{x} = \bar{\epsilon} ,$$

where E_{exo} is the excitation energy of the compound nucleus corresponding to the maximum of the excitation function, and B_{ni} is the binding energy of the i-th neutron. In the region of $A \approx 150$ studied by Simonoff and Alexander the mean energy carried off per evaporated neutron (containing the kinetic energy of the neutrons and the rotational energy carried off mainly by γ -rays) lies between 5 and 6.5 MeV. An analysis of available excitation functions showed/13/ that this relation holds true also in the mass region of interest here. Fig.2 shows the excitation function of the 0.56 sec activity for the reaction $^{121}Sb + {}^{12}C$. Using the formula we obtain from the maximum of the excitation curve

$$\epsilon_3/3 = (10.8 \pm 1.0)\ \text{MeV}$$
$$\epsilon_4/4 = (6.2 \pm 0.7)\ \text{MeV}$$
$$\epsilon_5/5 = (2.6 \pm 0.6)\ \text{MeV.}$$

The conclusion is that four neutrons were evaporated. The activity belongs, therefore, to the nucleide ^{129}La . In order to confirm this identification the excitation functions for the production of ^{128}La (6 min) and ^{130}La (9 min) by the reaction $Sb(^{12}C, xn)$ were measured. For this experiment a stack of thin natural Sb targets (3.3 mg/cm^2 on 1.7 mg/cm^2 Al backings) was irradiated for 7 min with 81 MeV Carbon ions. The activity of the foils was measured with a scintillation spectrometer. Using the relative intensities of the 280 keV γ -line from the decay of ^{128}La and of the 360 keV γ -line from the decay of ^{130}La the excitation curves for the reactions $^{121}Sb(^{12}C,5n)^{128}La$ and $^{121}Sb(^{12}C,3n) + {}^{123}Sb(^{12}C,5n)^{130}La$ were obtained (natural Sb contains 57 % ^{121}Sb and 43% ^{123}Sb , the energy of the bombarding ions was not sufficient to evaporate more than 5 neutrons) . Fig.3 shows that the maximum of the 5n reactions was not yet reached with the ion

energy available, whereas the maximum corresponding to the 3n reaction appears, as expected, below the maximum of the 4n reaction leading to ^{129m}La .

The gamma-ray spectrum of ^{129m}La measured with the Ge(Li) -detector is shown in fig.4. Because of the encapsulation of the detector it was not possible to observe the X -rays in this arrangement. The X -rays could, however, be measured using the scintillation detector (fig.5) . The γ -lines have the same excitation function and the same half-life of (0.56$\pm$0.05) sec (fig.7). Relative intensities of the observed γ -rays, after correcting for detector efficiencies, escape, and fluorescence yield (for the X -ray) are given in table 3.

3. Measurement of Conversion Electrons

Conversion electrons from the decay of ^{129m}La were first measured with a liquid-nitrogen cooled Li -drifted Silicon detector mounted inside the target chamber above the target (distance $\approx$ 4 cm). The electron spectrum obtained is shown in fig.6. A strong line corresponding to L + M conversion of the 104 keV transition is clearly seen, but the detector did not resolve the K conversion line of this transition and the conversion electrons from the 67.5 keV transition. Comparing very roughly absolute intensities measured with the Si - and NaJ -detectors we obtained a conversion coefficient $\alpha_{L+M} = 25 \pm 15$ for the 104 keV transition.

A more precise measurement of conversion electrons was possible using the iron-free toroidal β -spectrometer which was built at the University of Warsaw/14/ and installed at the ion beam of the cyclotron U-300 (fig.8). With this instrument, the electron spectrum was measured between beam pulses using the normal duty cycle of $\approx$ 5 msec determined by the pulsed ion source of the cyclotron. Because of the low over-all efficiency of such a single channel instrument it was not possible, in order to discriminate against long-living background activities, to use an early-late timing cycle as we did with the scintillation and solid-state spectrometers.

The technique could only be applied to a few spectrometer settings to see whether or not an electron line belonged to the isomeric activity. Fig.9 shows the electron spectrum from the reaction Sb(^{12}C,xn). The electron lines corresponding to K, L, M -conversion of the 104 keV transition and to L -conversion of the 67.5 keV transition are clearly seen. In a special measurement, the decay of the L-conversion electron line from the 104.5 keV transition was followed for more than two half-lives. The measured half-life coincided with that of the γ -lines measured with the Ge detector (fig.7). Furthermore, the β -spectrometer allows to determine the transition energies more precisely. Table 4 gives the energies and relative intensities of the conversion electrons. The energy difference $\Delta E = 33.4 \pm 0.5$ keV between the K and L-conversion lines of the 104 keV transition coincides with the theoretical value $\Delta E = 33.24$ keV expected for $Z = 57$, so we have an independent proof that the isomeric activity belongs to a Lathanum isotope.

4. The Decay Scheme of ^{129m}La and Its Interpretation

The data contained in the tables 3 and 4 allow to construct the decay scheme of the isomeric state. Theoretical internal conversion coefficients /15/ for both observed transitions are collected in table 5. The experimental values are consistent with the multipolarities E3 and M1 for the 104 and 67.5 keV transitions, respectively. This is confirmed by comparing the intensities of the γ -rays with the X -ray, produced by K -conversion of these γ -rays. We should have

$$\frac{I_{\gamma 67}\,\alpha_{K67} + I_{\gamma 104}\,\alpha_{K104}}{I_x} = 1.$$

The experimental value, using theoretical conversion coefficients, is 0.85 ± 0.20. Furthermore, the intensity relations between the γ-rays are in accord only with the assumption that both transitions form a cascade. Under this condition we expect

$$\frac{I_{\gamma 104}\,(1+\alpha_{tot})_{104}}{I_{\gamma 67}\,(1+\alpha_{tot})_{67}} = 1.$$

The experimental value is 0.95 ± 0.25. We think, therefore, that the decay scheme given in fig.10 is experimentally well established.

The very existence of the isomeric transition in a nucleus with 57 protons cannot be understood assuming a spherical shape and using the spherical shell model. However, if we look up the Nilsson scheme for a deformed nucleus the lowering of the state $11/2^-$[505] for oblate deformations can be made responsible for the observed isomerism. This is confirmed by the calculations of Arseniev et al./7/. These authors calculated energies and equilibrium deformations of one-quasiparticle states taking into account the pairing interaction and Coulomb repulsion. The results for ^{129}La agree very well with our experimental findings (fig.10).

We may, therefore, conclude that the nucleus ^{129}La has indeed an oblate deformation in its ground and low-lying excited states.

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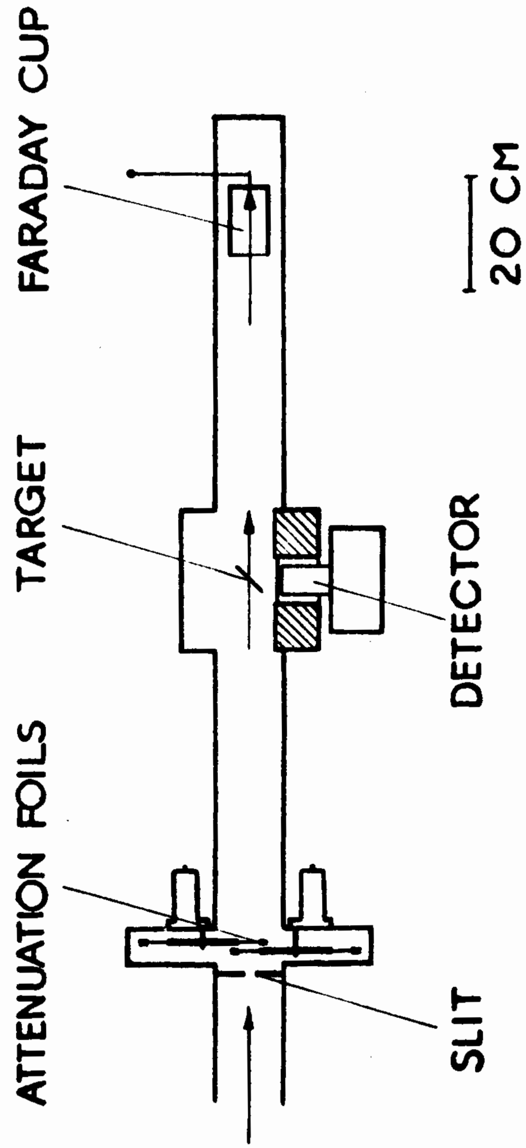

Fig.1 Schematic view of experimental arrangement for measuring γ-rays from isomeric activities by irradiation with heavy ions.

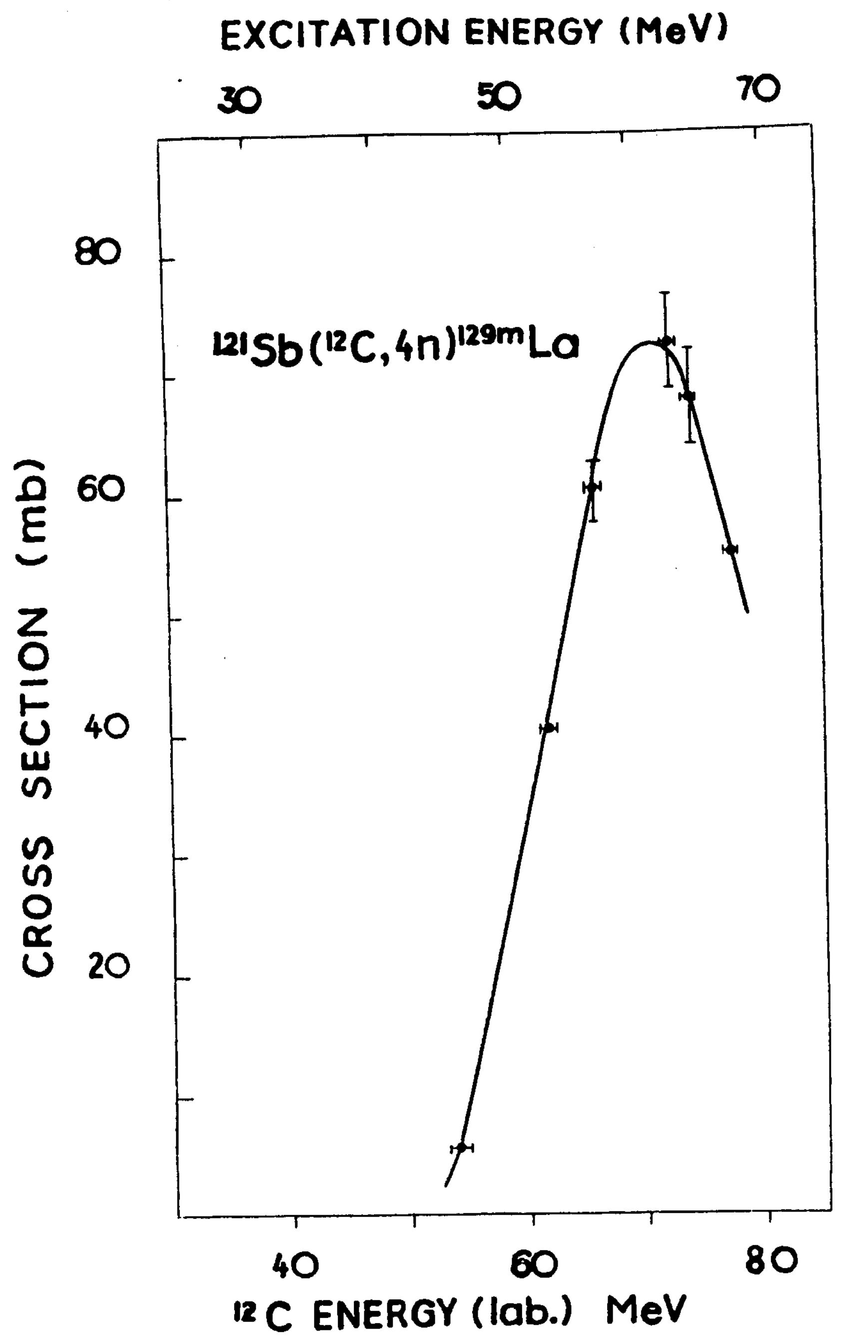

Fig. 2. Excitation function of the reaction $^{121}Sb(^{12}C, 4n)^{129m}La$. Absolute cross section from intensity measurement of 67.5 keV γ-ray, taking into account internal conversion.

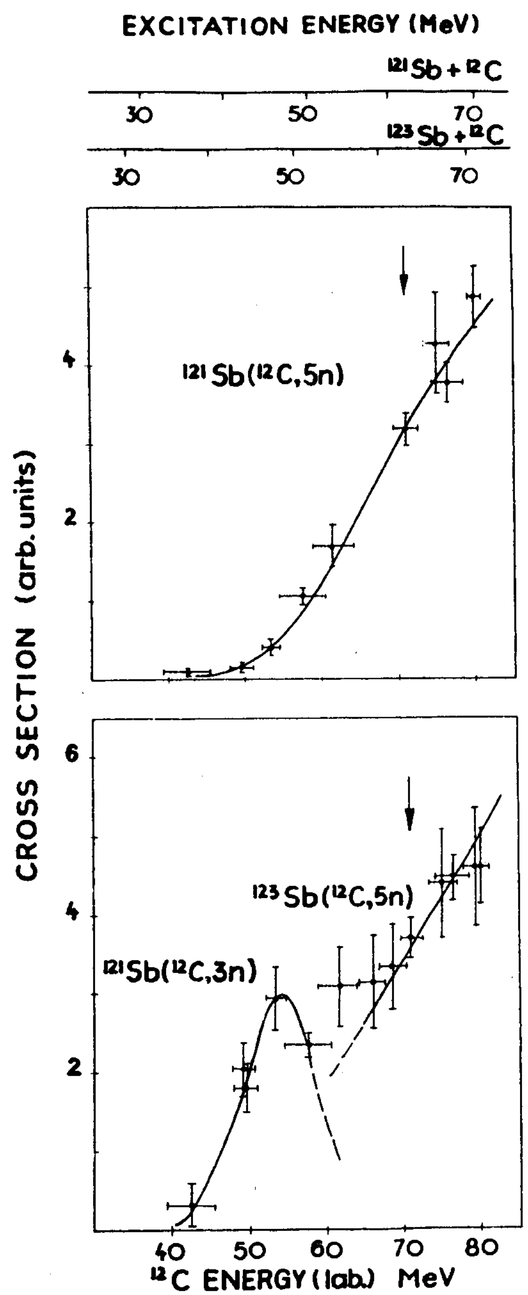

Fig. 3 Excitation functions for production of ^{128}La and ^{130}La in $Sb(^{12}C,xn)$--reactions. Arrow indicates maximum of the excitation function $^{121}Sb(^{12}C, 4n)$ ^{129m}La (see fig. 2).

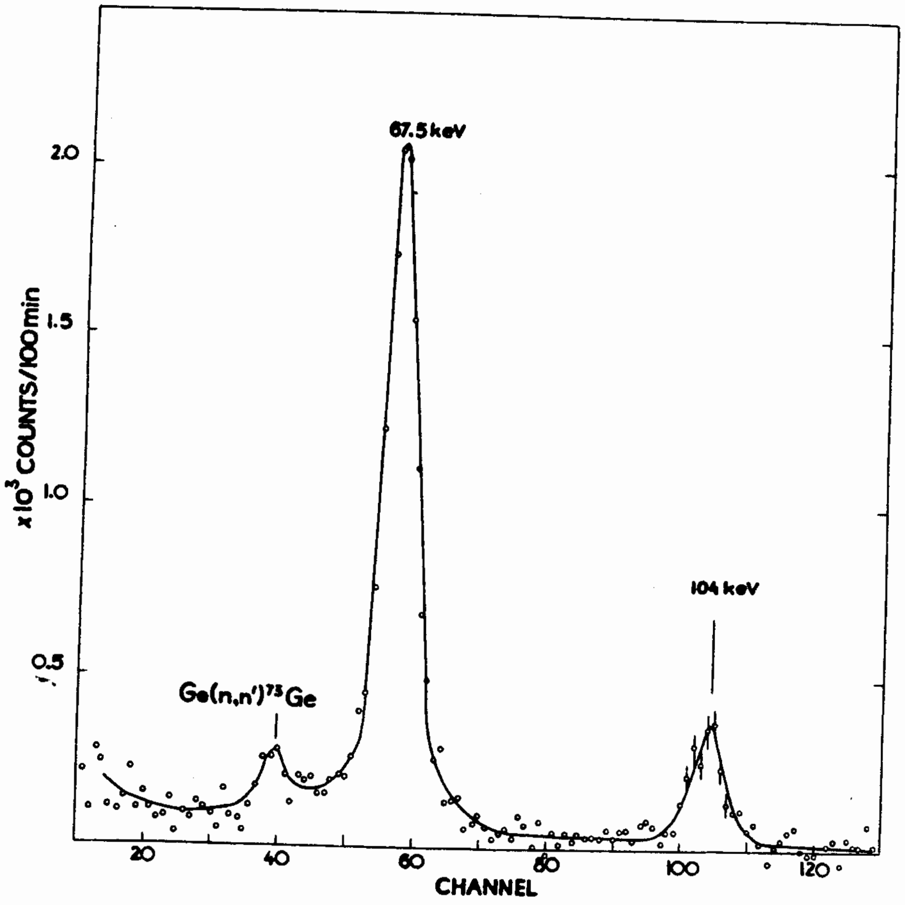

Fig.4. γ -ray spectrum of ^{129m}La produced in the reaction ^{121}Sb(^{12}C,4n). Ge(Li) -detector, 2.5 mm thick. Timing cycle : Activation 0.20 sec, spectrum measurement in 16 groups, 0.25 sec each. Shown is difference between first and 16 th group.

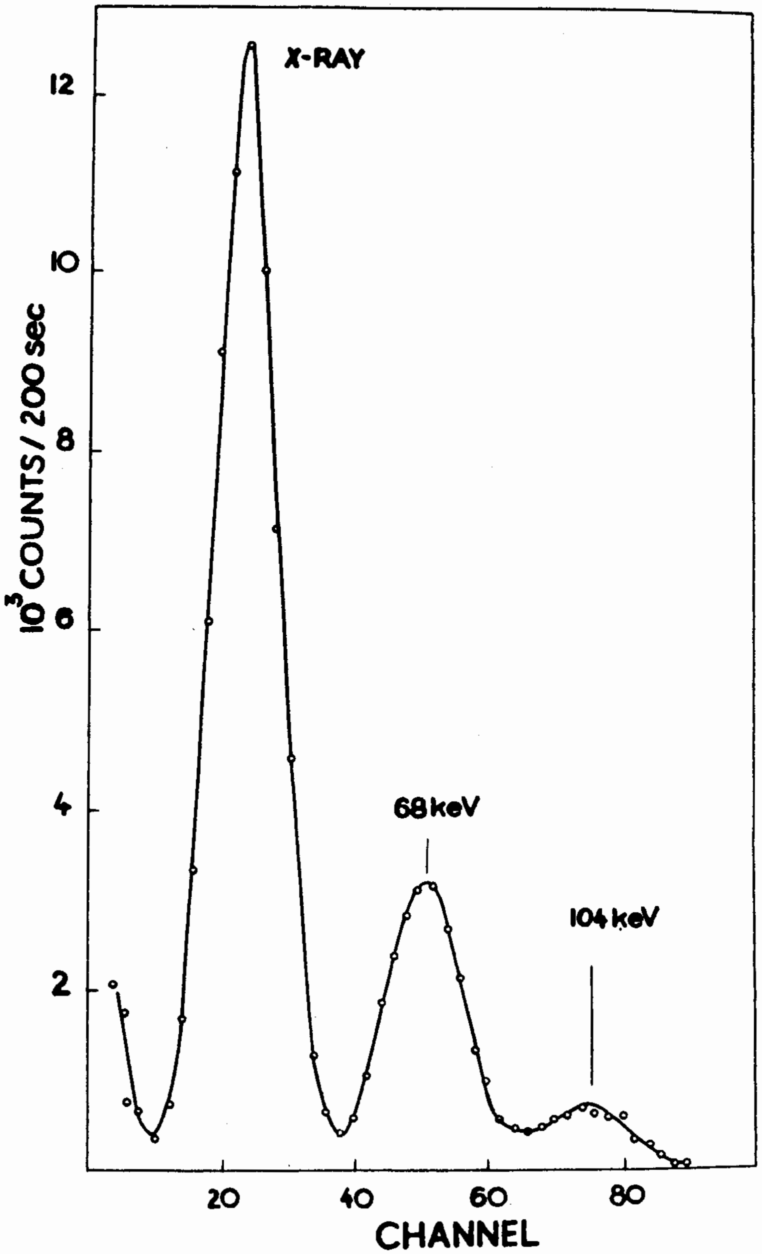

Fig.5. γ -ray spectrum of ^{129m}La produced in the reaction ^{119}Sn(^{14}N,5n). NaJ(Tl) -detector
Timing cycle: Activation 0.20 sec, effect measurement 1.6 sec, waiting time 0.5 sec, background measurement 1.6 sec. Shown is difference between effect and background measurements.

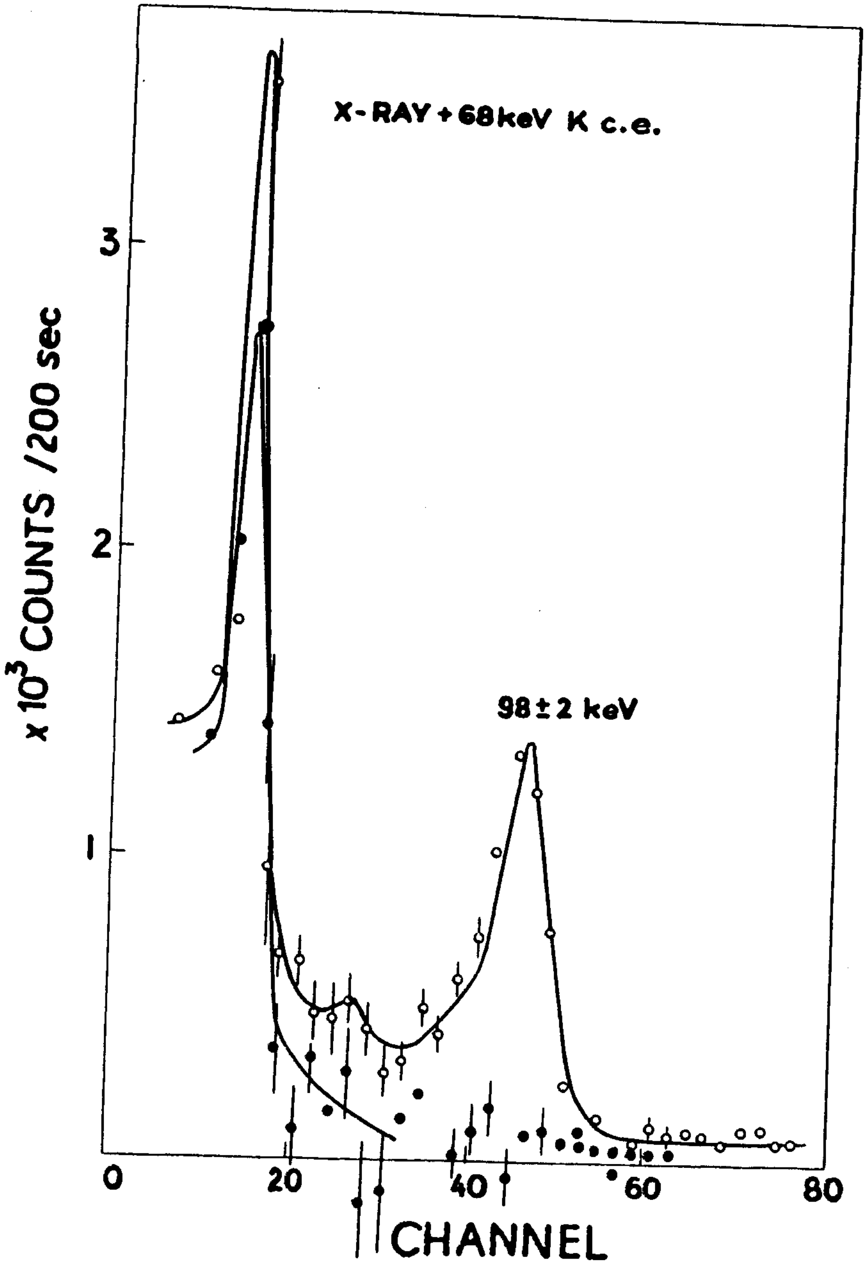

Fig.6. Conversion electron spectrum of ^{129m}La produced in the reaction $^{121}Sb(^{12}C,4n)$. Si(Li) -detector 0.65 cm^2, 2.3 mm thick. Same timing cycle as in fig.5. Black circles: Spectrum measurement with 30 mg/cm^2 Al absorber in front of detector.

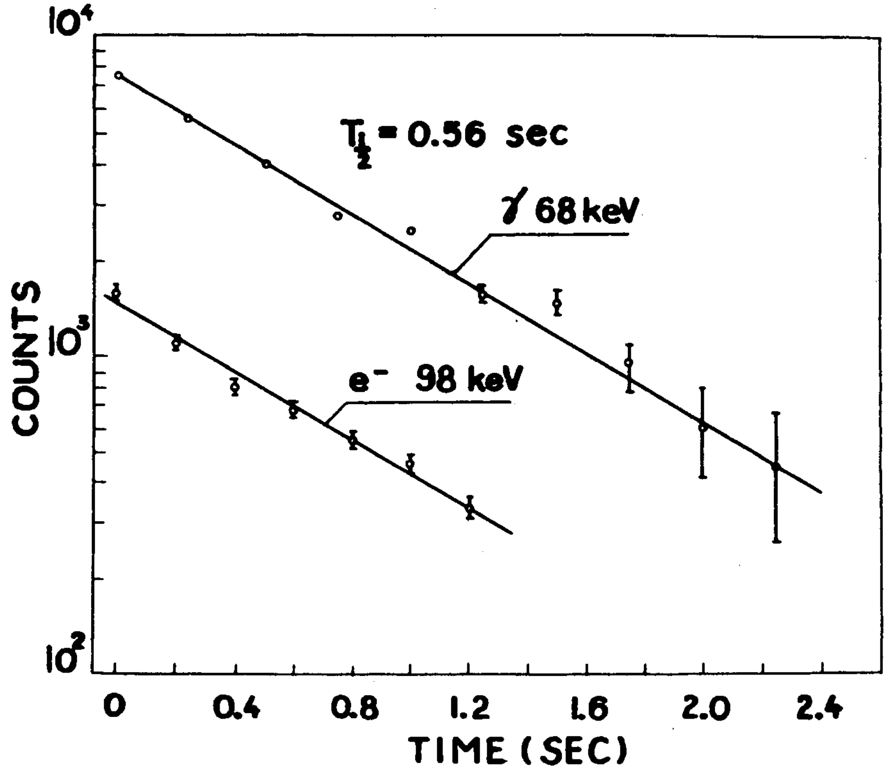

Fig.7 Decay curves of the 67.5 keV γ-ray and the 98 keV electron line belonging to ^{129m}La .

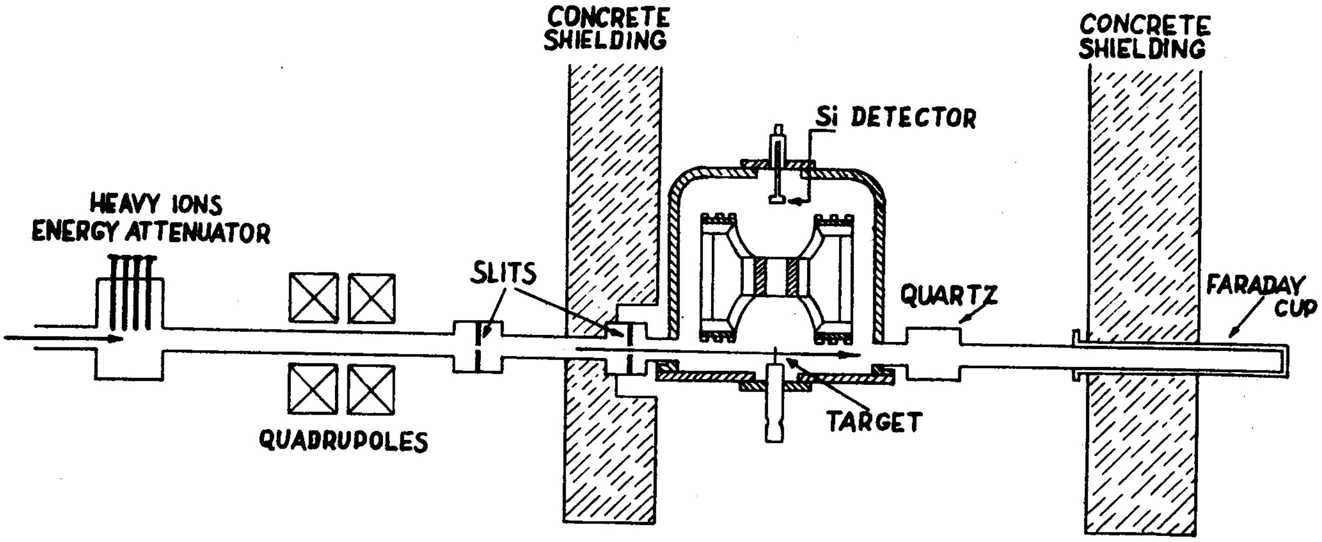

Fig.8 Schematic view of the toroidal iron-free β -spectrometer on the heavy-ion beam of the cyclotron U-300.

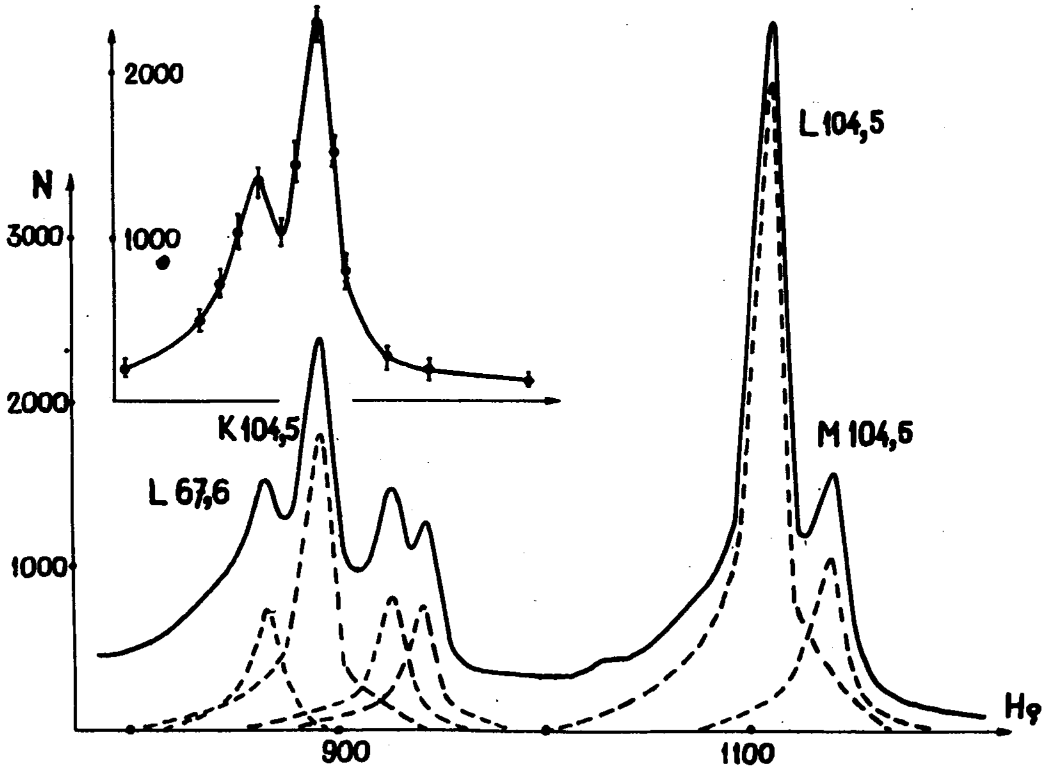

Fig. 9. Electron spectrum of the reaction $^{121}Sb(^{12}C,4n)^{139m}La$ measured with the toroidal β -spectrometer shown in fig.8. Insert shows difference spectrum measured with an early-late timing cycle. It proves that the lines at 70.3 and 71.3 keV do not belong to the isomeric activity.

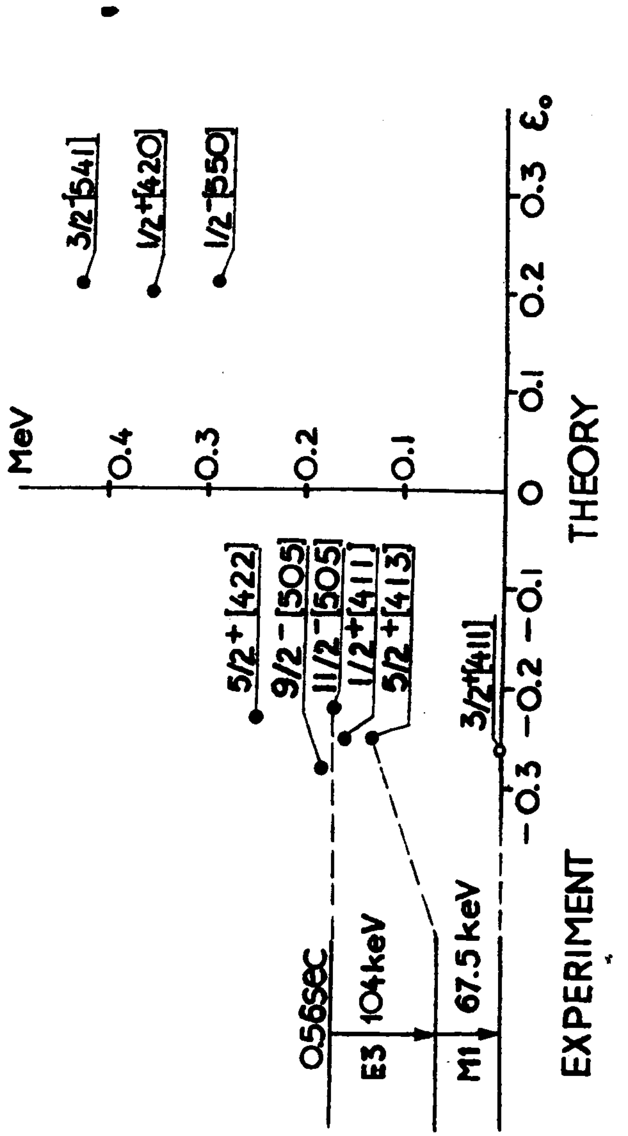

Fig.10 Comparison of the experimental decay scheme of ^{129m}La (left) with the calculated position of Nilsson orbitals in ^{129}La (see ref.7). Abscissa gives calculated equilibrium deformation of the states.

Table 1 Heavy-ion reactions in which the 0.56 sec isomeric activity was observed

Target	Ion	Ion energy range (MeV)	Maximum of exc.funct.	Interpretation
Sb natural 5.4 mg/cm^2 on 1.8 mg/cm^2 Al foil	^{12}C	50 - 81	72	^{121}Sb(^{12}C,4n)
Sb natural 3.7 mg/cm^2 self-supp.	^{12}C	50 - 83	74	^{121}Sb(^{12}C,4n)
^{121}Sb (99.6%) 15 mg/cm^2 on 1.8 mg/cm^2 Al	^{12}C	80	--	^{121}Sb(^{12}C,4n)
^{118}Sn (95.5%) 30 mg/cm^2 self-supp.	^{14}N	55 - 90	≈ 65 [a]	^{118}Sn(^{14}N,3n)
^{119}Sn (86.9%) 35 mg/cm^2 self-supp.	^{14}N	60 - 100	≈ 80 [a]	^{119}Sn(^{14}N,4n)
^{120}Sn (94.1%) 40 mg/cm^2	^{14}N	75 - 110	≈ 95 [a]	^{120}Sn(^{14}N,5n)
In natural 26 mg/cm^2 self-supp.	^{18}O	86	--	^{115}In(^{18}O,4n)

[a]) Value obtained by differentiating integral yield curve.

Table 2 Cross-bombardments in which the 0.56 sec isomeric activity was not observed

Target	Ion	Ion energy range (MeV)	Reactions excluded
^{120}Sn (94.1%) 40 mg/cm^2	^{12}C	55 - 81	$^{121}Sb(^{12}C,pxn)^{127,128}Ba$
^{122}Sn (80.2%) 42 mg/cm^2	^{12}C	55 - 81	$^{121}Sb(^{12}C,pxn)^{129,130}Ba$
^{116}Cd (86.6%) 3.6 mg/cm^2	^{15}N	60 - 100	$^{121}Sb(^{12}C,\alpha xn)^{126,127,128}Cs$

Table 3 Gamma-rays from the decay of ^{129m}La

Energy (keV)	Relative intensity
104 ± 2	0.18 ± 0.05
67.5 ± 1	1.00
35 ± 5 (X-ray)	4.7 ± 0.8

Table 4 Internal conversion electrons from the decay of ^{129m}La

Electron energy (keV)	Rel. intensity	Interpretation
62.0 ± 0.3	0.22 ± 0.1	L 67.6
65.6 ± 0.3	0.51 ± 0.11	K 104.5
98.8 ± 0.3	1.0	L 104.5
103.6 ± 0.3	0.26 ± 0.08	M 104.5

Table 5 Conversion coefficients for Z = 57 /15/

keV	Shell	E1	E2	E3	M1	M2	M3	exp.
67.5	K	0.56	3.5	15	2.9	34	250	
	L	0.090	4.6	180	0.40	12	270	0.44 ± 0.2
	M	0.027	1.4	54	0.12	3.6	81	
	α_{tot}	0.677	9.5	249	3.42	49.6	601	
104.5	K	0.18	1.07	5.3	0.85	7.0	45	
	L	0.024	0.50	13.1	0.10	1.2	25	} 25 ± 15
	M	0.007	0.15	3.9	0.03	0.36	7.5	}
	α_{tot}	0.21	1.72	22.3	0.98	8.56	77.5	
	K/L	7.5	2.1	0.40	8.5	5.8	1.8	0.51 ± 0.11