RECENT STUDIES OF THE ODD-MASS Sr, Y, Zr and Nb FISSION PRODUCTS (A = 95, 97, 99)

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Abstract

The decays of Sr, Y, Zr and Nb with masses A = 95, 97 and 99 have been studied with the mass separators Lohengrin (I.L.L. Grenoble) and Josef (K.F.A. Jülich). The mass assignment of the gamma lines has been performed with Lohengrin and the γ-γ coïncidence experiments have been done with Josef.

In this paper the decay schemes of the odd-mass nuclei in this region are presented, the even ones have been treated in a separate contribution to this conference.

The systematic of the levels of these nuclei shows a great number of isomers due mainly to the $9/2^+$ and $1/2^-$ spins in Y and Nb and to the place of the levels with $7/2^+$, $5/2^+$, $3/2^+$, $1/2^+$ spins in Sr and Zr.

For the mass 97, the β decay of Sr ($T_{1/2}$ = 0.40 sec) and the two isomers of Y ($T_{1/2}$ = 1.21 sec and 3.7 sec) and the level scheme of Y and Zr are given.

In mass 99, the β decay of Y ($T_{1/2}$ = 1.5 sec) and Zr ($T_{1/2}$ = 2.1 sec) and the level scheme of Zr and Nb are given.

1. Introduction

The nuclear fission is the most effective way to produce neutron rich nuclei far from the region of β-stability. In order to obtain detailed knowledge about level schemes in the region of transitional nuclei around A = 100, these nuclei have been produced by the thermal neutrons induced fission of ^{235}U and studied with the use of the gas-filled separator Joseph[1] at the research reactor FRJ-2 of the Kernforschungsanlage Jülich, Germany and the parabola separator Lohengrin[2] at the high flux reactor of the Institut Laue-Langevin in Grenoble, France. The use of these two apparatus make the isotope identification unambiguous. In this contribution, the results concerning the odd-mass A = 95, 97 and 99 are presented, the studies on even mass A = 96, 98 and 100 are described elsewere[3].

The Y-isotopes and the Nb-isotopes respectively with 39 and 41 protons are candidates to have isomeric state due to the neighbourhood of the $2p_{1/2}$ and $1g_{9/2}$ proton shells in this region. Such isomers are known for the light Y nuclei up to A = 93 and for the Nb nuclei up to A = 99. The search for isomeric states in the heavier Y-isotopes has been an aim of the present studies.

Moreover it was of great interest to know the neutron structure of ^{97}Zr and ^{99}Zr especially for the feeding and the desexcitation of the $g_{7/2}$ and $h_{11/2}$ levels.

2. Experimental Techniques

The facilities Joseph and Lohengrin separate the recoiling products of thermal neutron induced fission without retardation within a few microseconds after the fission event and enable the investigation of very short-lived neutron rich nuclei.

2.1 Experiment at Joseph

Joseph is a gas-filled device[2] with a 300° magnetic field. It separates the fission products according to the mass A and an average ionic charge, which is a well defined function of the nuclear charge Z. The mass and the nuclear charge resolution amount to A/ΔA = 79 and Z/ΔZ = 38 for light fission products with He at 4 Torr as gas-filling which are standard experimental conditions. This resolution is in most cases sufficient to identify the emitters of unknown radiation[4]. As the separation does not depend on the initial velocities and ionic charges of the fission products which are widely spread, the beam intensity is comparatively high. It amounts to up to 10^5 fission products per cm^2 and second with a size of 10 x 10 cm^2 of the focus. A discontinously moving tape is available for the transport of the collected activity to the front of the detectors within a negligible transport time. For increasing the beam density a gas-jet device has been built.

Two Ge(Li) detectors of 2.0 and 2.3 keV resolution for the 1332 keV γ-line from ^{60}Co and a intrinsic Ge detector of 540 eV resolution for the 122 keV γ-line from ^{57}Co have been used for the γ-ray measurements.

2.2 Experiment at Lohengrin

Lohengrin separates the fission products by a magnetic sector field and and electrostatic cylindrical field[2] according to the mass, the initial kinetic energy and ionic charge along a parabola of 72 cm length and a few mm width. The resolution A/ΔA can be chosen conveniently (of the order of 1000, FWHM) to provide a pure mass at the exit slit. The fission products are either handled with the use of a tape transport system[5] or with a gas-jet device[6]. The last technique is available since a few months only and corresponds to the following features : the fission fragments are slowed down in air at 200 Torr and then pumped through 17 capillaries uniformly spread along the collector of Lohengrin. The individual gas flows of each capillary are put together through an adapting device[6], into a 4 mm diameter tube whose length can be varied between 10 cm and 1 m. The radioactive nuclides are then deposited on a tape and concentrated into a 5 mm diameter source. The tape can be move either continuously or by a start-stop mode and γ-spectra can be recorded either directly behing the collecting spot of after a 15 cm transfert. A mechanical chopper has been installed on the 4 mm tube, so that the accumulation time of the radioactive nuclides can be varied. The overall transport time through the system is about 0.7 second and the efficiency around 80% for all the non volatile species.

Two Ge(Li) detectors of 2.3 keV resolution for the 1332 keV γ-line from ^{60}Co have been used for the γ-ray studies.

A part of the fission products can be also used at the exit slit of Lohengrin to perform delayed coïncidence measurements between themselves and delayed γ-rays emitted by isomeric states. The fission products are stopped in surface barrier detectors and the γ-rays in a Ge(Li) detector.

The measurements from Joseph have been :
- singles γ-ray spectra for the determination of the energies and intensities of the γ-transitions.
- singles γ-ray spectra as a function of the magnetic field strength B in order to identify the fission products from the intensity distribution versus B of their radiation[4].
- singles γ-ray spectra as a function of the time after the transport of the activity to the detector position for the determination of the half-lives.
- prompt and delayed γ-γ coincidence spectra.

The measurements from Lohengrin have been :
- singles γ-ray spectra for the identification and the determination of energies and intensities of the γ-transitions of a given mass.
- singles γ-ray spectra as a function of the time for the determination of the half-lives.
- delayed coincidence spectra between the fission fragments and the γ-rays emitted by microseconds isomeric states.

3. Experimental results

In the mass chain A = 95 only the isomeric state in ^{95}Y has been studied. The results of the investigations concerning the isobaric chains A = 97 and A = 99 are presented in fig.1-8. In spectra and level schemes, energies, intensities and half-lives of the γ-transitions are mean values of the results of Joseph and Lohengrin. The relative intensities are not corrected for internal conversion. The Q_β values have been determined at Lohengrin[7] from β-γ coincidence measurements.

3.1 ^{95}Y levels.

The level scheme of this nucleus has been studied by Herzog and Grimm[8] following the β-decay of ^{95}Sr. This work does not mention the β feeding of the 9/2 + state. By a coincidence measurement, between the fission fragments and the delayed γ-rays at the exit slit of Lohengrin, a 60 ± 5 μsec isomer decaying by two γ-rays of 261 and 827 keV has been found. These two isomeric γ-lines had been reported in previous measurements[9]. The γ-line of 261 keV is probably the M2 transition de-exciting the 1088 keV-isomeric level (9/2+) to the 827 keV level (5/2-). The life time of this level 9/2+ agrees with this multipolarity.

3.2 ^{97}Sr decay.

The γ-ray spectrum following the β decay of ^{97}Sr is shown in fig.1. The irradiation and measuring time is of 2 seconds. The mean value of the half-life of ^{97}Sr is : $T_{1/2}$ = 400 ± 30 msec. From the coincidence behaviour and the existence of an isomeric level in ^{97}Y (see section 3.3) a tentative level scheme has been deduced (fig.3).

In the single shell-model picture the ground state of ^{97}Y may be interpreted as a $\pi|p_{1/2}>$ state and the level at 667 keV as a $\pi|g_{9/2}>$ state. The corresponding spins and parities of these levels are in accordance with their β-decay properties (see section 3.3).

A γ-line of 667.5 keV which probably corresponds to the de-excitation energy of the isomeric level is seen in the decay of ^{97}Y ; but this γ-line is too weak to measure its half-live. However the partial half-life of this line agrees with a M4 transition.

In order to estimate the β feeding of the ground state (1/2-) of ^{97}Y a filiation measurement has been performed. A Ge(Li) detector located behind the exit slit of Lohengrin was recording a

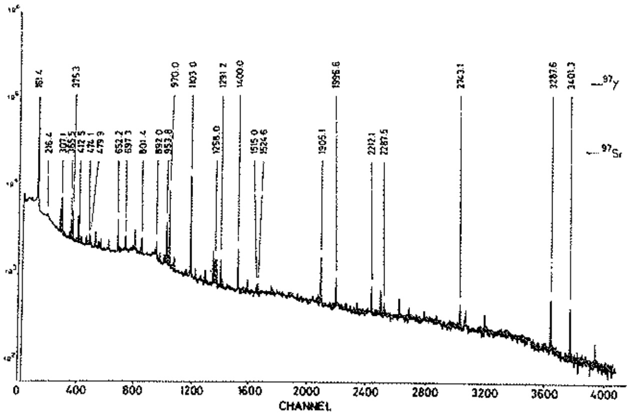

FIG. 1. Single γ-ray spectrum for the mass A = 97 with enhanced Sr activity.

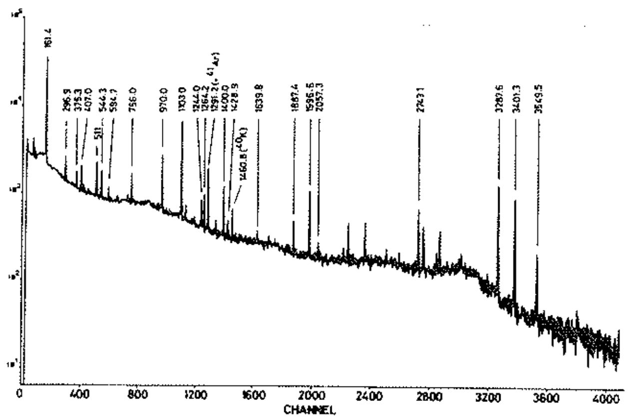

FIG. 2. Single γ-ray spectrum for ^{97}Y decay enhanced.

γ-spectrum accumulated from the very beginning of the irradiation and until completeness of all the decays in the chain. This measurement and the charge distribution results[10] show that the β-branch feeding the ground state (1/2-) of ^{97}Y represents (20 ± 10)% of the β-transitions. The very poor accuracy of the measurement is due to the weak activity of ^{97}Sr in the mass chain A = 97 and also to the long half-life of ^{97}Zr ($T_{1/2}$ = 16.8 h). However this value is confirmed by a measurement at Joseph by means of a Bρ analysis[11].

If we consider only allowed or first forbidden β-decay, the ground state of ^{97}Sr should be 3/2+ or 1/2+, the shell model configurations being $\nu|s^2_{1/2}, d_{3/2}>$ or $\nu|g^2_{7/2}, s_{1/2}>$. Moreover in the course of the investigations of μsec fission isomers (see section 2.2 and 3.1) a 0.55 μsec isomer decaying by two γ-rays of 140.5 and 167.2 keV has been found in ^{97}Sr (fig.10). This isomeric level is certainly similar to the 7/2+ level at 555.9 keV with a life-time of 22 μsec which exists in ^{95}Sr (ref.12).

The isomeric de-excitation sequence in ^{97}Sr is expected to be J^π = 7/2+ (307.7 keV) → 3/2+(167.2 keV) → 1/2+ (0). Therefore the ground state of ^{97}Sr should be 1/2+

3.3. ^{97}Y decay.

The γ-ray spectrum following the β-decay of ^{97}Y is shown in the figs. 1 and 2. In the fig.2 the irradiation and the measuring time is 4 seconds.

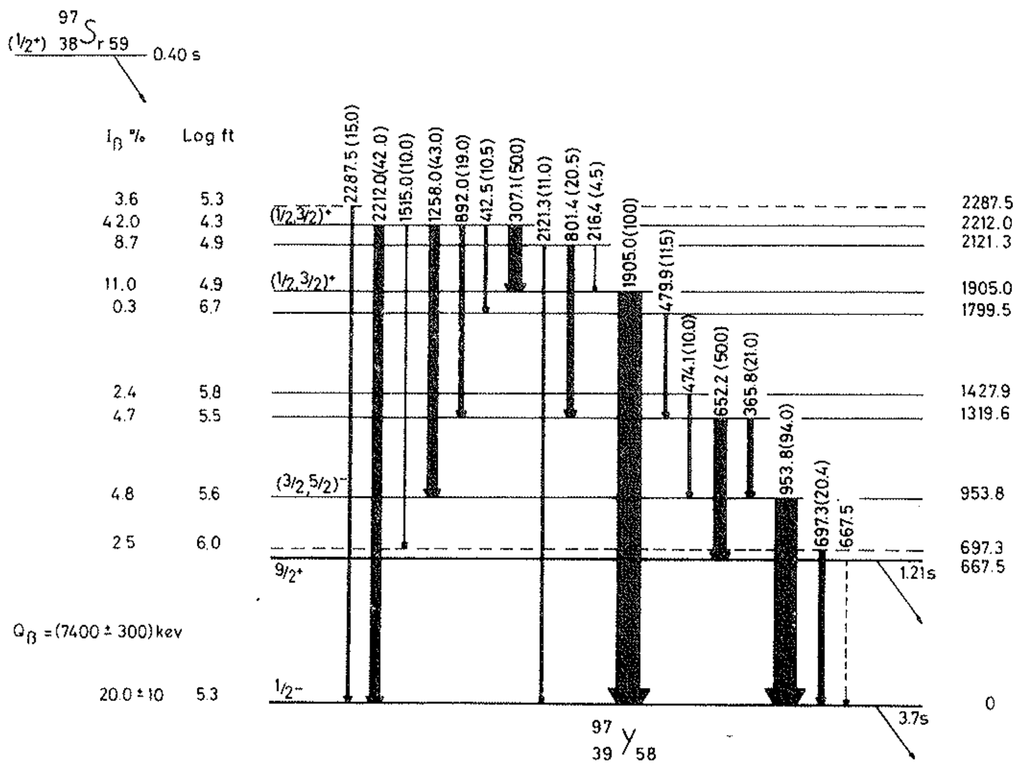

FIG. 3. The β-decay of ^{97}Sr and the level scheme of ^{97}Y.

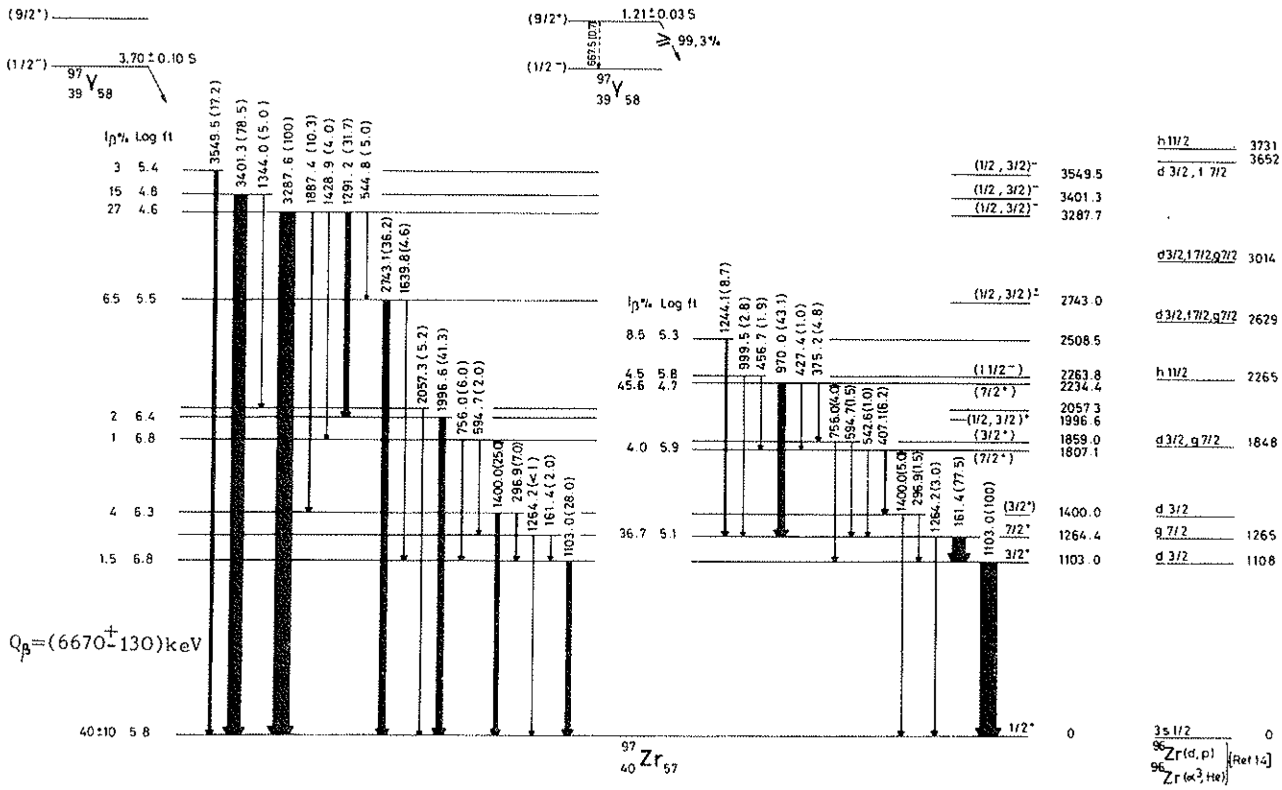

FIG. 4. The β-decay of ^{97}Y isomers and the level scheme of ^{97}Zr. On the right the levels observed in (d,p) and (α, ^{3}He) reactions[14].

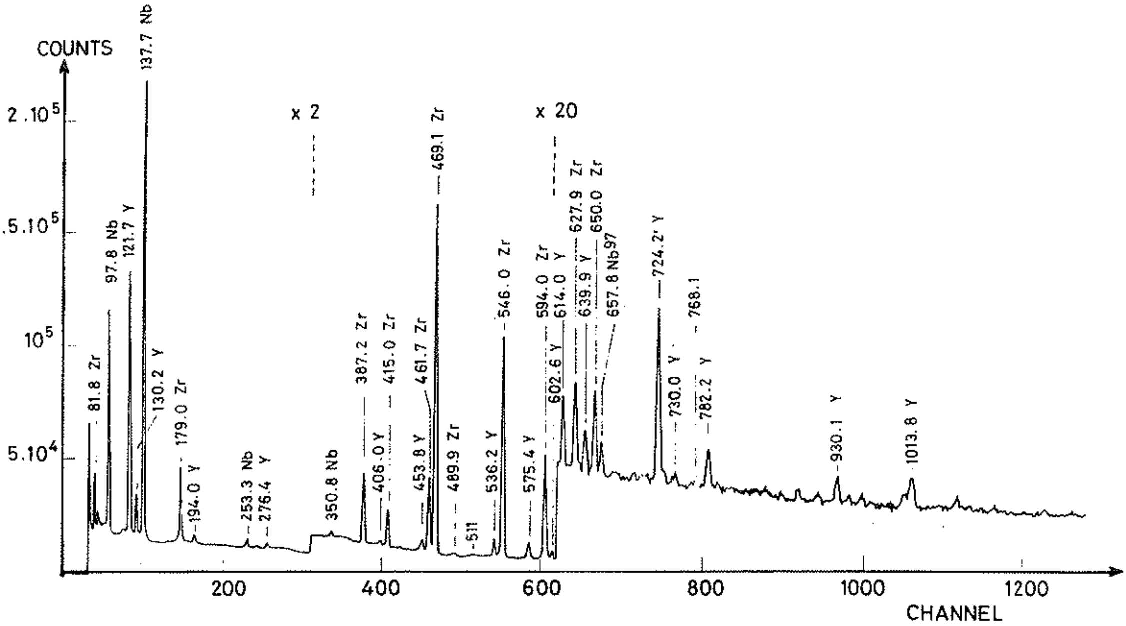

FIG. 5. Single γ-ray spectrum for the mass A = 99

and the cooling time is 2 seconds. The mean value of the half-life of the two isomers is $T_{1/2}$ = 1.21 ± 0.03 seconds and $T_{1/2}$ = 3.70 ± 0.1 seconds. A measurement at Joseph by means of a Bρ analysis[11] has shown that the 1.21 sec. isomer is mainly fed directly by the fission process and the 3.70 sec. isomer is fed by fission and β^--decay of ^{97}Sr.

The relative intensities of the γ-lines have been derived from the half-life analysis in order to separate the two possible components. The level schemes of the isomeric state and the ground state (fig.4) are deduced from the coincidence data.

3.3.1 Isomeric level decay. Up to 2.3 MeV the levels of ^{97}Zr populated by the 1.21 sec. isomer have also been observed in (d,p) and (α,^{3}He) reactions studies[13,14]. Presumably, levels at 1807.1 keV and 1859.0 keV are the two components of the doublet indicated at 1848 keV (ref.14).

The life-time of the $7/2^+$ level at 1264.4 keV has been measured to be 104 ± 5 μsec (ref.15), which is compatible with a single particle E2 transition (161.4 keV) to the $3/2^+$ level at 1103.0 keV. This is also compatible with a weak M3-transition (1264.4 keV) to the $1/2^+$ fondamental level of ^{97}Zr. But it is difficult to evaluate the intensity of this γ-line due to the possibility of summation between the two intense lines of 1103.0 and 161.4 keV. Most of the β-decay of the 1.21 sec. $9/2^+$ isomer feeds the two $7/2^+$ levels at 1264.4 and 2234.4 keV (they are allowed components with log ft value respectively equal to 5.1 and 4.7). This is consistent with the fact that this isomer is mainly produced by the fission process, where high spin is available.

3.3.2 Ground state decay. The β^--branch feeding the ground state of ^{97}Zr studied by a filiation measurement represents (40 ± 10)% of the β-decay. With a Q_β-value of 6670 ± 130 keV (ref.7) for the β-decay of the ground state of ^{97}Y, the log ft value of the β-branch feeding the ground state of ^{97}Zr is found to be 5.8. This value corresponds to a first forbidden β-branch which confirms the spin $1/2^-$ of the ground state of ^{97}Y.

Levels at 3287.7 and 3401.3 keV which are fed by allowed β-branches (log ft = 4.6 and 4.8) must have a negative parity with spin 1/2 or 3/2. These levels can be interpreted as particle hole protons states.

3.4. ^{99}Y decay.

The γ-ray spectrum following the β-decay of ^{99}Y is shown in fig.5. The irradiation and the measuring time is 2 seconds and the cooling time 1 sec. The mean value of the half-life is (1.5 ± 0.1) sec. The level scheme of ^{99}Y deduced from the coincidence data is shown in fig.6.

By analogy with ^{97}Y and in accordance with the shell-model picture the ground state of ^{97}Y may be interpreted as a $\pi|p_{1/2}>$ state. This agrees with the β-feedings of the ^{99}Zr states specially the three levels of low energy at 0, 121.7 and 251.9 keV. Like in ^{97}Zr the spins and parity of these three levels should be $1/2^+$, $3/2^+$ and $7/2^+$. Actually, as in ^{97}Zr the $7/2^+$ level at 251.9 keV is isomeric, its life-time has been measured to be

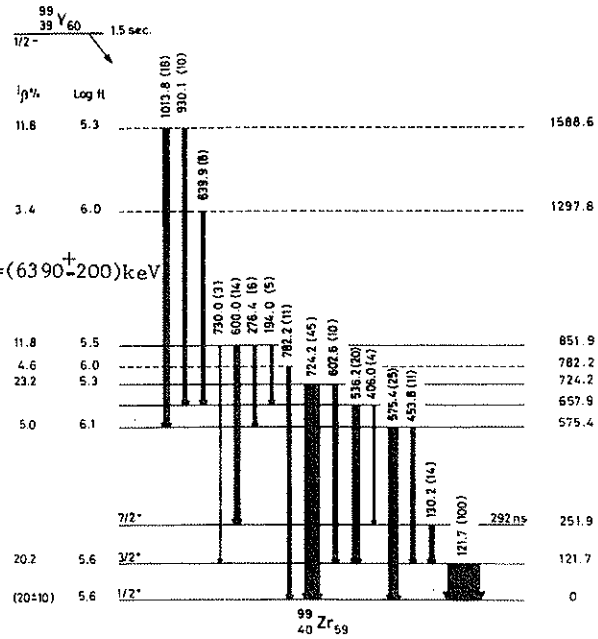

FIG. 6. The β-decay of ^{99}Y and the level scheme of ^{99}Zr

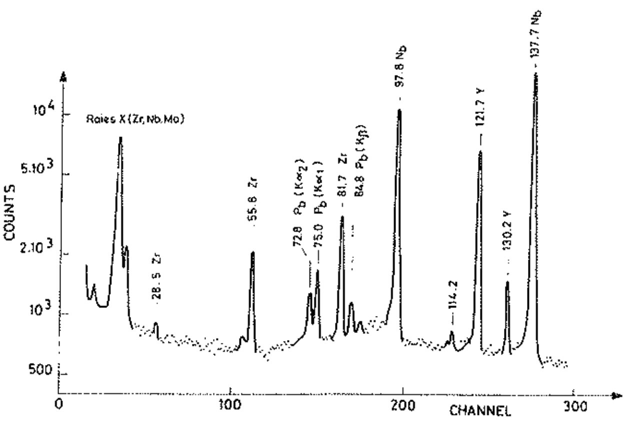

FIG. 7. Low energy (5-145 keV) γ-ray spectrum for the mass A = 99 with enhanced Zn activity.

292 ± 20 μsec, (Ref. 15), which agrees with a single particle E2 transition (130.2 keV) to the $3/2^+$ level at 121.7 keV.

The β feedings of the ground state and the first excited state of ^{99}Zr have been based on the assumption of equal log ft values for these β-branches. This give lof ft ≈ 5.6, for a Q_β-value of 6390 ± 200 keV (ref.7), with these β-feedings, the two levels at 724.2 and 1588.6 keV which have logft values of 5.3 should have a negative parity with spin 1/2 or 3/2.

3.5. ^{99}Zr decay

The energy levels of ^{99}Nb have been investigated first by Eidens et al.[16] after $^{235}U(n_{th}, f)$ at the older gas-filled separator at Jülich and by Bindal et al.[17] through the $^{100}Mo(d,^3He)$inelastic scattering. Different excited levels were found in these experiments. This was interpreted[17] as due as the fact that only states with negative parity were fed in the scattering experiments whereas the β-decay of ^{99}Zr populates exclusively levels of positive parity.

The γ-ray spectrum following the β-decay of ^{99}Zr is shown in fig.5 both with the β-decay of ^{99}Y (see section 3.4). The figure 7 shows the low energy γ-ray spectrum of ^{99}Zr measured with a Ge(Li) detector of very high quality of resolution and efficiency from the Mainz University Spectrometry Group. In this spectrum the irradiation and the measuring time is 4 secondes and the cooling time 1 sec. The γ-line of 28.5 keV seen in the fig.7 has been observed in a X-γ coincidence experiment[18]. The mean value of the half life is $T_{1/2}$ = 2.1 ± 0.1 sec. The level scheme of ^{99}Zr deduced from the coincidence data is presented in fig.8.

The relative intensity of the γ-transitions agrees with the assumption that the ground state of ^{99}Zr has spin and parity $1/2^+$. The ground state of ^{99}Nb is probably the $\pi|g_{9/2}+\rangle$ state. From single shell model consideration one would expect the configuration to be either $|(s_{1/2})^2(g_{7/2})^1\rangle$ or $|(s_{1/2})^1(g_{7/2})^2\rangle$ for the 59th neutron in ^{99}Zr leading to $I^\pi = 7/2^+$ or $1/2^+$ for the ground state of ^{99}Zr. If it were $7/2^+$, a high intensity transition should occur into the ground state of ^{99}Nb. This is not observed ; instead the β-decay feeds mainly the 959.2 keV and 1015.1 keV levels. Moreover, as the β transitions feeding these levels are allowed ones (log ft = 4.3 and 4.1 with Q_β = 4445 keV) these levels would then have $I^\pi = 5/2^+$, $7/2^+$ or $9/2^+$ and on would therefore expect that it decays directly into the ground state, in contradiction with the experimental results. The spin and parity assignment of $1/2^+$ to the ground state of ^{99}Zr leads to $I^\pi = 1/2^+$ or $3/2^+$ for the 959.2 keV and 1015.0 levels. The conversion coefficients for the 55.8 and 81.8 keV γ-lines in parallel to the transitions of 469.0 keV are in accordance with a multipolarity E2 for these transitions. The 2.6 min ^{99}Nb isomer which may be interpreted as a $\pi|p_{1/2}\rangle$ state in the single shell model picture is found at 365.2 keV in accordance with the level $1/2^-$ found by Bindal et al.[17]. A 365.2 γ-line observed in the decay of the 2.6 min ^{99}Nb (ref.18) may correspond to the γ-transition de-exciting this isomeric level. The partial half-life of this line agrees with a M4 transition.

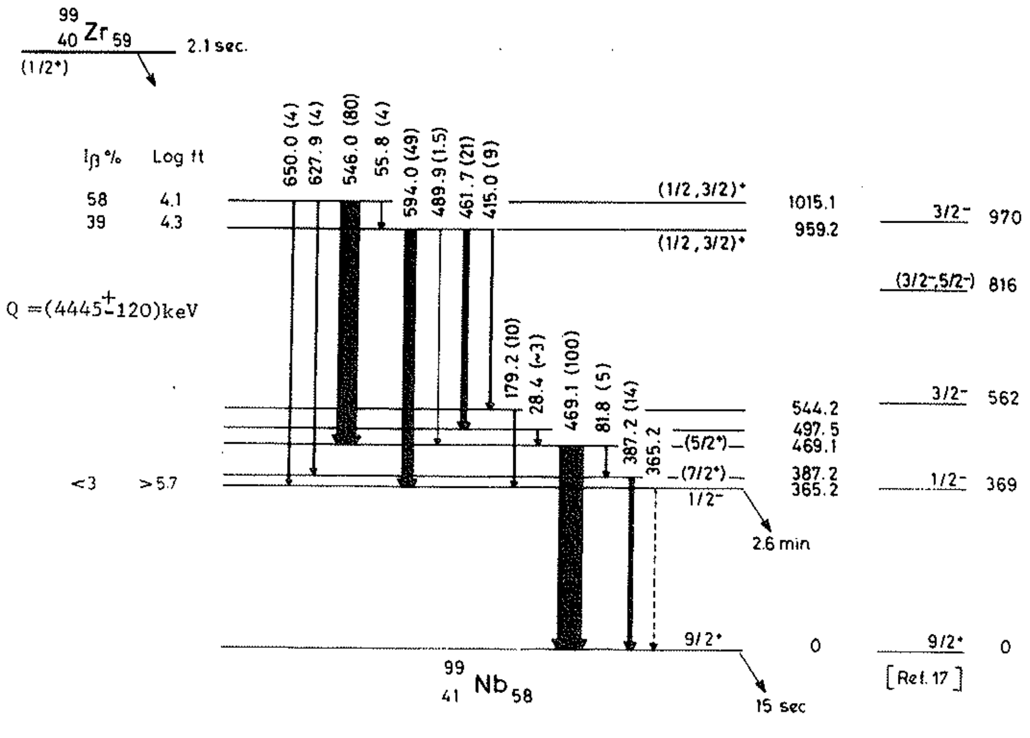

FIG. 8. The β-decay of ^{99}Zr and the level scheme of ^{99}Nb.

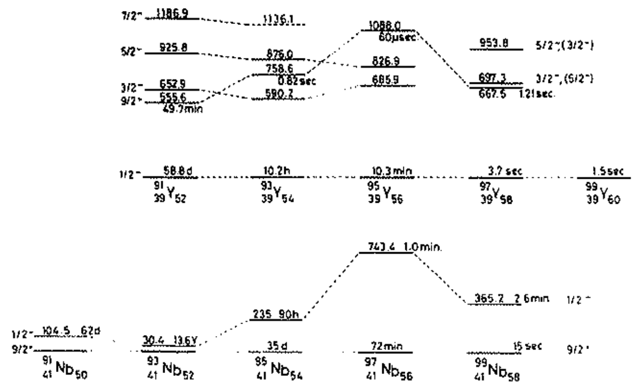

FIG. 9. The lower-energy levels of the odd-A isotopes of yttrium and niobium.

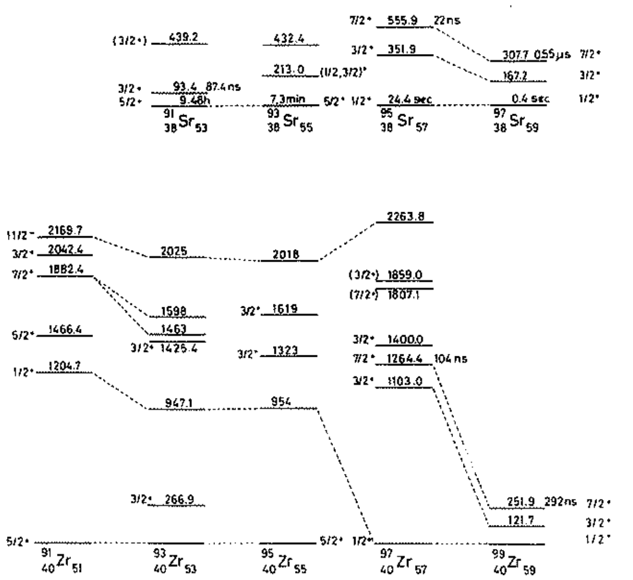

FIG. 10. The lower-energy levels of the odd-A isotopes of strontium and zirconium.

4. Discussion

The results obtained in these experiments have shown that the isomeric states exist also in the Y-isotopes heavier than A = 93.

In ^{95}Y the $9/2^+$ level which lies above the $5/2^-$ level is desexcited only by a γ-transition with a M2 multipolarity. The increase of the energy of the $9/2^+$ - level may be explained by the closure of the $d_{5/2}$ - subshell by 56 neutrons. This effect is well evidenced in the systematic of the low energy levels of the odd-A isotopes of yttrium and niobium (fig.9).

In ^{97}Y the $9/2^+$ level which is the first level above the $1/2^-$ ground state (like in ^{91}Y), becomes a β-decaying isomer, may be with a very weak γ-isomeric transition.

In ^{99}Y only the $1/2^-$ ground state has been found. In fig.9 we can see that the relative position of the $1/2^-$ and $9/2^+$ levels is the same in all odd-A isotopes of yttrium and niobium ; the 39^{th} and the 41^{th} proton having respectively the ground state configuration 2 $p_{1/2}$ and 1 $g_{9/2}$. The odd-A niobium isotopes have no level between the $9/2^+$ and $1/2^-$ levels ; on the contrary the odd-A yttrium isotopes sometimes exhibit intermediate $3/2^-$ and/or $5/2^-$ levels.

The systematic of the odd-A isotopes of strontium and zirconium (fig.10) shows that the 51^{th}, 53^{th} and 55^{th} neutrons have the ground state configuration 2 $d_{5/2}$ while the 57^{th} and 59^{th} neutrons have the ground state configuration 3 $s_{1/2}$. Besides the present work, the informations included in the systematics of fig.9-10 are obtained from ref. 12, 14, 17, 20-25).

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