THE β-DECAYS OF Sr AND Y ISOTOPES IN THE MASS CHAINS 96, 98, 100 AND THE LEVEL SCHEMES OF THEIR Y AND Zr DAUGHTERS

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Abstract

The fission product separators JOSEF at the Kernforschungsanlage Jülich, Germany and LOHENGRIN at the Institut Laue-Langevin, Grenoble, France were used for the investigation of the β-decays and the level schemes of short-lived Sr, Y and Zr isotopes with A = 96, 98 and 100 which lie at the onset of the deformed region. The β-spectra, singles γ-ray spectra, prompt and delayed γ,γ;β,γ and e^-,γ coincidences were measured. The half-lives of the decays of ^{96}Sr, ^{96}Y, ^{98}Sr, ^{98}Y and ^{100}Y were determined. Isomeric β-decaying states were found in ^{96}Y and ^{98}Y, they are interpreted as due to the neighbourhood of the $p_{1/2}$, $g_{9/2}$ proton shells and the $s_{1/2}$, $g_{7/2}$ neutron shells in this mass region. The level schemes of ^{96}Y, ^{96}Zr, ^{98}Y, ^{98}Zr and ^{100}Zr were established or extended. While the existence of a rotational-like cascade in ^{98}Y is confirmed, there is no evidence for the coexistence of spherical and deformed nuclear shapes in ^{96}Zr and ^{98}Zr. In ^{100}Zr the known rotational like cascade was also found after the β-decay of ^{100}Y. A low lying excited 0^+ state was found in this nucleus in analogy to the even Zr-isotopes with lower mass.

1. Introduction

The two fission product separators LOHENGRIN[1,2] and JOSEF[2,3] have been used for the investigation of neutron-rich short-lived nuclei with masses around A=100. In this contribution the results concerning the mass chains A=96, 98 and 100 are summarized. The studies on odd mass nuclei and on low lying excited 0^+ states are described in refs. 4 and 5.

Among the investigated nuclei the Zr isotopes are of special interest as they are supposed to exhibit a very rapid transition from spherical to stably deformed nuclear shapes[6]. While ^{96}Zr shows magic properties[7] in accordance with the spherical shell model, a deformation of $β_2$ = 0.32 is reported[8] for ^{100}Zr. One subject of the investigation described here was the feeding of the energy levels of the Zr-isotopes through the β-decays of the Y-precursors and their γ-depopulation. Such investigations should give informations about the possible coexistence of different nuclear shapes in these nuclei[6].

The Y-isotopes having 39 protons are candidates for β-decaying isomers due to the neighbourhood of the $2p_{1/2}$ and $1g_{9/2}$ proton shells in this region. Such isomers are known for the Y nuclei with A 93. The search for isomeric states in the heavier Y-isotopes has been another aim of the present studies. On account of the separation according both to the mass and the nuclear charge of the fission products JOSEF offers special possibilities for the investigation of isomeric states.

The Qβ-values of the decays in these mass chains have been determined at LOHENGRIN which is especially suited to this purpose due to its high mass resolution. For details about the Qβ-determination see ref.[9]. A detailed description of part of the results of the investigations is given elsewhere[10,11]. In the following section the experimental techniques used are briefly described. Sections 3 and 4 contain the basic results and their discussion.

2. Experimental Techniques

The facilities JOSEF and LOHENGRIN are recoil spectrometers. They separate the products of thermal neutron induced fission within a few microseconds after the fission event. Hence, they enable the investigation even of the shortest-lived β-decaying nuclei.

2.1 Experiments at JOSEF

JOSEF is a gas-filled device[3] with a 300° magnetic field. The separation of the fission products occurs according to their mass A and their average ionic charge q along the path in the gas-filled magnet. Here q 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[12].

As the separation does not depend on the initial velocities and ionic charges of the fission products, the beam intensity is comparatively high. Thus up to $2 \cdot 10^5$ fission products per cm and sec are focussed onto an area of dimensions 10 x 10 cm^2. A discontinuously moving tape is used 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.

During the course of these experiments the following measurements were made:

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 rigidity Bρ in order to identify the fission products from the intensity distribution versus Bρ of their radiation.

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-coincidences

Delayed e^-, γ-coincidences

Ge(Li)-detectors of 2.0 and 2.3 keV resolution at 1332 keV and an intrinsic Ge-detector of 540 eV resolution at 122 keV were used for the study of the γ-rays, and a plastic scintillator was employed for the electrons.

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2.2 Experiments at LOHENGRIN

LOHENGRIN separates the fission products by a magnetic sector field and a cylindrical electrostatic field[1] according to the mass, the initial kinetic energy and the ionic charge along a 72 cm long and a few mm wide section of a parabola. The resolution can be chosen conveniently (of the order of 1000, FWHM) in order to obtain a beam of an essentially pure mass. The activity is transported from the focus to the detectors by means of a tape moving continuously along the parabola. A gas-jet device is used for the concentration of intensity which otherwise amounts up to $2 \cdot 10^3$ fission products per sec and cm of parabola length.

Here, the measurements include:

Singles γ-ray spectra resulting in the determination of energies and intensities of the γ-transitions.

Singles γ-ray spectra as a function of the tape velocity and/or as a function of the time after chopping the gas-jet for the measurement of half-lives.

Delayed β,γ coincidences

Beta ray spectra

A Ge(Li) detector of 2.3 keV resolution served for the γ-ray measurements and a 5 x 5 cm anthracence crystal was used for the studies of electrons.

3. Results

The results of the investigations concerning the isobaric chains A=96 and A=98 are depicted in figs. 1 - 7. Figs. 1 - 4 present the tentative level schemes of ^{96,98}Y and ^{96,98}Zr as they are populated through the β-decays of the corresponding precursors. The energies E_γ and relative intensities I_γ (in brackets) of the γ-transitions are mean values of the data from both separators. The results from the two facilities agree within the experimental uncertainties, that is $\Delta E_\gamma = \pm 0.2$ keV for $E_\gamma < 1300$ keV, $\Delta E_\gamma = \pm 0.5$ keV for $E_\gamma > 1300$ keV and $\Delta I_\gamma = \pm 5$ % for $I_\gamma > 20$, $\Delta I_\gamma = \pm 10$ % for $20 > I_\gamma > 10$ and

$\Delta I_\gamma = \pm 20$ % for $I < 10$. The relative intensities are not corrected for internal conversion. Some of the γ-transitions were masked by background-lines at JOSEF and other weak ones could not be observed at LOHENGRIN. The positions of the γ-transitions are defined unambiguously by the results of the γ,γ-coincidence experiments except for those populating or depopulating levels which are hatched in figs. 1 - 4. The Qβ-values were determined at LOHENGRIN, where possible from β-spectra which were measured in coincidence with γ-transitions leading into the ground states. The half-lives are the average values of the results for several γ-transitions, which were mainly obtained at JOSEF.

^{96}Y (fig. 1): The level scheme comprises states which are depopulated by strong γ-transitions[13]. The γ-lines of 122.2 keV and 809.6 keV have first been observed[14] at the older gas-filled separator at Jülich. There the γ-transitions were assigned to ^{97}Zr, which due to the inferior resolution of the older separator was also a candidate. Good agreement concerning the energies, half-lives and intensities of the strongest γ-transitions is obtained with the results of refs.[15,16].

^{98}Y (fig. 2): The level scheme of this nucleus consists of two parts with very little overlap. The left hand side shows the levels which are fed through the β-decay, whereas on the right hand side the results of the studies[17] on μsec-isomers among the fission products are given. The data are independently normalized to 100 for the 119.0 keV-transition. The feedings at the right refer to the fractional independent fission yield of ^{98}Y. The ground state feeding by the β-decay (left) has been determined with the filiation method at LOHENGRIN. The β-feedings take into account probable values of the internal conversion with the multipolarities given in the brackets. The results concerning the β-decay are in good agreement with the information of ref.[16].

The μsec studies[17] had been performed at the older gas-filled separator at Jülich where ^{97}Y and ^{98}Y were determined as possible emitters. The level
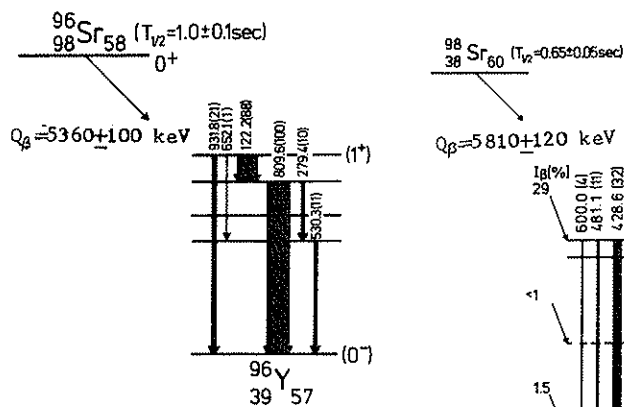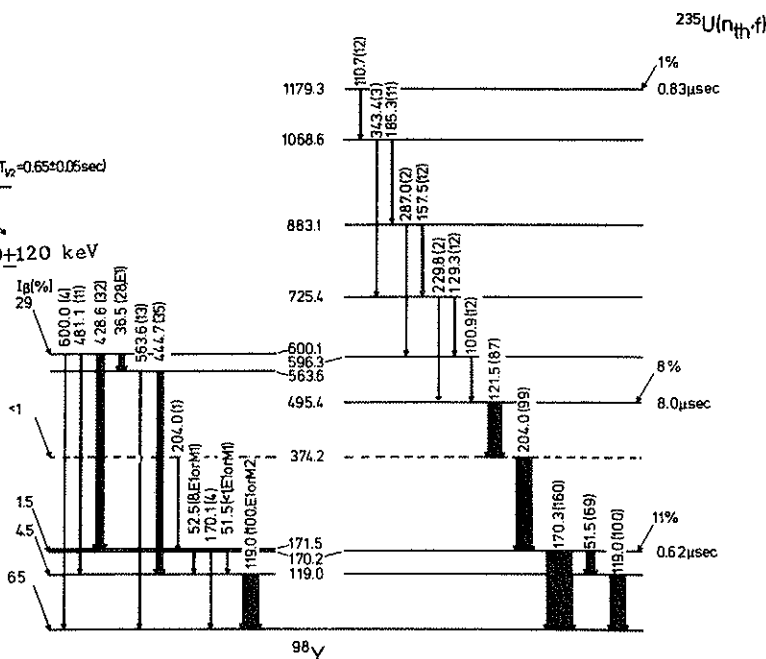

Fig. 1: Level scheme of ^{96}Y
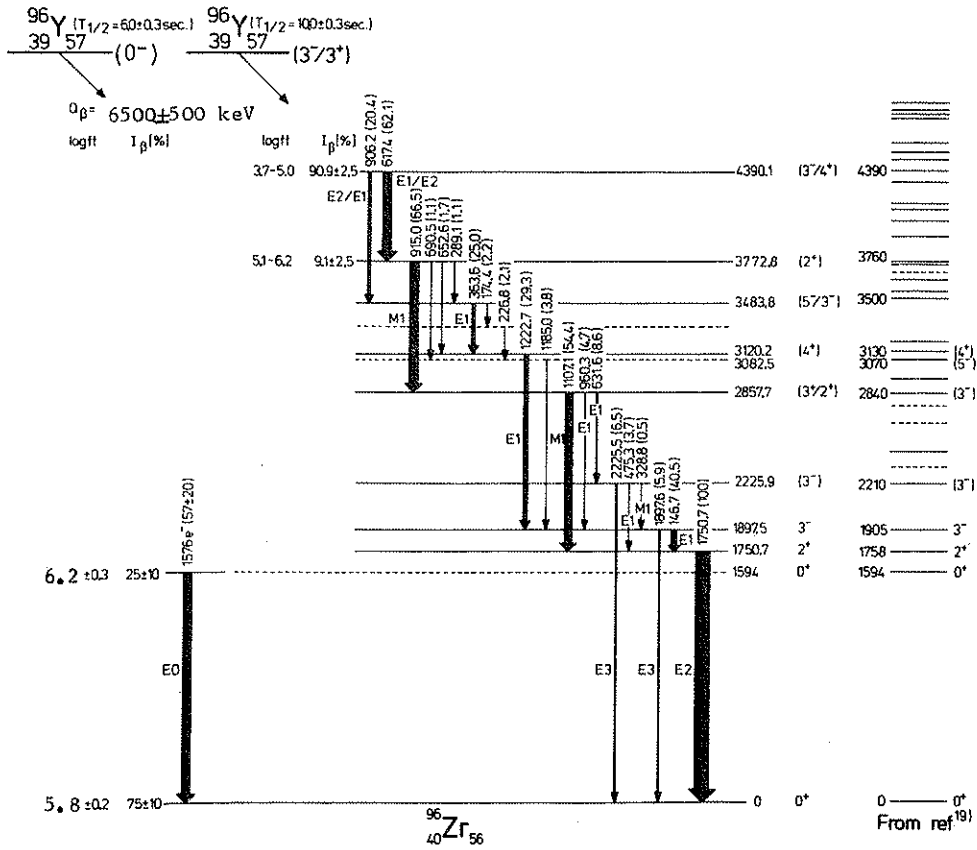

Fig. 2: Level scheme of ^{98}Y

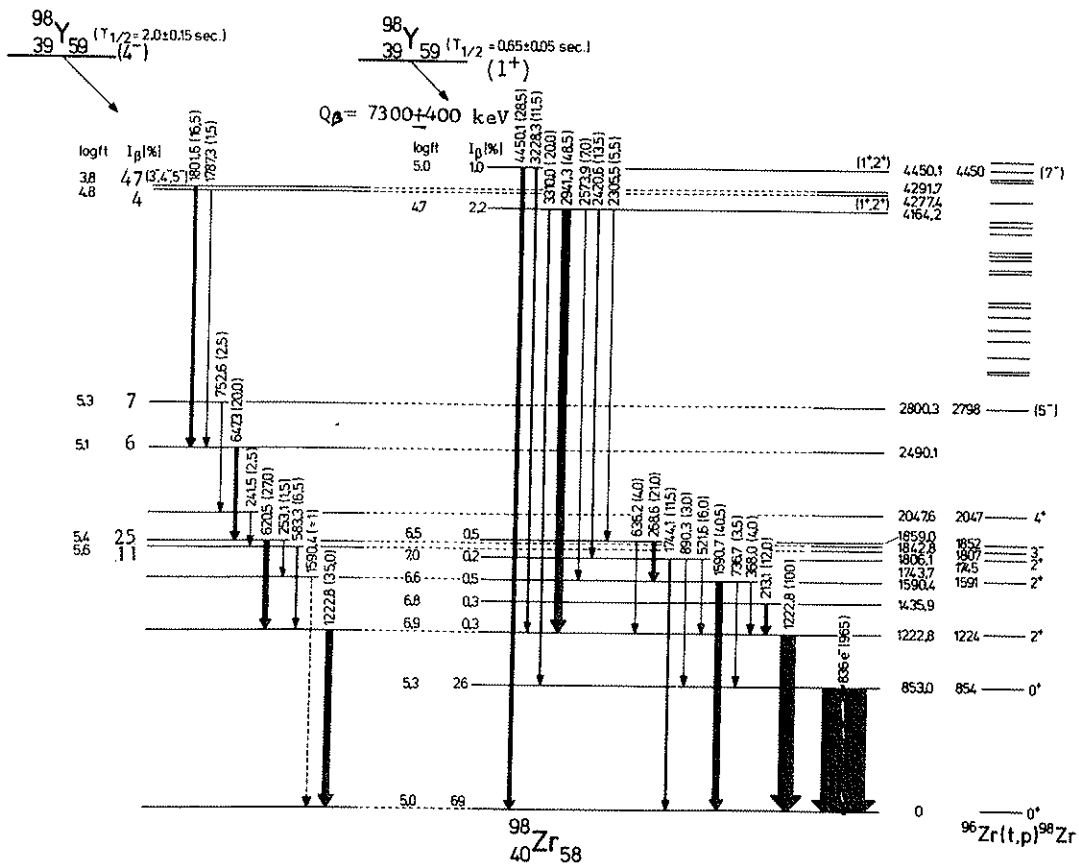Fig. 3: Level scheme of ^{96}Zr

Fig. 4: Level scheme of ^{98}Zr

scheme was tentatively assigned to ^{97}Y from spin considerations. The calibration procedure at JOSEF and the mass assignment from LOHENGRIN identified, however, ^{98}Y as the emitter. At LOHENGRIN the μsec-isomers have been reinvestigated recently. The energies and intensities of the γ-lines have been reproduced except for the three crossovers at 229.8, 287.0 and 343.4 keV the intensity of which was too weak under the actual experimental conditions. Part of these γ-transitions were also found after the spontaneous fission of ^{252}Cf[18].

^{96}Zr (fig. 3): The levels of this nucleus[10] were known hithero mainly from nuclear reaction investigations the results of which are compiled in ref.[19]. For comparison the adopted levels of this reference are given. To all the energy levels which are fed through the β-decay there corresponds a state in the reaction data within the rather large uncertainties of those experiments. The γ-transitions have been investigated at the same time with the use of rapid chemical separation methods[20]. There is good agreement for the observed energies and intensities. The results of earlier investigations[21] on the β-decay of ^{96}Y were not confirmed. The multipolarities and spins and parities which are given in this case are deduced from a comparison of the relative intensities with the expected transition probabilities and relying on the spins and parities of the lowest four states. An ambiguity is left for the highest lying lines. The values for the β-feeding in the 0^+ states are different from the data in

ref.[10]. The feeding has been redetermined from the results of the conversion electron measurements at JOSEF[5]. The Q_β-value is changed correspondingly.*

The totally converted E0 transition depopulating the excited 0^+ state was first observed as a bump in the β-spectrum at LOHENGRIN. It was then investigated in detail[5] with a windowless Si(Li)-detector at JOSEF and independently at the OSIRIS separator[22]. It turned out that the half-life of this transition (6.0s) which was measured at LOHENGRIN, OSIRIS and JOSEF differs from the half-lives with which the γ-lines decay (10.0 s). This indicates the existence of an isomeric state in ^{96}Y. The existence of it is confirmed by the comparison of the intensity distribution versus the magnetic rigidity Bρ at JOSEF of the E0 transition and of the 1750.7 keV γ-line, cf. fig. 5a. Those nuclei which emit the E0 transition have obviously been ^{96}Sr when the separation took place. On the contrary, the γ-transition is almost exclusively fed by nuclei which were already ^{96}Y at the moment of separation. Hence, the 0^+ state is fed by a twofold β-decay of ^{96}Sr via an isomeric state of 6.0 s half-life in ^{96}Y whereas the γ-transition is populated through a state of ^{96}Y with 10.0 s half-life which is excited directly in fission.

*The Q_β-values of ^{96}Zr and ^{98}Zr are not included in ref. 9), they are deduced from separate measurements of singles β-ray spectra.
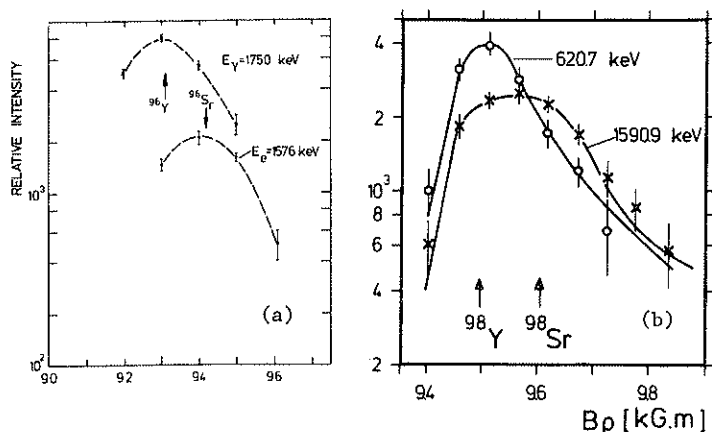

Fig. 5: Intensity versus Bρ distributions for transitions in ^{96}Zr (a) and ^{98}Zr (b). The lines are fits to the experimental data.
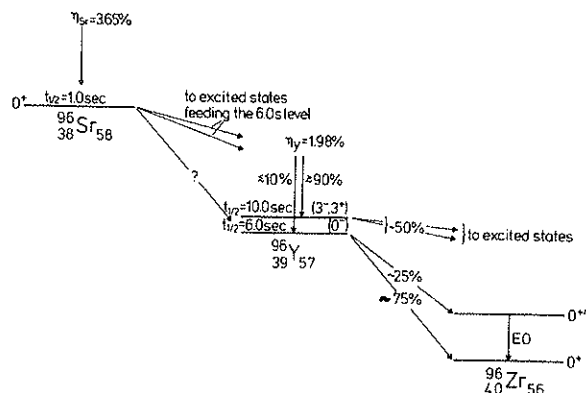

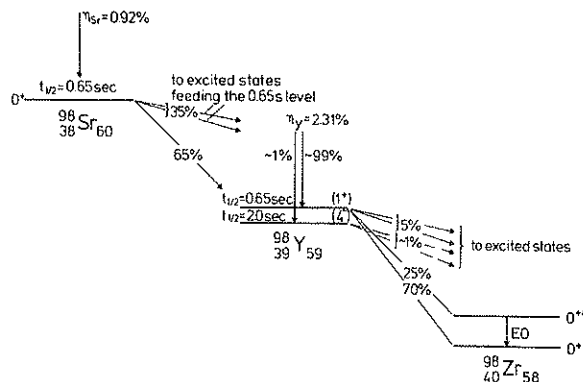Fig. 6: Salient features of the β-decay chain with A=96. The fission yields are from ref.[27].

Fig. 7: Salient features for the A=98 chain.

All other γ-transitions have similar intensity distributions.

The situation is illustrated in fig. 6 which reveals the salient features on the β-decay chain with A = 96 as far as they were investigated here. The conclusions are supported by the fact that none of the γ-transitions of ^{96}Zr have been observed in the studies of the mass chain A = 96 at the OSIRIS separator where the Y-isotopes have negligible yields[10]. Furthermore, for the β-spectrum from the decay of ^{96}Y the two half-lives have been observed the low energy part having 10.0 s[10].

^{98}Zr (fig. 4): The energy levels have been studied through the ^{96}Zr(t,p) reaction[23,7]. The results of ref.[7] are given for comparison. Most of the levels which are fed in the β-decay were also found in these investigations. Again an isomeric β-decaying state is found in the Y-mother. This is obvious from the different half-lives of 2.0 ± 0.15 s and 0.65 ± 0.05 s of the γ-transitions, the assignment of which to the same nucleus is proved through the γ,γ-coincidence measurements, and from the different intensity versus Bρ-distributions, see fig. 5b. The 620.7 keV-transition which is fed by the 2.0 s state shows the intensity distribution of ^{98}Y. The 1590.7 keV-line from the 0.65 s β-decay has a composite intensity distribution. Hence, while the 2.0 s state is only populated directly in fission, the feeding of the 0.65 s β-decay mode of ^{98}Y occurs both through the β-decay of ^{98}Sr and directly in fission.

A quantitative analysis of the intensity distributions taking into consideration the fission yields and the experimental conditions[12] resulted in the fits through the experimental data in fig. 5b. The conclusions are given in fig. 7 together with the β-feeding as it was determined at LOHENGRIN through the filiation method. Both the β-decay of ^{98}Sr and the direct production of ^{98}Y feed fully into the 0.65 s state. The 2.0 s state absorbs only about 1 % of the directly produced ^{98}Y. The γ-transitions in ^{98}Zr are only induced by about 5 % of the β-decays of the 0.65 s state. The total intensity of the γ-transitions from the 2.0 s level amounts to 1 % relative to the β-decay of the 0.65 s mode.

The ground state feeding is again determined from the filiation measurements at LOHENGRIN. The relative intensities of the γ-transitions in fig. 4 are normalized to the 0.65 s fraction of the 1222.8 keV-line, whereas the β-feedings take into account also the transitions into two 0$^+$ states. The totally converted E0 transition has been studied with Si(Li) detectors[5,24]. The results of ref.[5] confirm the above-mentioned conclusions concerning the two β-decay modes. The mean-life of the 853.0 keV-level has been determined by the measurement of the delayed coincidence between the 3310.0 keV-line and the conversion electrons[5] to be 78 ± 14 ns.

^{100}Zr. For this nucleus the well known γ-transitions[25] of 212.7 and 352.1 keV were also observed after the β-decay. Additionally weak γ-transitions of 118.5 and 667.0 keV were unambiguously assigned to this nucleus from the mass identification at LOHENGRIN and from the coincidence results of JOSEF. A special search for a low lying excited 0$^+$ state in ^{100}Zr in analogy to the lower mass isobars was performed[5]. With the window-less Si(Li)-detector a conversion electron line of 313 keV has been observed at JOSEF which most probably has E0 character and belongs to ^{100}Zr. Hence, a 0$^+$ state exists at 331 keV which is, however, not the first excited state. Most probably it feeds into the 2$^+$ state at 213 keV through the 118.5 keV transition[5].

4. Discussion

The investigations which are described here, have shown that the occurence of isomeric states in the Y-isotopes continues also for the neutron rich nuclei. In ^{98}Y this implies a β-isomer in addition to the three μsec-isomeric states. The position of the isomeric levels in the decay schemes of ^{96}Y and ^{98}Y could not be determined in these investigations of β-decaying fission products as in both nuclei only one state is populated through the decay of the Sr-precurser, see figs. 6 and 7. The following conclusions can be drawn from the properties of the Zr-levels into which the different β-decay modes disintegrate and from simple shell model considerations.

A=96: The 39th proton has the ground state (g.s.) configuration 2p$_{1/2}$ in the lower mass Y-isotopes. It is assumed that this is also true for ^{96}Y and ^{98}Y especially as the energy gap between the 2p$_{1/2}$ and 1g$_{9/2}$ states amounts[3] to 667 keV at ^{97}Y. The 57th neutron is reported to have the g.s. configuration 3s$_{1/2}$ in ^{97}Zr and ^{99}Mo. Hence, the g.s. of ^{96}Y is assumed to have the configuration $(\pi p_{1/2})^1 (\nu s_{1/2})^1$ with I$^\pi$ = 0$^-$ taking into consideration the coupling rules of ref.[26]. This is in reasonable agreement with its decay into the 0$^+$ states of ^{96}Zr with a log ft value of about 5.8. The β-decay consists of the conversion of the s$_{1/2}$ neutron into a p$_{1/2}$ proton. The 10.0 s state is supposed to lie at least 400 ± 200 keV above the g.s., cf ref.[10]. Its β-decay into the 4390.1 keV state certainly is an allowed one. No unique proposal can be made for the spin and parity of this state. Candidates are 3$^-$ and 3$^+$ considering the possible spins of Zr-levels in which the β-decay of this state feeds.

A=98: Here the allowed beta feedings from ^{98}Sr and to ^{98}Zr fix spin and parity of the 0.65 s β-decaying level of ^{98}Y to 1$^+$. The simple shell model configuration giving these values is $(\pi g_{9/2})^1 (\nu g_{7/2})^1$. If it is assumed that the g.s. configuration of the 39th proton is 2p$_{1/2}$, the 0.65 s state is an excited one. A possible g.s. configuration is $(\pi p_{1/2})(\nu g_{7/2})$ 4$^-$ as the 59th neutron is in the g$_{7/2}$ configuration in the g.s. of ^{101}Mo. This spin assignment is compatible with the observed isomerism if the excitation energy of the 0.65 s state is less than 300 keV, and it is in agreement with the β-feeding into the 5$^-$ state at 2800.3 keV. It is interesting to note that in ^{96}Y and ^{98}Y the high spin isomers are fed only through the fission process where high spin is available.

In ref.[6] it has been suggested from a survey of the even parity states that in the even,even Zr isotopes two bands belonging to different nuclear shapes might exist with the 0$^+$ states forming the band heads. According to this suggestion, up to ^{98}Zr the band belonging to a deformed nuclear shape ("deformed" band) is based on the low-lying excited 0$^+$ states whereas the band which is supposed to correspond to a spherical nuclear shape ("spherical" band) is situated on the ground state. From ^{100}Zr on the "deformed" band belongs to the ground state. If this picture is correct it should influence the β-feedings and the γ-intensities. Thus transitions between levels belonging to different shapes of the nuclei are expected to be hindered.

No evidence has been found for this interpretation of the levels of the Zr isotopes in the present investigations. Both 0$^+$ states in ^{96}Zr and ^{98}Zr are fed strongly through the β-decay of the same state in ^{96}Y and ^{98}Y. The differences in the feeding are essentially in accordance with the different endpoint energies and no additional hindrance is apparent.

According to ref.[6] the levels of the "spherical" band in ^{96}Zr are the 0, 1720 and 3130 keV states; to the "deformed" band should belong the 1594 keV level and a 1933 keV state. It is assumed that the corresponding levels in fig. 3 are 0(0^+), 1750(2^+), 3120 (4^+) keV and 1594(0^+) keV. A 1933 keV level with $I^\pi = 2^+$ was not seen, it has also not been observed in the nuclear reaction investigations[7]. The 0^+ state is not populated by γ-transitions. This is in accordance with the energy dependence of γ-transition probabilities and requires no extra hindrance due to shape influences. The $4^+ \to 2^+$ transition in the spherical band between the 3120 keV and 1750 keV is not observed. Instead the 4^+ level is depopulated by a strong E1 transition of comparable energy. If the $4^+ \to 2^+$ transition has escaped detection, its intensity is at least a factor of 20 smaller than that of the E1 transition. From this the maximum hindrance factor for the E1 transition probability compared to single particle units can be deduced to be smaller than 10^{-4} if the E2 transition is assumed to be not enhanced. If the E2 is enhanced the hindrance factor of the E1 is reduced correspondingly leading to unusually low values.

In ^{98}Zr only the ground state is given as a member of the "spherical" band. As members of the "deformed" band the 854(0^+), 1223(2^+) and 2048(4^+) keV states are proposed[6]. Here, members of both bands are populated by γ-transitions from higher lying levels with comparable probabilities. For example, strong transitions lead from the 4450.1 keV state to the g.s. and the 2^+ state of the "deformed" band. The intensity difference of the transition probabilities is in accordance with an E_γ^3-dependence assuming E1 character. No intraband transitions are seen in the "deformed" band. Especially the $2^+ \to 0^+$ transition of 369.8 keV is lacking. The experimental limit for its intensity corresponds to 0.5 in the relative units of fig. 4. From the E_γ^5-dependence of the probabilities of E2-transitions a relative intensity of 0.25 would be expected if the 369.8 and the 1222.8 keV transition were of the same nature. That means that a maximum value of two for the enhancement of the intraband transition of 369.8 keV or for the hindrance of the 1222.8 keV transition between the bands is possible.

It should be pointed out that the occurence of a rotational like cascade in ^{98}Y is strengthined by the repetition of the measurement on the μsec-isomers at LOHENGRIN.

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