NUCLEAR STRUCTURE STUDIES OF MICROSECOND ISOMERS NEAR $A = 100$*

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A large variety of shapes may be observed in Sr and Zr nuclei of the $A = 100$ region when the number of neutrons increases from $N = 58$ to $N = 64$. The lighter isotopes are rather spherical. It is also well established that three shapes co-exist in the transitional odd-A, $N = 59$, Sr and Zr nuclei. For $N > 59$, strongly deformed axially symmetric bands are observed. Recently, a new isomer of half-life 1.4(2) μs was observed in ^{95}Kr, the odd–odd ^{96}Rb has been reinvestigated and a new high-spin isomer observed in the even–even ^{98}Zr. These nuclei were studied by means of prompt γ-ray spectroscopy of the spontaneous fission of ^{248}Cm using the EUROGAM 2 Ge array and/or measurements of μs isomers produced by fission of ^{239,241}Pu with thermal neutrons at the ILL (Grenoble). To allow spectroscopic studies of isomeric states with lifetimes around 100 ns, across a broad range of medium-heavy neutron-rich nuclei, an experiment was performed at a neutron guide of the ILL using thermal-neutron-induced fission. Fission fragments were identified using a small spectrometer consisting of a section to measure time-of-flight and an ionization chamber. Isomeric γ rays emitted from complementary fragments were detected in an array of Ge detectors.

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1. Introduction

The region of neutron-rich nuclei near $A = 100$ is distinctive for the sudden change in the ground-state properties of nuclei [1]. In particular, for the even $_{38}$Sr and $_{40}$Zr isotopes a sudden onset of strong deformation is observed at $N = 60$, whereas the lighter isotopes up to $N = 58$ are rather spherical. The isotones with $N = 59$ neutrons are of special interest as they lie on the border of these two regions.

Previous experiments have shown that their ground and low-lying states are rather spherical [2, 3], while deformed bands with $\beta_2 \sim 0.3$ are present at about 600 keV of excitation energy [1] and the maximum deformation of the region, $\beta_2 \sim 0.4$, is reached for the $9/2^+[404]$ band recently observed at 829.8 and 1038.8 keV, in ^{97}Sr and ^{99}Zr respectively [4–6]. The large β_2 value found for this band is observed for several even and odd Sr and Zr nuclei above $N = 60$. A simple explanation of the shape-coexistence mechanism has been proposed. It is based upon the Nilsson diagram and stresses the fundamental importance of the unique-parity states [7, 8]. This article summarizes the results obtained in this field by our collaboration and explains a recent experiment which is hoped will give further insights into the nuclear structure of neutron-rich medium-heavy nuclei. After the description of the experimental techniques in Section 1, experimental results in the $N = 58$–60 region will be presented (Section 2). A description of an experiment to measure isomers in neutron-rich medium-heavy nuclei with lifetimes of 100's of ns will be given in Section 3.

2. Experimental techniques

The Lohengrin mass spectrometer was used to select nuclei, according to their mass-to-ionic charge ratios (A/q), recoiling from a thin $^{239 \text{ or } 241}$Pu target which was undergoing thermal-neutron-induced fission. The flight time of the nuclei through the spectrometer was around 1.6 μs. The fission fragments (FFs) were detected in an ionization chamber filled with isobutane gas. Two different setups have been used at the focal plane of the spectrometer.

In the first setup, the FFs were detected in a 13 cm long ionization chamber, and subsequently stopped in a 12 μm thin mylar foil. Behind the foil, two cooled adjacent Si(Li) detectors covering an area of 2×6 cm^2 were placed to detect the conversion electrons and X-rays, while the γ-rays were measured by two 60% Ge detectors placed perpendicular to the beam. This setup allows conversion electrons to be detected down to low energy (15 keV) and also allows γ-electron coincidences to be obtained. Details on this experimental setup can be found in [9, 10].

In the second setup, the FFs were detected in an ionization chamber filled with isobutane gas at a pressure of 47 mb. This ionization chamber has high resolution and can perform nuclear charge (Z) identification for light-mass fission fragments. It consists of two regions of gas, ΔE1=9 cm and ΔE2=6 cm, separated by a Frisch grid. This system is able to identify the nuclear charge in the $Z \sim 40$ region, with a resolution (FWHM) of about two units of Z. The γ rays deexciting the isomeric states were detected by a Clover Ge detector and a Miniball Ge triple cluster [11]. These detectors were placed perpendicular to the ion beam in a tightly packed geometry, possible because the ionisation chamber was only 6 cm thick. The total efficiency for γ-ray detection is 20% and 4% for photons of 100 keV and 1 MeV respectively. Any γ rays detected in the germanium detectors up to 40 μs after the arrival of an ion were recorded on the disk of the data acquisition system. A time window of 250 ns was used for γ–γ coincidences in the data-analysis software.

3. The $N = 58$–60 isotopes

3.1. ^{95}*Kr*

Two μs isomers have been observed in the $A = 95$ mass chain. The strong γ line of 260.6 keV in Fig. 1a deexcites an isomeric level of 56.2 μs half life, already assigned to ^{95}Y [12]. The two weaker γ-rays of 81.7(2) and 113.8(2) keV energies belong to a new isomer [13]. As seen in Fig. 1(b), the two transitions are in coincidence with each other. This new isomer has a half life of 1.4(2) μs.

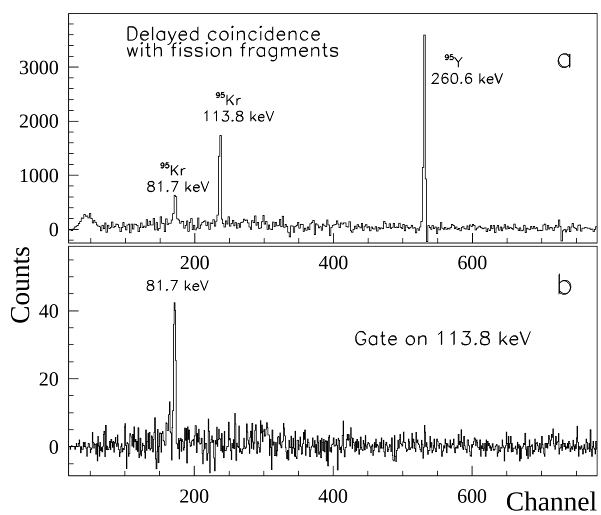

Fig. 1. (a) γ Decay spectrum of the ^{95}Kr and ^{95}Y isomers. (b) Coincidence spectrum gated on the 113.8 keV γ ray.

The method used for the nuclear charge (Z) identification of this new isomer of mass 95, is shown in Fig. 2. Figure 2 shows ΔE1 spectra for the known isomer in ^{95}Y, the whole of the mass 95 chain (dominated by ^{95}Sr) and coincidences between ions and new isomeric γ rays, in parts (a), (b), and (c) respectively. The position of the centroid of the ΔE1 distribution allows the nuclear charge $Z = 36$ to be assigned to this new isomer unambiguously. More details on the method can be found in Ref. [13].

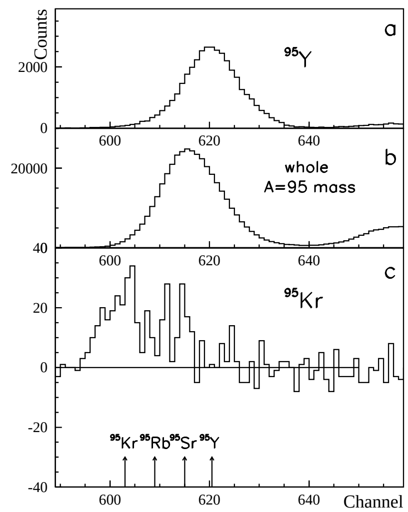

Fig. 2. Energy lost in the first stage of gas ΔE1, for (a) the ^{95}Y isomer, (b) the whole $A = 95$ mass chain, and (c), the ^{95}Kr isomer.

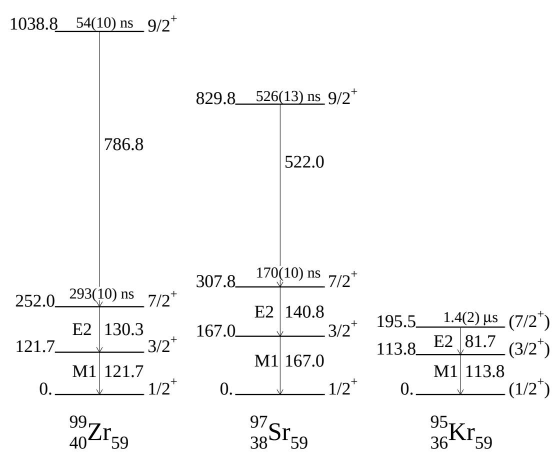

Fig. 3. Decay schemes of the ^{99}Zr, ^{97}Sr, and ^{95}Kr isomers.

In Fig. 3, the level scheme of the new isomer observed in ^{95}Kr is shown and compared with the previously known isomers in the $N = 59$ isotones of ^{97}Sr and ^{99}Zr [2–5, 14].

In these three nuclei, the low-lying isomer decays by an E2 transition. The measured B(E2) values, 1.33(5), 1.75(10) and 1.47(27) W.u., for ^{99}Zr, ^{97}Sr and ^{95}Kr, respectively, are comparable, which suggests that the three transitions have an analogous nature and that the three isotones have the same spins. The ground and the two first excited states of these three isotones are very likely spherical, as suggested by the measured B(E2) values, and their dominant configurations are the $\nu s_{1/2}$, $\nu d_{3/2}$ and $\nu g_{7/2}$ shell-model states, respectively. One may notice that their energies change very little between ^{99}Zr, which is quite close to the line of stability and ^{95}Kr, which is very far from it.

In contrast, we have not observed the $9/2^+[404]$ strongly deformed isomer, present in the two other isotones [4]. The non observation of this isomer means that either this level does not exist in ^{95}Kr, it is too weakly fed by fission, or its half life is shorter than about 0.5 μs, because the flight time throw the Lohengrin spectrometer is about 1.7 μs.

3.2. ^{96}Rb

The N=59 odd–odd very neutron-rich ^{96}Rb nucleus has been reinvestigated [15]. It was previously measured by Genevey *et al.* [16] with the Lohengrin spectrometer. The γ-ray statistics obtained in this new measurement are about ten times higher than in the previous one. The level scheme based on γ–γ and e–γ coincidences is shown in Fig. 4

This scheme is very similar to the one observed in ^{98}Y [17]. The low-lying levels are rather spherical as well as the 10^- isomeric state. In both cases the rotational bands are fed by μs isomers close in excitation energy, 1181.5 keV in ^{98}Y and 1135 keV in ^{96}Rb, and the isomeric transitions have comparable B(E2) values. All these features, strongly suggest that the two isomers have the same $(\pi(g_{9/2})\nu(h_{11/2}))_{10^-}$ configuration. A strongly attractive n–p interaction explains the presence of these isomers at a relatively low energy. Consequently, the strong n–p interaction may induce a competition between high-spin, fully-aligned spherical configurations and the levels of rotational bands in this transitional region. Moreover, it is interesting to note that the neutron and proton orbitals present in the configuration of the spherical isomer and in the deformed band of these odd–odd nuclei both originate from the same spherical unique-parity states $\pi(g_{9/2})$ and $\nu(h_{11/2})$.

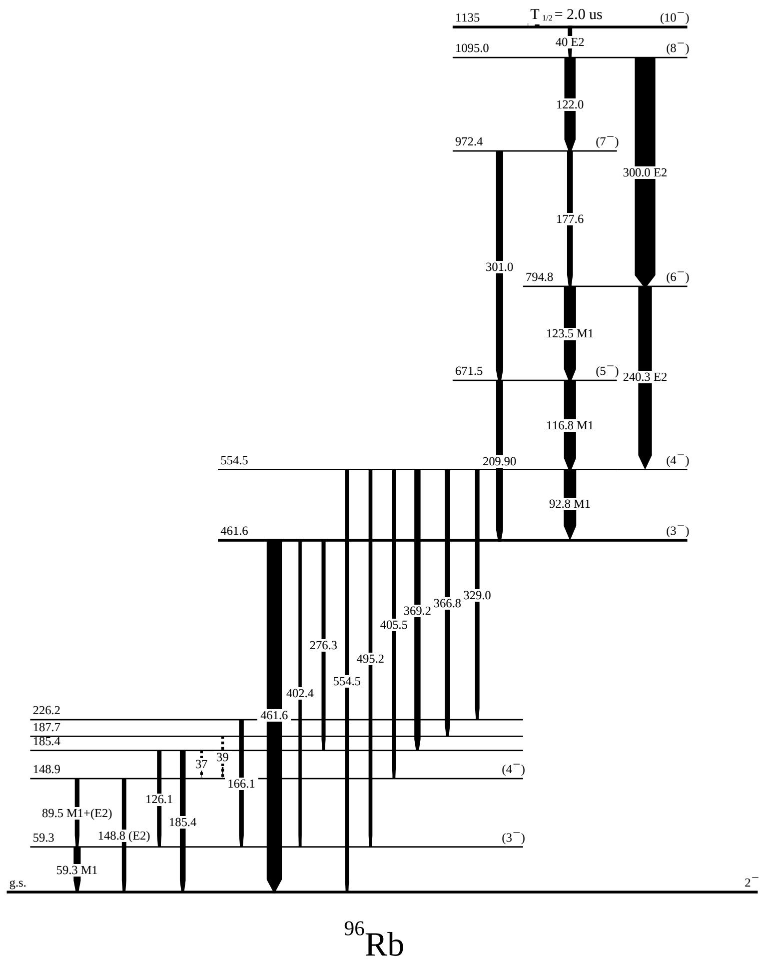

Fig. 4. Decay scheme of the 2.0 μs isomer in ^{96}Rb obtained in the present work. The low-lying levels and the isomer at 1135 keV have rather spherical configurations, while a rotational band develops above 460 keV.

3.3. ^{98}*Zr*

A new (17^{-}) μs isomeric state at 6603.3 keV has been observed for the first time in ^{98}Zr [18]. Mass and isotopic identification of the isomer were performed by examining coincidences between the mass-separated ions, detected in the ionization chamber, and the isomer-delayed γ rays. Much of the decay scheme below the isomer has already been assigned to ^{98}Zr. This nucleus has previously been studied by prompt γ-ray spectroscopy of secondary fission fragments, populated by light-ion-induced [6] and spontaneous fission [1, 19]. The proposed level scheme is presented in Fig. 5.

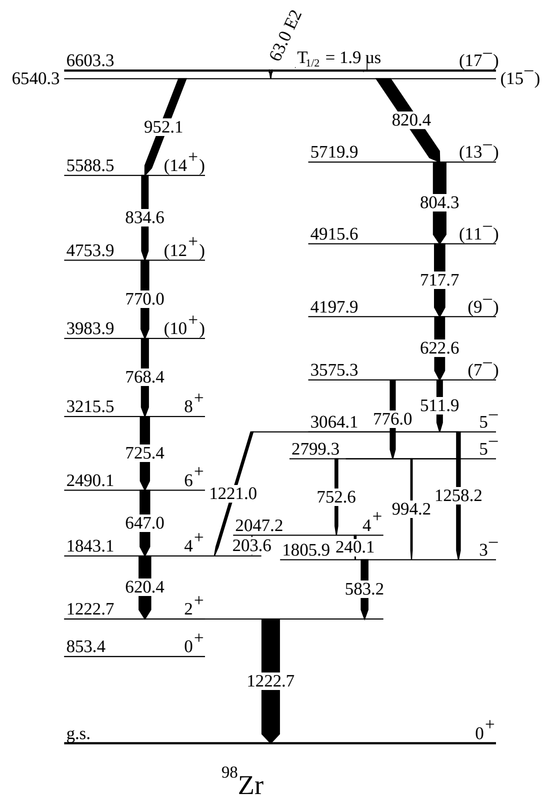

Fig. 5. Decay scheme of the 1.9(2) μs isomer observed in the present work. The 853.4 keV 0^+ bandhead [1] is also included.

This new 1.9(2) μs isomer at 6603.3 keV observed in ^{98}Zr, with a proposed configuration of $\pi(g^2_{9/2})\nu(g^1_{7/2}h^1_{11/2})$ and a single particle nature, decays by a pure, or almost pure, E2 transition into a 15^- state, which then decays into two collective bands, one of positive parity, the other negative, the latter of which is observed for the first time. The existence of a spherical, single-particle state at such a high energy (6603.3 keV) and spin (17^-) is quite unusual, in fact both these values are the highest known for a μs isomer in this region. These high-spin, shape-coexisting states again demonstrate the richness of nuclear structure phenomena in this region.

4. Studies of isomeric fission fragments using a neutron guide

The flight time of fission fragments through the Lohengrin spectrometer range from 1.5 to 2.8 μs, limiting the observation of isomeric states in fission fragments to lifetimes greater than $\sim 0.5\mu$s. In order to investigate better isomeric states in fission fragments in the lifetime range tens-to hundreds-of-nanoseconds a compact spectrometer (FiFi) and a small array of Ge detectors were installed around a thin ^{235}U target at the PF1B neutron guide of the ILL. A schematic drawing of the experimental setup is shown in Fig. 6. Fission fragments stopping in the foil at the centre of the Ge array and emitting isomer-delayed γ-rays could be approximately identified from knowledge of the complementary fission fragment identified by the FiFi mass spectrometer. The variation in the number of neutrons emitted per fission and the range Z values for each mass prevents an exact identification. However, limiting the number of possible candidates to just a handful of nuclei is very useful and knowledge of just one gamma ray emitted from the nucleus from β-decay or from prompt fission spectroscopy can allow the nucleus to be identified.

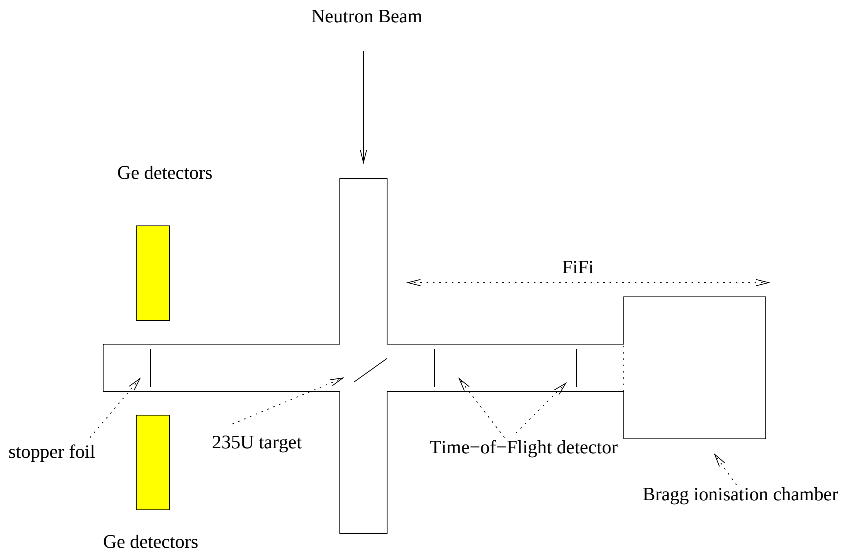

Fig. 6. Schematic of the experimental setup to search for isomers at the PF1B neutron-guide with the FiFi spectrometer.

The FiFi spectrometer, described in detail in [20], consists of a time-of-flight section and a Bragg ionisation chamber. It is able to measure fission fragment masses with a resolution (FWHM) of about 6 mass units. Thermal-neutron guides perfectly reflect neutrons of thermal and cold energies emanating from reactors or spallation sources. These beams are almost free from γ-ray background and fast neutrons, and hence are suitable places to perform spectroscopic studies. Thermal-neutron-induced fission brings little excitation energy into the compound nucleus, so few neutrons ($\sim$ 2–3) are evaporated from the primary fission fragments, hence the secondary fragments remain very neutron-rich. A broad range of targets, from Th to Cf, with thermal-neutron fission cross-sections of the order of hundreds-to-thousands of barns, can be exploited. By changing the Z and A of the initial fissioning system access to regions difficult to study with spontaneous fission sources is possible, especially around ^{132}Sn and $A \sim 95$. Analysis of the experimental data is currently ongoing. An example of a known isomer already observed in the data set is the 164 ns 6^+ state ^{134}Te [21]. Its three γ-ray transitions are shown in Fig. 7.

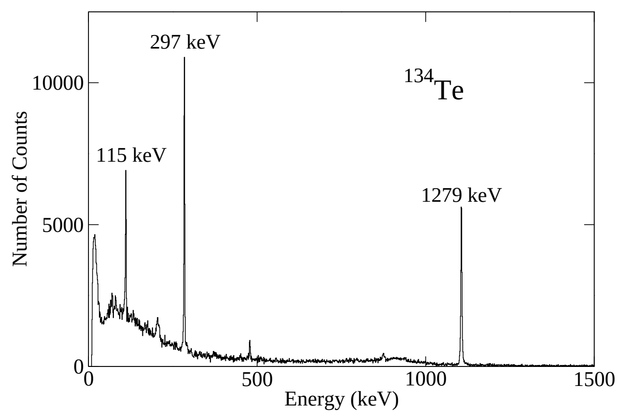

Fig. 7. Summed γ-ray coincidence spectrum for the 164 ns isomer in ^{134}Te. The gating transitions were the 115, 297 and 1279 keV decays.

Several new isomeric cascades have been discovered and will be the subject of a forthcoming publication. This experiment has shown that spectroscopic studies of very neutron-rich medium-heavy nuclei can be performed at neutron guides. This opens the door to future investigations of fission fragments either through isomeric states and prompt γ-ray spectroscopy.

5. Conclusion

A great wealth of information has been recently gained in the odd-mass and odd–odd $N = 59$ isotones. It is now well established that three shapes coexist in ^{97}Sr and ^{99}Zr, while two different shapes were seen in ^{96}Rb. The two unique-parity states $\pi(g_{9/2})$ and $\nu(h_{11/2})$ play a considerable role in all these nuclei. The relative occupation of these orbitals is able to change drastically the shape of the nucleus.

For $N = 60$ Sr and Zr nuclei the β_2 deformation is at the maximum value of the region.

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