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Short-lived isomers in ^{94}Rb

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The medium-spin structure of the neutron-rich, odd-odd nucleus ^{94}Rb was studied by means of γ-ray spectroscopy. Excited levels were populated in the neutron-induced fission of ^{235}U and in the spontaneous fission of ^{252}Cf and ^{248}Cm. Two isomeric states were found at 1485.2 and 2074.8 keV with half-lives of 18 and 107 ns, respectively. The probable structures of the two isomers involve the fully aligned, proton-neutron configurations $[\pi(g_{9/2}) \otimes \nu(g_{7/2})]_{8^+}$ and $[\pi(g_{9/2}) \otimes \nu(h_{11/2})]_{10^-}$, respectively. These new data give information on the single-particle energies in the region.

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Presently, much effort is being devoted to producing and studying the properties of nuclei with high neutron excess, with the aim of testing the influence of this excess on nuclear properties. In some particular mass regions, for example around $A = 95$, such nuclei are difficult to produce in quantities sufficient for spectroscopic studies, in reactions other than low-energy fission. Spontaneous fission (SF) of heavy nuclei such as ^{248}Cm or ^{252}Cf is known to provide nuclear species with high neutron excess. However, in these processes the fission-fragment yield peaks at around $A = 105$ (the Zr and Mo isotopes) and nuclei such as Rb are not strongly produced and are difficult to identify in the prompt γ-ray data. In constrast, the mass distribution from induced fission of uranium peaks around $A = 95$ and gives high production rates for Kr and Rb isotopes. The fission of ^{235}U has been intensively used to study neutron-rich nuclei via β^- decay (see, for example, Refs. [1] and [2]). Some experimental information is also available on the medium-spin structure of the Kr isotopes [3,4], but the structure of neutron-rich Rb isotopes still remains rather unexplored. An exception here is the odd-odd ^{96}Rb nucleus, which was recently studied in detail thanks to the presence of a microsecond isomeric state [5]. The decay of isomeric states in fission products is not contaminated by the burst of prompt γ rays that accompany fission, which greatly facilitates studies of such neutron-rich species.

The high-j, single-particle orbitals in the $A = 95$ region are $\pi(g_{9/2})$, $\nu(g_{7/2})$, and $\nu(h_{11/2})$. These orbitals are known to cause nuclear isomerism, as observed in ^{96}Rb [5]. If analogous isomeric states were present also in lighter Rb isotopes, they would aid the investigation of their nuclear structure. In this work, a search for such isomers was made using neutron-induced fission of ^{235}U. This measurement was then complemented by high-fold γ-ray coincidence studies based on the data from the spontaneous fission of ^{248}Cm and ^{252}Cf nuclei.

In the neutron-induced fission experiment, a thin ^{235}U target was placed into the thermal-neutron beam of the PF1b neutron guide of the high-flux reactor at the Institut Laue-Langevin (ILL) in Grenoble, France. Both fission products could escape from the target. One of them traveled a distance of 70 cm before being implanted into a thin stopper foil where the decay of nanosecond isomeric states was observed with a compact array of 16 HPGe detectors. The complementary fragment was identified in one arm of the Manchester Fission-Fragment Identifier (FiFi) [6]. The FiFi arm consisted of two time-of-flight (TOF) detectors [secondary-electron detectors using multichannel plates (MCPs)] and one axial ionization chamber (IC) for kinetic energy measurements of fission products. The MCP signals were also used to trigger the data acquisition. A more detailed description of the experimental setup can be found in Ref. [7]. The combination of TOF and energy measurements allowed the mass spectrum of the complementary fission fragments to be reconstructed. Subsequently, gating on the complementary-fragment mass enabled the total γ-ray spectrum from the fragments implanted into the stopper to be greatly simplified. In addition it was possible to determine the isobaric origin of the γ rays observed following the decay of isomeric states.

Analysis of γ-γ correlation matrices constructed from the event-by-event data gated on the complementary-fragment mass disclosed a number of unknown delayed transitions related to nuclei from the region of interest, as shown in Fig. 1. In particular, we observed a cascade of 111.1–169–217.2–339.2–648-keV transitions, which was not known to depopulate any previously identified isomer. It is interesting to note that some of these transitions were observed previously in high-precision prompt and delayed γ-ray spectroscopy experiments [8–10] but their isotopic identification remained an issue that could not be resolved by the experimental techniques used.

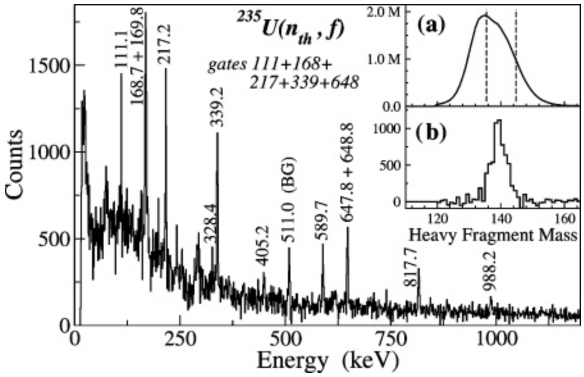

FIG. 1. Summed spectrum of coincident isomeric γ-ray transitions obtained from the total fragment γ spectrum gated on the heavy complementary-fragment mass as shown in inset (a). (b) Complementary-fragment mass distribution after gating on the unknown isomeric γ rays.

In the present work, the mass distribution of fragments complementary to the nucleus with the new isomer was used to assign the mass. This distribution was obtained by summing gates on the most intense γ rays in Fig. 1. A Gaussian fit to the resulting mass distribution displayed in Fig. 1(b) delivered the center-of-gravity value, shown as a horizontal dashed line in Fig. 2.

The same procedure was applied to γ rays from the decay of known isomers from the region, abundantly produced in the fission of ^{235}U. This provided the mass calibration needed to identify the mass of the new isomer. Transitions from the decay of nanosecond isomeric states in ^{95}Sr ($T_{1/2} = 22$ ns [9]) and ^{97,99}Zr ($T_{1/2} = 103$ and 400 ns, Refs. [11] and [12], respectively) were taken for this purpose. The decay of longer lived isomeric states in ^{94}Y ($T_{1/2} = 1.35$ μs [13]) and ^{88}Br ($T_{1/2} = 5.4$ μs [14]) was also observed, due to either a quite high production probability (^{88}Br [15]) or an unusually high isomeric ratio (^{94}Y [13]).

The centroid values determined from distributions of masses complementary to the mentioned known isomers are plotted in Fig. 2 as a function of the isomer mass number. The data points show a linear trend. A straight-line fit to the calibration points provides the required mass calibration.

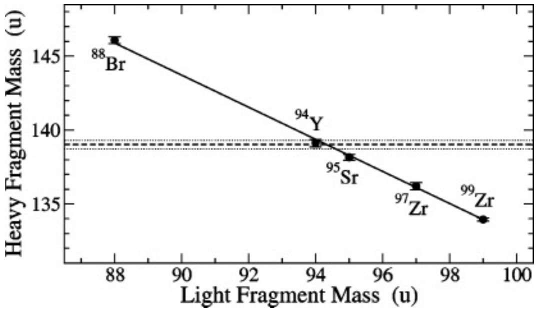

FIG. 2. Centroids of heavy-fragment mass distributions plotted against the mass number of complementary short-lived isomers. The solid line is a fit to the calibration data (solid points). The centroid associated with the unknown isomer is shown with a dashed line, along with its 1-σ confidence limits (dotted lines).

The intersection of the bar corresponding to the new isomer with the fitted calibration line allowed the mass of the unknown nucleus to be identified as $A = 94$. In the $A = 94$ isobaric chain, the most abundantly produced nuclei are Rb, Sr, and Y [15]. The medium-spin structures of ^{94}Y [13] and ^{94}Sr [16] are known. This leaves ^{94}Rb as a possible candidate for the new isomeric state.

To learn more about the new isomer and the yrast structure of the ^{94}Rb nucleus, an analysis has been made of the high-fold γ-ray coincidence data collected previously with large arrays of Ge detectors [16,17] from the spontaneous fission of ^{248}Cm and ^{252}Cf. Though the region of $A = 95$ is less intensively populated in the fission of these nuclei, when compared to that of the uranium isotopes, the high efficiency of those arrays provided a large number ($\geqslant 10^{10}$) of triple-γ events. In these data we could observe the newly identified cascade of delayed γ rays and were also able to add new prompt γ-ray lines to the excitation scheme of ^{94}Rb.

Spectra, doubly-gated on lines from the new isomeric cascade in both the ^{252}Cf and the ^{248}Cm γ-γ-γ cubes, are shown in Fig. 3. Compared to Fig. 1 the spectrum in Fig. 3 (upper panel) shows a number of new coincident transitions. These new transitions have been assigned to be prompt γ rays feeding the isomeric state or bypassing it. In Fig. 3 the insets show the low-energy parts of the gated spectra, where X rays of Pm (upper panel) and Pr (lower panel) are seen. The element complementary to $_{37}$Rb in the fission of $^{252}_{98}$Cf is $_{61}$Pm and in the fission of $^{248}_{96}$Cm it is $_{59}$Pr. The observed X rays confirm the assignment of the new isomer to be a Rb isotope. A combination of the data from delayed and prompt spectroscopy experiments allowed, thus, the assignment of the new isomer to $^{94}_{37}$Rb^{57}. Further analysis of the spontaneous fission data allowed the construction of the level scheme of ^{94}Rb as shown in Fig. 4.

The level scheme includes both delayed and prompt γ-ray transitions. Because no overlap has been found with the transitions measured in β^- decay [1], the excitation scheme proposed in this work is built on top of the $I = 3$ ground state [19].

The ground-state spin and parity arise from the coupling of the odd proton to the odd neutron occupying the orbitals $f_{5/2}$ and $s_{1/2}$, respectively. From the quadrupole moment value measured in Ref. [20], $Q = 0.163(50)$ b, it was concluded that the ground state is spherical. A detailed β^--decay study made by Lhersonneau *et al.* [1] has shown that at low excitation energies the structure of ^{94}Rb, along with the ground-state spin value and parity, can be explained within a spherical shell-model approach. The nature of the excited levels in Fig. 4 is currently under investigation and will be part of a forthcoming publication.

The energy of the isomeric level was determined to be 2074.8 keV. The isomer decays with a half-life of 107(16) ns as obtained from the time spectrum gated on the 589.7-keV transition cut from the ^{252}Cf(SF) data; the $T_{1/2}$ value is in agreement with the half-life obtained by Sund, Weber, and Verbinski [9] for the most intense 217.2-keV transition from the reactions ^{235}U(n, f) and ^{239}Pu(n, f) [94(9) ns and 128(32) ns, respectively]. A closer analysis of the time spectra showed the presence of another isomeric state in the level scheme,

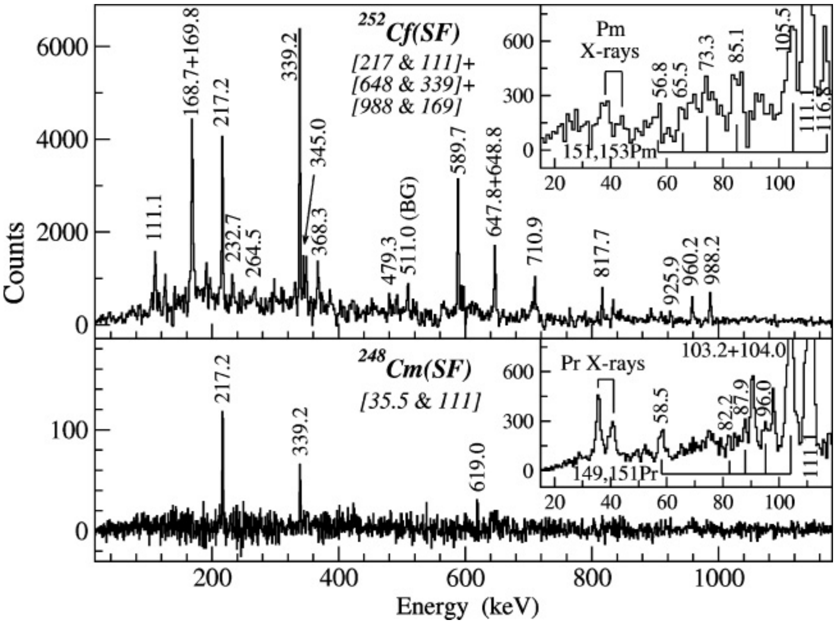

FIG. 3. (Upper panel) Spectrum of coincident γ rays obtained as a sum of three double gates on the ^{252}Cf γ-γ-γ cube. The low-energy region of the spectrum is expanded in the inset. Positions of Pm X rays and γ rays from ^{151,153}Pm isotopes are shown. (Lower panel) γ-ray spectrum from the ^{248}Cm data gated on the Pr X rays and the 111.1-keV transition. The inset shows the presence of Pr X rays and γ rays [18].

located at 1485.2 keV. The half-life of 18(1) ns for the second isomer was also determined from the ^{252}Cf data set. In Fig. 5, the time spectrum gated on transitions depopulating the 1485.2-keV isomer is shown; the contribution from both isomers can be seen.

Considering the observed branchings and transition energies and assuming that the spin grows with the excitation energy, as commonly observed in the level schemes populated in fission, the spins and parities to the excited levels in ^{94}Rb were assigned as shown in Fig. 4.

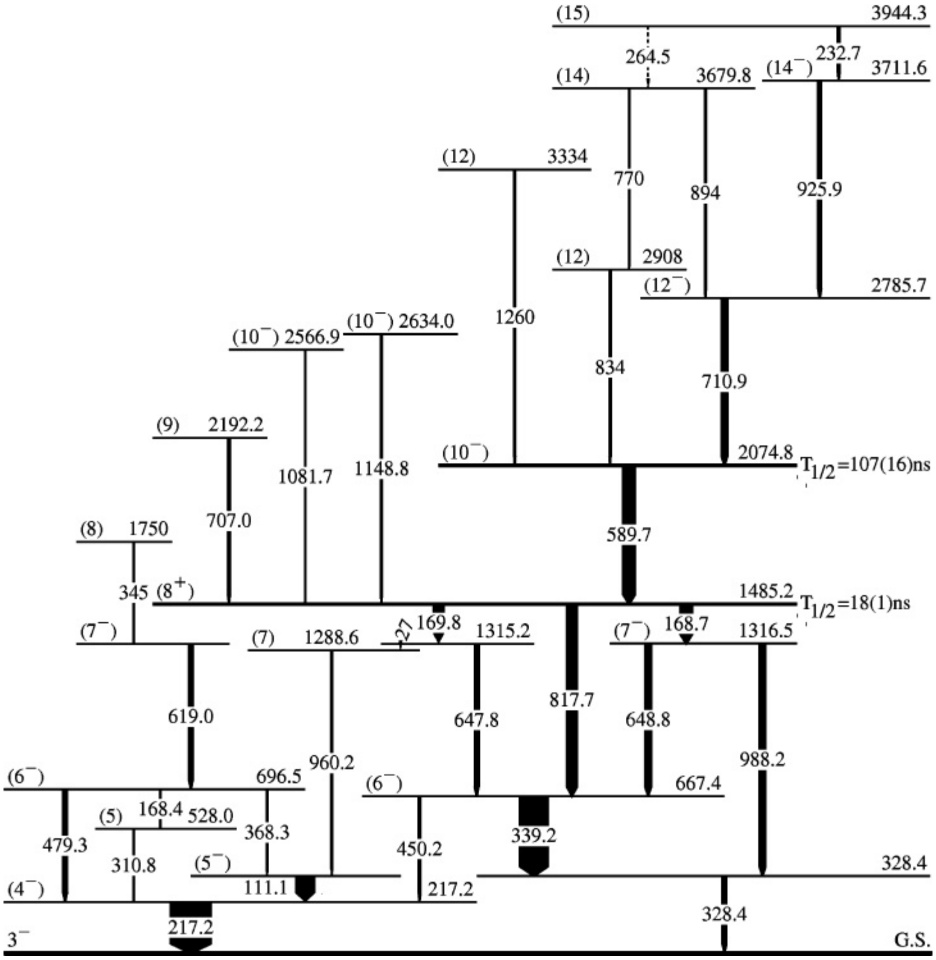

FIG. 4. Level scheme of ^{94}Rb. All the transitions are new.

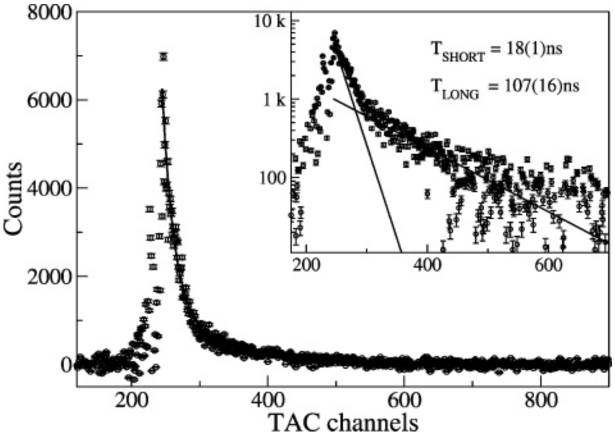

FIG. 5. Time spectrum gated on transitions depopulating the 1485.2-keV isomer in ^{94}Rb.

The spin and parity of the 1485.2-keV isomer is assigned to be (8^+) and the likely configuration of this level involves the $[\pi(g_{9/2})\nu(g_{7/2})]_{8^+}$ coupling. The proton $g_{9/2}$ orbital is known to give rise to isomeric states in the odd-Z nuclei of the region, for instance, ^{95}Y, $T_{1/2} = 57\ \mu$s at 1088 keV [21]. The neutron $g_{7/2}$ orbital also causes isomerism, in the odd-N nuclei ^{95}Kr ($T_{1/2} = 1.4\ \mu$s at 196 keV [4]) and ^{95}Sr ($T_{1/2} = 23$ ns at 556 keV [9]). One may, therefore, expect that the combination of these two orbitals forms an isomeric state in the odd-odd ^{94}Rb nucleus.

The neutron orbital above $g_{7/2}$ is $h_{11/2}$ and it is proposed that the 2074.8-keV isomeric state corresponds to a fully aligned, $[\pi(g_{9/2})\nu(h_{11/2})]_{10^-}$ spherical configuration. The same configuration was recently found to be responsible for the microsecond isomer in the neigboring odd-odd rubidium isotope ^{96}Rb [5]. Consequently, it is proposed that the 2074.8-keV isomer decays via an $M2$ transition of 589.7 keV, which is consistent with the observed half-life of this level, from a consideration of Weisskopf estimates.

In summary, the yrast, medium-spin structure of the neutron-rich odd-odd ^{94}Rb was studied for the first time via neutron-induced and spontaneous fission reactions. The combination of data sets from delayed and prompt γ-ray spectroscopy experiments allowed the mass and atomic number of the nucleus to be clearly identified and a level scheme to be built. In total, 20 excited states were found, including two isomeric states with half-lives of 18(1) and 107(16) ns. It is proposed that the isomers are due to the attractive interaction of the proton $\pi(g_{9/2})$ orbital with the $\nu(g_{7/2})$ and $\nu(h_{11/2})$ neutron orbitals, respectively. The new data provide information on the energies of these shell-model states in the $A \sim 95$ region.

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