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Beta-decay study of ^{94}Kr

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Beta-decay of neutron-rich nuclide ^{94}Kr was reinvestigated by means of a high resolution on-line mass separator and $\beta-\gamma$ spectroscopy. In total 22 γ-ray transitions were assigned to the decay of ^{94}Kr, and a new isomeric state was identified. The new information allows us to build detailed levels systematics in a chain of odd-odd rubidium isotopes and draw conclusions on nuclear structure for some of the observed states. The discussed level structure affects the evolution of β-decay half-lives for neutron-rich selenium, krypton and strontium isotopes.

I. INTRODUCTION

Short-lived krypton isotope ^{94}Kr is an even-even nucleus formed by 36 protons and 58 neutrons. The nearest doubly-magic nucleus is ^{78}Ni, thus ^{94}Kr has 8 protons and 8 neutrons added to the closed core. Despite the large number of valence nucleons, it is believed to be close to spherical in shape, as was shown by laser-spectroscopy measurement of moments and radii in the chain of krypton isotopes [1]. In β-decay of ^{94}Kr the odd-odd nucleus ^{94}Rb is formed. Odd-odd nuclei are in general less well studied, both by experiment and theory, due to the sophisticated nature of their nuclear levels. Nevertheless, their study can reveal an ample amount of information on nuclear structure. One of the primary methods for studying the excitation levels is β-decay of the even-even precursors. Due to β-decay selection rules, this method is complementary to reaction studies and prompt γ emission following spontaneous or induced fission.

Beta-decay of ^{94}Kr was previously studied experimentally in 1973 (unpublished, although results are cited in [2, 3]), 1979 [4], and, most recently, in 1989 [3]. In total, the decay scheme include 12 γ-rays (additional 5 tentatively placed) estabilishing 7 excited states in ^{94}Rb (additional one state tentatively placed). A detailed discussion of levels in ^{94}Rb populated in a spontaneous fission of ^{252}Cf and ^{248}Cm was shown in Ref. [5], but no common levels with those observed in β-decay were reported.

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In this article we report a new β-decay studies of ^{94}Kr and excited states populated in ^{94}Rb.

II. EXPERIMENTAL TECHNIQUE

The experiment was performed at the Holifield Radioactive Ion Beam Facility (HRIBF) [6, 7] at Oak Ridge National Laboratory. A 50 MeV proton beam with an average intensity of 9 μA irradiated a UC_x target of 6 g/cm^2 thickness. Radioactive ions produced in an proton-induced fission were extracted, mass-analyzed, accelerated to 200 keV and again mass analyzed by a high-resolution electromagnetic mass separator ($m/\Delta m \approx$ 10000). The separated ion beams of interest were then transmitted to the Low Energy Radioactive Ion Beam Spectroscopy Station (LeRIBSS) [7]. The estimated implantation rate of ^{94}Kr was up to 50 ions/s, with an average value of 30 ions/s.

At LeRIBSS the ions were implanted into a tape operated by a Moving Tape Collector (MTC). The MTC was run in a three-step cycle consisting of a period of 1 second during which ions were implanted into the tape, a decay measurement period of 1 second during which the ion beam was deflected, and a tape-transport period, lasting 425 ms, during which the irradiated spot on the tape was moved into a lead-shielded chamber. An array of four high-purity clover germanium detectors and two plastic β-counters closely surrounded the implantation point. The germanium detectors were used without anticomption shields to ensure high geometrical efficiency.

The photo-peak efficiency for the clover array was 34% for γ-rays of 81 keV and 6% for 1.33-MeV γ rays. The experiment lasted for a total of 8 hours.

The readout of the detection system, including MTC logic signals, was based on the XIA Pixie16 Rev. D digital electronics modules [8]. The acquisition system was operated without a master trigger, and all events were recorded independently and time-stamped with a 100 MHz clock synchronized across all modules. The timings of the signals were corrected for the walk effect. The signals from the germanium clover detectors were subject to the "add-back" procedure (summing of signals from four crystals of each detector). The time gates of 100 ns were applied in order to construct $\gamma-\gamma$ and $\beta-\gamma$ coincidences. The delayed $\beta-\gamma$ coincidences, up to 1 μs, were used in order to detect isomeric transitions following β-decay.

A more detailed description of the LeRIBSS detector system is given in Ref. [9].

III. RESULTS AND DISCUSSION

A. Experimental results

Figure 1 shows the β-gated γ-ray spectrum measured during the experiment. The energy spectrum was recorded up to 8.2 MeV. However, since no γ-ray transitions above 1 MeV were assigned to the decay of ^{94}Kr, only the low-energy region is shown. The transitions were identified based on the half-life and coincidences with the known γ-rays. We have been able to assign 22 γ-ray transitions to the decay of ^{94}Kr (see Table I). A half-life based on a weighted average of the strongest transitions (187, 220 and 629 keV) was found to be 227(14) ms, in good agreement with the adopted value of 212(5) ms [10, 11]. In order to extract the ^{94}Kr half-life from grow-in/decay pattern of the γ-ray transitions we had to take into account krypton diffusion from the tape. More details on ^{94}Kr half-life determination are given in Ref. [9].

Based on $\beta-\gamma-\gamma$ coincidences the decay scheme of ^{94}Kr was built. An example of $\beta-\gamma-\gamma$ coincidence data is presented in Fig. 2. The previously published decay scheme included only 12 firmly established transitions. We confirm the placement of the major transitions, however, some γ-rays previously tentatively assigned (203, 472 keV) were not observed in our experiment or (121 keV, probably corresponding to 119 keV in our work) were assigned to different cascades [3]. The 32.6 keV transition is not detected directly, but its existence is based on clear coincidence between 135 and 187 keV γ-lines. Moreover, with the help of the coincidence data, the 293 keV transition was found to be a doublet (cf. Fig. 2). The decay scheme, as shown in Fig. 3, will be discussed in more detail in the next section. It is worth noticing that there is no correlation to results from any of the prompt γ-ray emission from fission measurements [5].

TABLE I. Summary of γ lines assigned to the decay of ^{94}Kr. Intensities are given relative to the 629 keV transition ($I_\gamma = 100$).

Energy (keV)	I_γ	$\beta-\gamma-\gamma$
32.6(4)[a]	6.5(15)	
99.9(2)[b]	10.7(6)	119
119.4(2)	4.1(3)	100, 135, 764
134.7(2)	14.7(8)	187, 220, 629
167.3(2)	25.5(13)	187, 191, 629
187.0(2)	35.0(18)	135, 167, 629
191.3(2)	6(2)	167, 629
219.6(2)	81.4(42)	135, 629, 764
288.2(2)	32.8(17)	293, 402, 696
292.9(4)[c]	7(3) + 8(3)	288, 293, 402
320.8(2)	27.5(15)	662
354.5(2)	31.0(17)	629
358.8(2)	38.4(20)	629
390.7(2)	14.0(8)	593
395.0(2)	20.9(12)	593
402.2(2)	24.0(13)	288, 293
593.0(2)	34.0(19)	391, 395
629.1(2)	100.0(52)	135, 167, 187, 191, 220, 354, 359
662.1(2)	24.4(14)	321
695.5(2)	21.7(13)	288, 293
764.1(2)	43.7(24)	119, 220
984.2(2)	21.8(13)	-

[a] Based on coincidence data (see text for more details)
[b] $T_{1/2} = 130(15)$ ns
[c] Doublet resolved with the coincidence data

B. Discussion

The total orbital momentum of the ground state of ^{94}Rb is known from observations of hyperfine structures, to be equal to $3\hbar$ [12]. The ground states of neighboring nuclides, i.e. isotopes of rubidium [12], krypton [1] and strontium [13], have been established with the same method. From these data we can draw the conclusion that the ground state of ^{94}Rb is due to coupling of a proton hole in the $\pi f_{5/2}$ orbital and a neutron in the $\nu s_{1/2}$ orbital (cf. Fig. 4).

A number of pairs of transitions shifted by approximately 4.3 keV are observed: 191-187, 292-288, 359-354, and 395-391 keV. The coincidence data confirm that the energy of the first excited state is equal to this difference. Since a low-lying 2^- state from a $\pi f_{5/2} \otimes \nu s_{1/2}$ multiplet is expected as a first excited state, we tentatively assign such a spin and parity to this level. The transition $2^- \rightarrow 3^-$ would be of M1 type, it is expected to be strongly converted ($\alpha_{tot} \approx 180$ [14]) and cannot be observed directly by γ-ray detectors.

The 99.9 keV transition was found to have a half-life of 130(15) ns. This value was measured by comparing

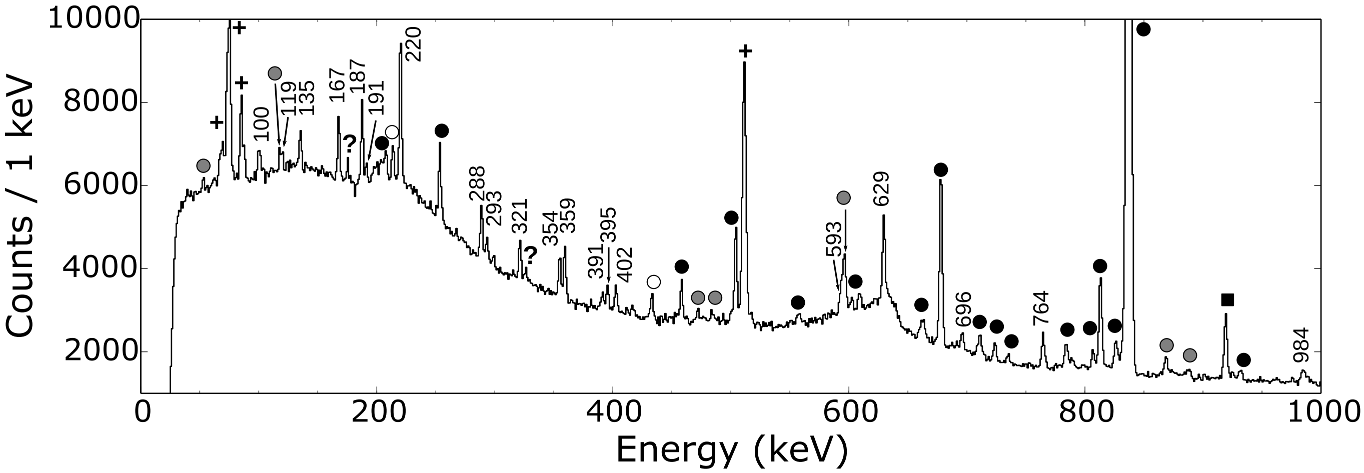

FIG. 1. Portion of the β-gated γ-ray spectrum obtained in the experiment. Transitions identified by energy were assigned to the decay of ^{94}Kr. Other transitions are marked by parent decay: black circles (^{94}Rb), gray circles (new lines assigned to decay of ^{94}Rb), open circles (^{94}Rb βn), black squares (^{94}Y), crosses for background γ-rays, and question marks for unassigned transitions.

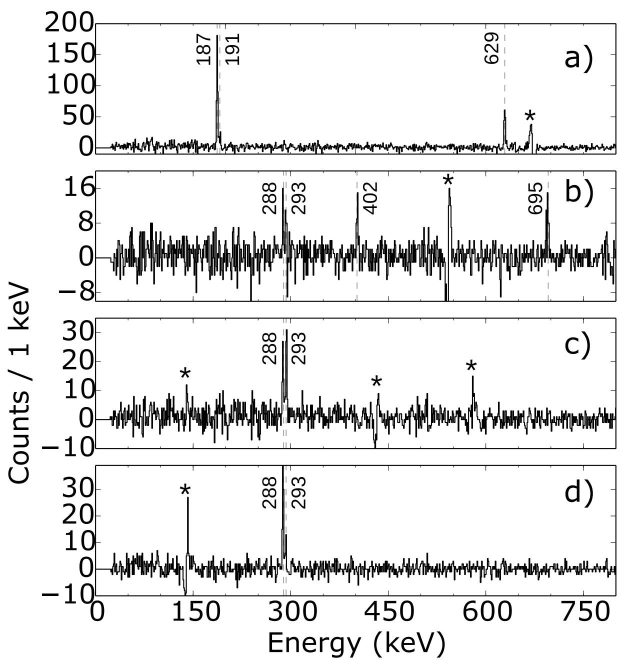

FIG. 2. Background-subtracted $\beta-\gamma-\gamma$ coincidence spectra gated on the following transitions: (a) 167 keV, (b) 293 keV, (c) 402 keV, and (d) 695 keV. The peaks marked with star ($\star$) are artifacts due to the background-subtraction procedure.

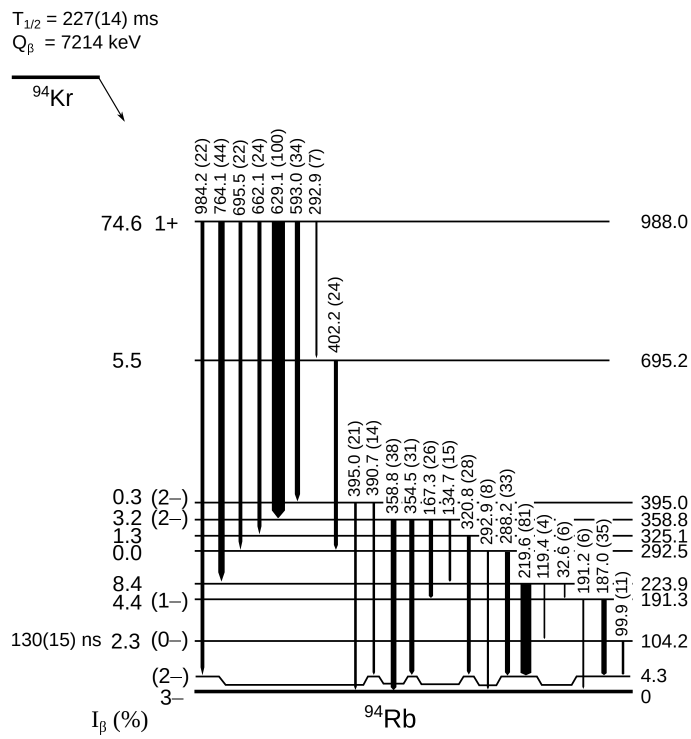

FIG. 3. Proposed β-decay scheme of ^{94}Kr. Intensities of γ transitions (in brackets) are relative to the 629 keV transition. Apparent β-feedings are calculated from γ-ray transitions intensities.

the difference in time between registration of a β-particle in the fast scintillating detector and a γ-ray in an HPGe detector. In the $\beta-\gamma-\gamma$ spectrum we found the 100-keV transition to be in coincidence with 119-keV γ-ray. The 119 keV line was found to be also in coincidences with the 135 and 764-keV transitions. This allows us to place the isomeric state above the 4.3 keV level. The observed half-life suggests an E2 type transition (17 W.u.), thus the possible spin assignments are 0^- or 4^-. The 4^- choice is rejected based on the data from ^{252}Cf fission, where the yrast states are populated, and a low-lying 4^- state should be observed (lowest 4^- state is reported at 217 keV). Therefore we tentatively assign $I^\pi = 0^-$ to this state. The 0^- state was observed as the ground state of ^{90,92}Rb, therefore we assume that the 0^-_1 state in ^{94}Rb is

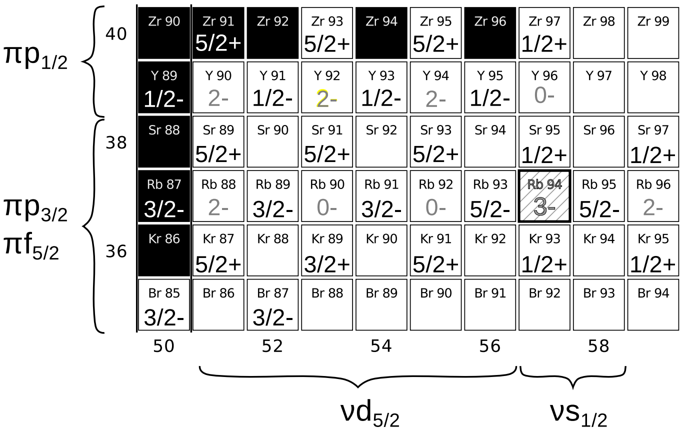

FIG. 4. Fragment of chart of nuclides around ^{94}Rb. The spin and parity of the ground state for odd-mass, and odd-odd isotopes are shown.

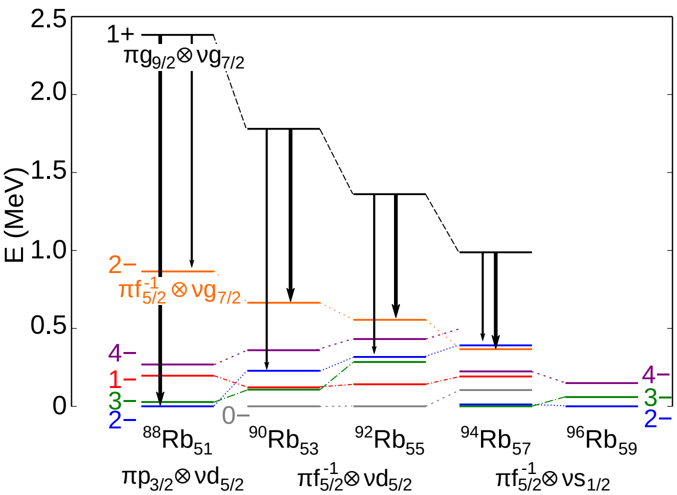

FIG. 5. (Color online) Evolution of low-lying levels in odd-odd rubidium isotopes.

of similar nature, build on the $\pi f_{5/2}^{-1}\otimes\nu d_{5/2}$ configuration.

A distinct feature of decay of neutron-rich even-even isotopes is a strong feeding to 1^+ states. The Fermi transition is isospin forbidden (the analogue states are above the ground state of the precursor), as well as are Gamow-Teller transitions $0^+ \to 0^+$. Thus, the only possible choice for an allowed transition is $0^+ \to 1^+$. In the decay of ^{94}Kr we observe 75% of β-transitions feeding the 988 keV state, resulting in an apparent $\log(ft)$ of 4.0. Since the Q_β of ^{94}Kr is 7215(12) keV [11], this should be regarded as a lower-limit for $\log(ft)$ due to the possible "pandemonium" effect [15]. Nevertheless, such a small $\log(ft)$ strongly suggests a 1^+ assignment to this state. Similar states were also observed in ^{88}Rb (2232 keV), ^{90}Rb (1780 keV), and ^{92}Rb (1361 keV). A systematic plot of these states is presented in Fig. 5.

We propose that the observed 1^+ state is mainly built on the $\pi g_{9/2}\otimes\nu g_{7/2}$ configuration. The attractive residual interaction between these particles is expected to bring down the excitation energy from 2.3 MeV found in a single particle model. The expected states from this multiplet with the lowest energy are 1^+ and 8^+ (c.f Fig. 6). Indeed an 8^+ isomeric state at 1485 keV excitation energy was observed [5], which supports our interpretation. An energy difference of about 300 keV between 1^+ and 8^+ states calculated with the SDI interaction [16] matches well the observed gap of 497 keV. Other members of that multiplet (i.e. $2^+ - 7^+$) are expected at higher energies and have not been observed.

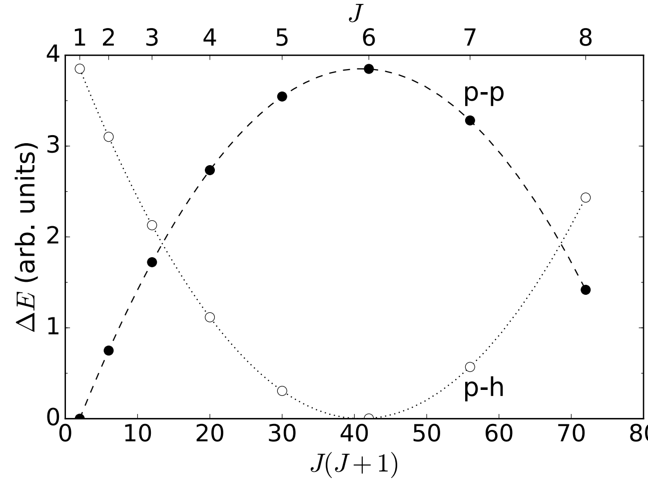

FIG. 6. Schematic representation of the energy shifts due to the residual interaction value in coupling of the odd-odd particle-particle (closed symbols, dashed line) and particle-hole (open symbols, dotted line) systems. Presented multiplet is $\pi g_{9/2}\otimes\nu g_{7/2}$ but similar parabolas may be created for other orbitals.

The de-excitation pattern of the lowest 1^+ state is preserved throughout all odd-odd rubidium isotopes starting from $A = 90$. This state decays predominantly via E1 transitions to the 2^- states. We expect the 2^- states to be build on the $\pi f_{5/2}^{-1}\otimes\nu g_{7/2}$ configuration (stronger transition) and the $\pi p_{3/2}\otimes\nu d_{5/2}$ (weaker transition). The latter constitutes the ground state of ^{88}Rb and may be traced in heavier isotopes as well. The former configuration moves down together with the 1^+ state, and the transition is of similar energy in all the isotopes in question. This behavior is understandable as the Fermi level moves toward the $\nu g_{7/2}$ orbital as the number of neutrons increases. The weaker transition $\pi g_{9/2}\otimes\nu g_{7/2} \to \pi p_{3/2}\otimes\nu d_{5/2}$ is not a single particle transition, as opposed to $\pi g_{9/2}\otimes\nu g_{7/2} \to \pi f_{5/2}^{-1}\otimes\nu g_{7/2}$, therefore we suggest that the strength of the weaker transition comes mainly from mixing of the 2^- states. With this assumption, we estimated the mixing strength between the configurations to be 8 keV. This low value is in accordance with the significantly different single particle nature of the two states.

The half-lives of krypton isotopes were calculated with

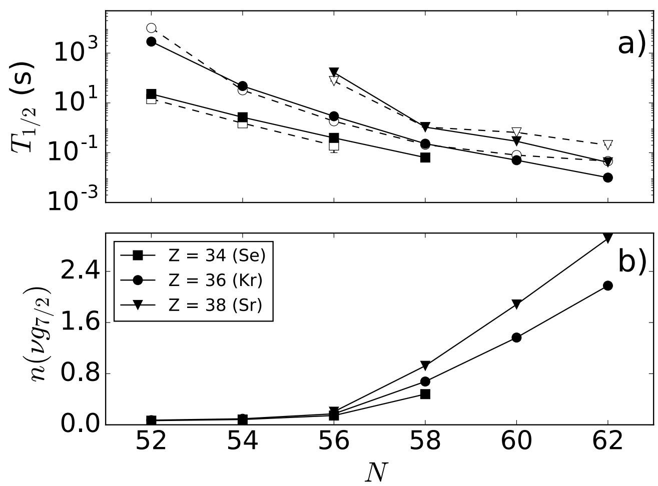

FIG. 7. a) Comparison between calculated (full symbols) and experimental (open symbols) half-lives of even-even selenium, krypton and strontium isotopes.
b) Average occupation of the $\nu g_{7/2}$ state calculated with BCS equation.

a model based on single particle levels, BCS paring interaction and allowed β-transitions. The single particle orbitals were found using Woods-Saxon potential with "universal" parametrization [17] and used in BCS equation to find the occupation of the levels. Experimental Q_β values and allowed single-particle Gamow-Teller transitions elements were used. The transition $\nu g_{7/2} \rightarrow \pi g_{9/2}$ is the only energetically possible decay path. With increasing number of neutrons the Fermi surface moves towards the $g_{7/2}$ orbital, and particles are more likely to be found in that state (see Fig. 7b). This simple model explains surprisingly well the observed half-lives of isotopes of krypton and neighboring strontiums and seleniums (cf. Fig. 7). It is worthwhile to notice that, as expected, with the onset of deformation above N = 60, the model based on spherical single particle levels starts to deviate significantly from the experimental half-lives.

IV. SUMMARY

Detailed study of the β-decay of ^{94}Kr revealed 10 new firmly assigned γ-ray transitions. The more complete decay scheme, including an previously unknown isomeric state, allowed us to study the systematical evolution of states in the chain of odd-odd rubidium isotopes. The pattern of the strongly-fed 1^+ state de-exciting to 2^- states preserves throughout the chain. Their dominant structure can be understood using basic single-particle coupling schemes. This interpretation is reinforced by the good description of half-lives for the selenium, krypton and strontium isotopic chains. The deviations become apparent only when the onset of deformation is reached and the spherical model is not suitable anymore.

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