Search for the low-lying $(\pi 1g_{\frac{9}{2}})^4\ 6_2^+$ state in ^{94}Ru

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Excitations in ^{94}Ru were populated through the β^+/ϵ decay of ^{94}Rh following the fusion evaporation reaction ^{58}Ni(^{40}Ca,3*pn*)^{94}Rh. Recoiling nuclei were implanted on the Yale moving tape collector at the Wright Nuclear Structure Laboratory, and delayed γ-rays were observed via an array of four Compton suppressed HPGe clover detectors. Nine new γ-transitions and five new levels were added to the level scheme of $(\pi 1g_{\frac{9}{2}})^4_{J^\pi=6^+}$ level, in close agreement with prediction.

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I. INTRODUCTION

The existence of isomers in the two-particle ground state bands of even-even nuclei is consistently predicted and observed with great success (e.g., see [1–3], and references therein). However, these systematics fail for neutrons in the $1g_{\frac{9}{2}}$ orbital in the region $40<N<50$; while seniority $\nu = 2$ isomers are known for $^{70}_{28}$Ni$_{42}$ [4,5] and $^{76}_{28}$Ni$_{48}$ [6,7], the corresponding states have been sought in $^{72}_{28}$Ni$_{44}$ and $^{74}_{28}$Ni$_{46}$ [8,9] to no avail.

Empirical shell model calculations (ESM) using experimental data to derive the effective nucleon-nucleon interaction [8,10,11] offer an explanation for these missing isomers in the form of a seniority 4 $(\nu 1g_{\frac{9}{2}})^n\ 6_2^+$ level below the seniority 2 $(\nu 1g_{\frac{9}{2}})^n\ 8_1^+$ level in these species (with n the occupation number of $\nu 1g_{\frac{9}{2}}$). The presence of the seniority four 6^+ allows for a relatively unhindered decay from what otherwise would have been an isomeric two particle 8^+ excitation. However, as put forth by [11], calculations using the S3V interaction place this ν=4 6^+ level above the ν=2 8^+ level, at odds with the ESM prediction and its explanation for the missing nickel isomer.

When the ESM calculations are repeated for $^{94}_{44}$Ru$_{50}$ (valence mirror to $^{72}_{28}$Ni$_{44}$), a low-lying $\nu = 4$ 6^+ state arises via the protons in $1g_{\frac{9}{2}}$ [10], in keeping with the prediction for $^{72}_{28}$Ni$_{44}$ and consistent with valence mirror symmetry (though in $^{94}_{44}$Ru$_{50}$ the two proton ground state band is not intercepted by any $\nu = 4$ states and isomerism remains in the $\nu = 2$ 8^+ level). Due to the evident valence mirror symmetry in these calculations, it is possible to find support for the ESM explanation for the missing ν=2 isomer in $^{72}_{28}$Ni$_{44}$ without examining this experimentally difficult (see [8]) isotope directly, by identifying the corresponding ESM-predicted low-lying 6^+ excitation in $^{94}_{44}$Ru$_{50}$. To this end, a spectroscopic study of this nuclide was conducted employing the β^+/ϵ decay of $^{94}_{45}$Rh$_{49}$.

II. EXPERIMENT

Excitations in ^{94}Ru were populated through the β^+/ϵ decay of ^{94}Rh following the fusion evaporation reaction ^{58}Ni(^{40}Ca,3*pn*)^{94}Rh, with a beam energy of 160 MeV similar to the previous work [12]. Wright Nuclear Structure Laboratory's ESTU tandem accelerator provided ∼ 50 enA of ^{40}Ca^{10+} on a 500 μg/cm^2 isotopically enriched ^{58}Ni target. The reaction was performed at the Yale moving tape collector [13], where recoils were implanted on a 16 mm wide aluminized Kapton tape and thereon transported to a counting station consisting of four coplanar Compton-suppressed HPGe clover gamma detectors. A 3 mm diameter Au beam stop was placed 73 mm downstream of the target and 15 mm in front of the tape to block the primary beam, while passing an acceptance arc including ∼80% of the reaction products as calculated using PACE4 [14]. To optimize the γ-statistics following the beta decay of ^{94}Rh, the tape was advanced after 45 s of implantation and counting, roughly two half-lives of the 8^+ isomer of ^{94}Rh ($t_{\frac{1}{2}} = 25.8$ s [15]). This cycle time suppressed γ rays from the β^+/ϵ decay daughters of some of the longer-lived predominant contaminants (^{91,92}Tc, ^{92}Ru, $t_{\frac{1}{2}} \sim$ 1–4 min), but admitted those following the decays of ^{50}Mn and ^{53,54}Co ($t_{\frac{1}{2}} \sim$ 200–300 ms, thought to be produced via beam reactions with ^{12}C and ^{16}O found either in the tape, or as contamination in the target chamber), as well as ^{91}Ru ($t_{\frac{1}{2}} = 9$ s).

After 100 h of singles-triggered data collection, approximately 150×10^6 singles events and 13×10^6 coincidences were acquired. The data were sorted into singles and doubles histograms with $E_{\gamma\max} \approx 2.8$ MeV in analysis off-line.

Nine new γ-rays and five newly placed levels in ^{94}Ru were seen following beta decay of the ^{94}Rh 8^+ isomer compared to the previous study [15]; the new proposed level scheme for ^{94}Ru is shown in Fig. 1, Table I lists these levels with their estimated beta branching ratios ($\beta_{\rm B.R.}$) from ^{94}Rh as well

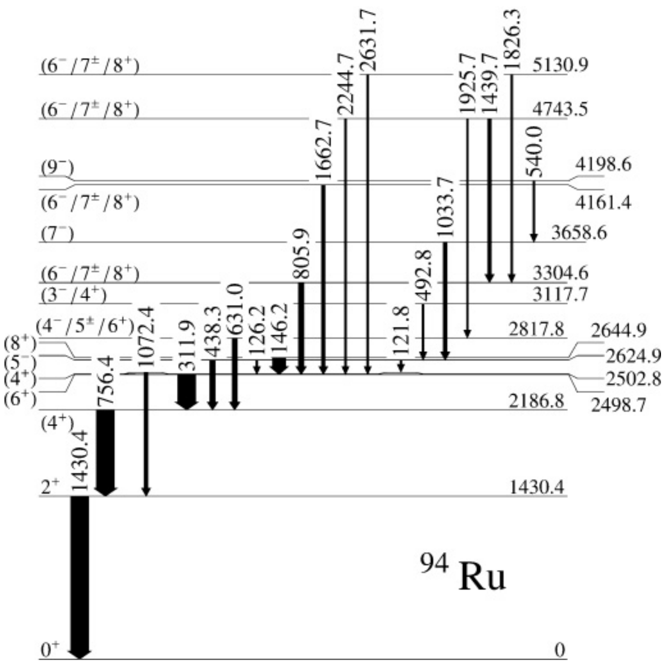

FIG. 1. Levels and γ-rays seen in the present work in ^{94}Ru. Level energies and γ-ray transitions are marked with their energy in keV. Arrow widths are logarithmically proportional to relative γ-ray intensity measured in the present work.

as their depopulating γ-rays, and the singles spectrum with labeled yrast lines can be seen in Fig. 2(a).

Since electrons were not detected directly, estimating the $\beta_{\mathrm{B.R.}}$ required the assumption that levels were populated exclusively by the β^+/ϵ decay, and population by unseen γ-rays from high-lying levels was negligible (the extent to which this assumption is borne out is discussed below). Since all the levels in ^{94}Ru for which [15] reported any $\beta_{\mathrm{B.R.}}$ from the decay of the 4^+ ground state of ^{94}Rh show extremely weak β-feeding here, no β-decay was attributed to the ^{94}Rh ground state. Furthermore, since the tape cycle time was optimized to detect gamma rays following the decay of the 25.8 s 8^+ isomer of ^{94}Rh, the $t_{\frac{1}{2}} = 70.6$ s cascade from the 4^+ ground state was suppressed, further masking any potential β-decay from this state. Thus, estimates for the J^π of each new level in ^{94}Ru were made according to the spin-parity assignments consistent with their β-feeding assumed to come from the 8_1^+ isomer in ^{94}Rh, as well as with the selection rules for γ-decay to the ^{94}Ru excitations with previously reported J^π. The J^π assignments for all previously seen levels were taken from the literature, save for that of the level at 2503 keV; while [15] suggests a J^π of (2^+) or (4^+), the observation of a new γ-ray in this work to this level from a (5^-) state supports a (4^+) assignment.

III. DISCUSSION

Overall, the level scheme observed here shows excellent agreement with [15]. Only one previously seen γ-ray of 553 keV from a level at 3178 keV went unobserved here;

TABLE I. Excited states and γ-ray transitions placed in ^{94}Ru.

E_i(keV)	J_i^π	$\beta_{B.R.}$[a]	γ decays E_γ(keV)	J_f^π	I_γ[b]
0	0^+	0	–	–	–
1430.4(1)	2^+	0	1430.4(1)	0^+	100
2186.8(1)	(4^+)	0	756.4(1)	2^+	99.6(1)
2498.7(2)	(6^+)	.04(1)	311.9(1)	(4^+)	96.4(2)
2502.8(4)	(4^+)	.005(4)	1072.4(4)	(2^+)	0.9(3)
2624.9(4)	(5^-)	.022(7)	121.8(1)[c]	(4^+)	0.4(2)
			126.2(1)	(6^+)	0.57(2)
			438.8(4)	(4^+)	2.54(3)
2644.9(2)	(8^+)	.84(2)	146.2(1)	(6^+)	86.37(8)
2817.8(2)[c]	$(4^-/5^\pm/6^+)$	.008(3)	631.0(1)[c]	(4^+)	1.19(9)
3117.7(7)	$(3^-/4^+)$	.0025(7)	492.8(5)	(5^-)	0.25(2)
3304.6(2)[c]	$(6^-/7^\pm/8^+)$	.04(1)	805.9(1)[c]	(6^+)	4.3(3)
3658.6(2)	(7^-)	.006(2)	1033.7(1)	(5^-)	1.07(2)
4161.4(3)[c]	$(6^-/7^\pm/8^+)$	.006(1)	1662.7(3)[c]	(6^+)	0.66(2)
4198.6(3)	(9^-)	.005(2)	540.0(2)	(7^-)	0.50(6)
4743.5(3)[c]	$(6^-/7^\pm/8^+)$	.019(8)	1439.7(4)[c]	$(6^-/7^\pm/8^+)$	1.3(3)
			1925.7(3)[c]	$(4^-/5^\pm/6^+)$	0.33(1)
			2244.7(4)[c]	(6^+)	0.28(1)
5130.9(4)[c]	$(6^-/7^\pm/8^+)$	.007(2)	1826.3(3)[c]	$(6^-/7^\pm/8^+)$	.45(1)
			2631.7(7)[c]	(6^+)	.31(3)

[a]Branching ratios are relative to total decays from the combined 4^+ ground state and 8^+ isomer of ^{94}Rh.
[b]Normalized to $I_{1430.4} = 100$.
[c]New level / transition in this study.

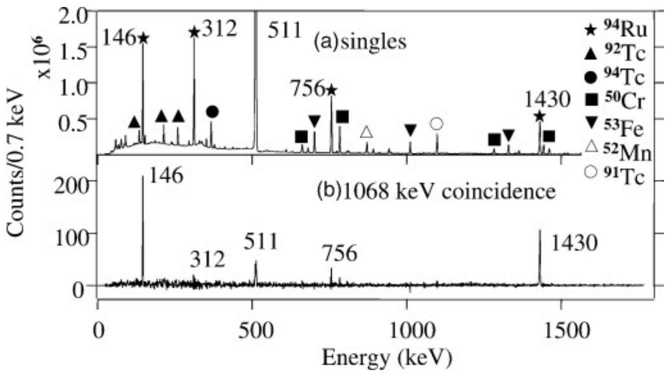

FIG. 2. (a) γ-ray singles spectrum. Peaks are labeled with the nuclei they are attributed to. Peak intensity at 511 keV is attenuated for clarity. (b) Spectrum of γ-coincidences with the transition at 1068 keV. Both spectra are truncated above $\sim$ 2 MeV to emphasize the relevant peaks.

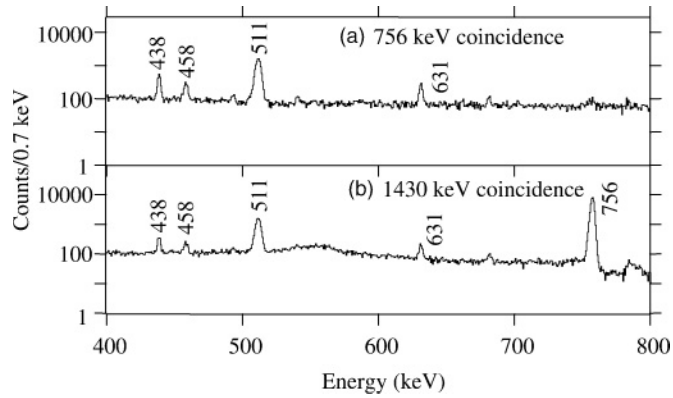

FIG. 3. (a) Spectrum of γ-coincidences between 400 and 800 keV with the transition at 756 keV. (b) Spectrum of γ-coincidences between 400 and 800 keV with the transition at 1430 keV. Both spectra show a clear coincidence with a new transition at 631 keV, a potential decay from a new 6_2^+ candidate in ^{94}Ru.

Ref. [15] only observed this level following the decay of the 4^+ ground state in ^{94}Rh, which was not populated significantly by the present heavy ion fusion reaction. Deexcitations from the ^{94}Ru level (at 2502.8 keV) with the largest $\beta_{\rm B.R.}$ (30.7% as per [15]) from the decay of ^{94}Rh 4_1^+ made up less than 1% of the total ^{94}Ru γ-intensity in this experiment. Since [15] reports the $\beta_{\rm B.R.}$ to this level to be $\sim$15 times greater than that to the level deexciting via the 553 keV γ-ray, the 553 keV decay can be expected to represent $\leqslant 0.07\%$ of the total γ-intensity here, an order of magnitude smaller than the weakest placed gamma-ray transition, and thus below our experimental sensitivity.

A notable exception compared to the present level scheme for ^{94}Ru is the dismissal of the 1068 keV γ-decay from the previously placed level at 3255 keV. The coincidence gate for this transition is presented in Fig. 2(b). Immediately evident are the strong coincidences the 1068 keV line shows with the 146 keV and 1430 keV yrast γ-rays, relative to the singles spectrum. The coincidence between the 1068 and 146 keV transitions is not consistent with the previous placement of the 1068 keV transition, and the simultaneous strong coincidence with the 1430 keV γ-ray and lack of proportional coincidences with the intermediate members of the yrast band suggests that the 1068 keV γ-ray observed here is a sum peak between the 312 and 756 keV transitions. The apparent peak at 756 keV in Fig. 2(b) is an artifact below statistical significance, which remains after background subtraction and random coincidence suppression. As such, the 1068 keV γ-ray is dismissed as a sum peak between the 312 and 756 keV transitions. Since the level in ^{94}Ru previously proposed at 3255 keV is based solely on the 1068 keV γ-ray, no evidence remains for this excitation.

A new γ-ray of 631.0 keV depopulating a new level at 2817.8 keV in ^{94}Ru is identified in this study via this transition's strong coincidence with the 1430.4 and 756.4 keV yrast decays (these coincidence gates are presented in Fig. 3). This new excitation is very close to where the ESM calculations [10] predict the $\nu = 4$ 6_2^+ excitation to lie. Experimental results reported here are compared to the relevant ESM theoretical levels (originally presented partially in [10] and entirely in [16]) in Fig. 4, with generally good agreement. However, this 6_2^+ candidate is the only new level for which no spin and parity can be assigned that is consistent with both its electromagnetic decay to the low-lying (4^+) state, and with the estimated strength of its β^+/ϵ feeding from the 8_1^+ level in ^{94}Rh. A tentative proposal of (6^+) may be made for the J^π of this level as per the ESM calculations, allowing for an $E2$ decay to the (4^+) excitation below. However, this proposal

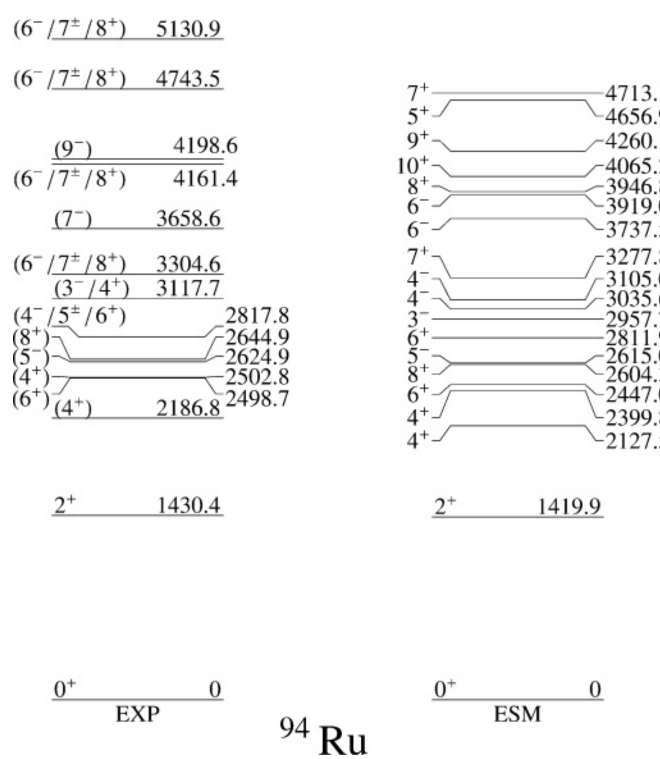

FIG. 4. Levels in ^{94}Ru seen in the present experiment are presented on the left, compared to the ESM prediction [10,16] on the right. Excitation energies are quoted in keV.

suggests that the β^+/ϵ branch from the 8^+ isomer in ^{94}Rh to this excitation is second forbidden, which is inconsistent with the observed 0.8(3)% β-branch estimated for this level. In light of these disagreements, all the electromagnetically consistent J^π assignments for this level are retained, $\beta_{\mathrm{B.R.}}$ estimates notwithstanding; it must be emphasized that since electrons were not detected directly, these $\beta_{\mathrm{B.R.}}$ are based on the necessary but potentially specious assumption that the population of each level is due in its entirety to a β-branch from ^{94}Rh. It remains unclear how much of the population of the level at 2.818 MeV is in fact due to direct β-population, and how much is due to population via unseen γ-rays from high-lying levels, which may reduce the $\beta_{\mathrm{B.R.}}$ and eliminate the aforementioned inconsistency. Similar unseen γ-population likely accounts for the abnormally high β-branches of 2.2(7)% and 4(1)% to the levels at 2.625 and 2.499 MeV, respectively. $\beta_{\mathrm{B.R.}}$ of 2% and <8%, respectively, were reported by [15] for these levels, where the same explanation of missing γ-intensity was offered. Weak, high-lying γ-rays may also contribute to the weak population of levels at 3.118 and 2.503 MeV, which were only populated by decay of the ^{94}Rh 4_1^+ state in [15].

IV. CONCLUSION

Among the nine new γ-rays and five new excitations found in ^{94}Ru, a new level at 2.818 MeV agrees very closely in energy with the ESM prediction for the $\nu = 4$ 6_2^+ state made by [10], suggesting support for the results of these calculations in the valence mirror ^{72}Ni. However, further study is needed to unambiguously determine the J^π for this (6_2^+) candidate, before it can be identified as the predicted level with confidence.

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