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Influence of the np interaction on the $\beta$ decay of $^{94}$Pd


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We present results from stopped beam rare isotope spectroscopic investigations at the GSI (RISING) experiment based on the detection of $\gamma$-ray transitions following the $\beta$ decay of $^{94}$Pd. A comparison between the measured low-lying level scheme of $^{94}$Rh and the prediction from shell-model calculations reveals the important roles of the $g_{7/2}$ and $g_{9/2}$ orbitals in explaining the structural features. The low values of the Gamow-Teller strengths $B(\text{GT})$ can be attributed to the influence of the neutron-proton interaction, which gives rise to an increased seniority mixing for the nuclear states, thereby leading to a fragmentation of the strength to several daughter levels. These results provide further strong indications that $^{94}$Pd resides in the middle of a structural transition region in the Pd isotopes as the $N=Z$ line is approached.

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The phenomena exhibited by $N \sim Z$ nuclei in the region southwest of $^{100}$Sn can generally be understood by considering only a few valence orbitals and are particularly dominated by the $g_{9/2}$ shell. As a result, shell-model calculations for these nuclei are feasible and the corresponding experimental data can serve as an excellent testing ground for such models [1–4]. A particularly interesting feature in this part of the nuclear landscape is the gradual demise of the $N=0$, $Z=0$ line as the stability line is approached [5]. Recently, a rapid change in structure has been observed, as the $N=50$ isotones, as the $N=Z=0$ line is approached. Indeed, the evidence for the direct two-proton decay of the $^{21}$+ isomeric state in $^{94}$Ag has been initially supported [11] and later disputed [12–14] by utilizing the data for the surrounding nuclei $^{92,94}$Rh [14]. Further interest in these nuclei results from the relevance of their properties for the understanding of the astrophysical rapid-proton [15], $v_p$ [16] processes, type II supernova explosions [17] and for precision tests of the standard model [18].

In the case of $^{94}$Rh, only limited low-lying structural information is available from previous works [19–22]. Two long-lived states are known with half-lives $T_{1/2}$ = 70.6 (6) and 25.8 (2) s. These are henceforth referred to as $^{94m_{1}}$Rh($4^{+}$) and $^{94m_{2}}$Rh($8^{+}$), respectively, following the convention of Batist et al. [19,21]. It was established that the longer lived state was populated in the first $\beta$-decay study of $^{94}$Pd [20]. The order of their excitation energies is, however, not known. Evidence for a few $\gamma$ rays with energies of 558, 724, 798, 822, and 846 keV in $^{94}$Rh was also found, but they could not be placed in a level scheme [20]. Batist et al. obtained $T_{1/2}$ = 9.6 (2) s for the ground-state decay of $^{94}$Pd in a total absorption spectroscopy (TAS) study [21], a result that is in good agreement with Refs. [23,24]. This work also revealed...
the existence of four \( (1^+ \) states and a new \( (2^+ \) isomeric state in \( ^{94}\text{Rh} \). The latter is referred to as \( ^{94}\text{Rh} \) with \( T_{1/2} = 0.48 \) (3) \( \mu s \) and decays via a 55 keV \( E2 \gamma \) transition. Spin and parity assignments for these levels were based on their properties, such as half-lives, the conversion coefficients of the resulting \( \gamma \) rays, \( \beta \)-decay selection rules, and the decay data of \( ^{94}\text{Rh} \) as well as through a comparison with shell-model calculations [21].

The present work contributes to the essential data on the \( \beta \) decay of nuclei below the \( N = 50 \) shell gap and to the theoretical understanding in this region. We present a level scheme of \( ^{94}\text{Rh} \), which is based on the detection of the individual \( \gamma \) transitions following the \( \beta \) decay of \( ^{94}\text{Pd} \) using the state-of-the-art RISING facility. A comparison between our results and shell-model calculations of level structure as well as the fragmented GT strengths indicate an increased influence of the \( g_{7/2} \) orbital and the \( np \) interaction leading to mixed seniority states in this region. The previously reported two proton decay in \( ^{94}\text{Rh} \) is also briefly discussed in the context of the observed 2906-keV \( \gamma \) transition.

\( ^{94}\text{Pd} \) nuclei were produced together with other nuclei of interest by the fragmentation of an 850 MeV/nucleon \( ^{124}\text{Xe} \) primary beam, with an intensity of \( 10^8 \) particles/s on a 4 g/cm\(^2 \) \( ^{16}\text{Be} \) target, from the SIS-18 synchrotron at the GSI Helmholtzzentrum für Schwerionenforschung laboratory, Darmstadt, Germany. Details of the setup can be found in Refs. [7,25,26]. The fragments were identified on an event-by-event basis after their separation using the fragment separator (FRS) [26–31]. Figure 1 in Ref. [25] corresponds to the data obtained from this experiment and shows a clean identification of \( ^{94}\text{Pd} \) nuclei. The ions were slowed down using an aluminium degrader at the \( S4 \) focal plane of the FRS, where the RISING [28–31] stopped beam setup was located. They were implanted in an “active stopper” that consisted of nine double sided silicon strip detectors (DSSSDs) arranged in three horizontal rows perpendicular to the beam direction, with three detectors in each row. Each DSSSD had 1-mm thickness, 5 × 5-cm\(^2 \) area and 16 X and 16 Y strips [32], thus allowing the location of the implantation position of the nuclei as well as the detection of the particles emitted from their subsequent decays [33]. \( \gamma \) rays were detected by using the 15 EUROBALL cluster detectors, each cluster comprising seven individual HPGe crystals, which were placed around the active stopper. A timing signal from a scintillator, that was placed upstream from the \( S4 \) focal plane, gave information about the implantation time of the nuclei (see, e.g., [28,29,34] for details). This was used to deduce the correlation time between the arrival of the nuclei of interest and their subsequent decays.

Since the experiment was not explicitly designed for the study of \( ^{94}\text{Pd} \), the implantation profile of these nuclei in the silicon detectors was not ideal, but concentrated on the back-left DSSSD in the furthest row downstream and to the left as viewed by the beam approaching the stopper. It was found that 14 of the 16 X and all of the Y strips, totalling 224 pixels of this “active DSSSD,” contained good data that were considered in our analysis. This procedure of selecting only a relevant subset of Si pixels increased the number of true spatial correlations between the implanted \( ^{94}\text{Pd} \) and their subsequent decays in the active stopper. The total implantation rate varied over the pixels, but an average value for all types of ions was \( \sim 0.5 \) Hz per pixel. In other words, the time between any two consecutive implantations was \( \Delta t_{\text{impl}} \sim 2 \) s. Therefore, the true implantation-decay correlations were only possible over a correlation time, \( \Delta t_{\text{corr}} \), much less than 2 s.

Figure 1 shows the prompt \( \gamma \)-ray spectra associated with the decay of (a) \( ^{94}\text{Pd} \) and (b) all of the nuclei implanted into the active DSSSD. It is evident from Fig. 1(a) that the 558-, 798-, 822-, 846-, 896-, 1638-, 1766-, and 2906-keV transitions are enhanced with respect to the contaminant lines. Ideally, these spectra should have been created with a correlation time much longer than the \( T_{1/2} = 9.0 \) s for the ground-state \( \beta \) decay of \( ^{94}\text{Pd} \). Several contaminant lines are present in Fig. 1(a), because \( \Delta t_{\text{corr}} \sim \Delta t_{\text{imp}} \sim 2 \) s, while the true temporal correlations can only be expected for a \( \Delta t_{\text{corr}} < \Delta t_{\text{imp}} \). It is worth noting that the aforementioned selection of a subset of pixels, where \( ^{94}\text{Pd} \) are mostly implanted, helps in reducing false temporal correlations with any other ions. The cleanliness of the spectra was sacrificed in the present study to gain statistics related to the relatively slow \( ^{94}\text{Pd} \) \( \beta \) decay. Most of the contaminant \( \gamma \) rays are identified as belonging to the daughter activities of \( ^{94}\text{Pd} \), \( ^{96}\text{Mo} \), and \( ^{96}\text{Ag} \) nuclei, as indicated in Fig. 1.

A \( \gamma \)-ray spectrum was also created with the same conditions as those for Fig. 1(a), but requesting events delayed by 0.33 to 1.75 \( \mu s \) with respect to the \( \beta \)-decay signal. This time window was chosen according to the known half-life, \( T_{1/2} = 0.48(3) \mu s \), of the \( 2^+ \) state in \( ^{94}\text{Rh} \). In this spectrum, the 55-keV \( \gamma \) ray is observed, as expected, to be one of the prominent lines. A few contaminant lines, for example, delayed \( \gamma \) rays from the daughters of \( ^{96}\text{Ag} \) and \( ^{96}\text{Pd} \), were also seen.

We obtained values for the “correlation efficiency” (CE), which is defined as the ratio between the number of counts in Figs. 1(a) and 1(b) (i.e., the \( \gamma \)-ray spectra associated with the decay of \( ^{94}\text{Pd} \) and all of the other nuclei, respectively) for a \( \gamma \) line at a given energy. These results reveal higher CE values for the \( \gamma \) transitions in \( ^{94}\text{Rh} \) due to their expected enhancement in Fig. 1(a). As can be seen from Fig. 1(c), the CE values for the strong \( 558-, 1766-, \) and 2906-keV lines are indeed similar and at least five to six times higher than the values for the contaminant lines, such as those at energies of 382, 871 \( ^{94}\text{Mo} \), 942 \( ^{96}\text{Ru} \), 1351/1352 \( ^{95}\text{Ru}^{95}\text{Rh} \), 1415 \( ^{96}\text{Pd} \), and 1431 \( ^{94}\text{Ru} \) keV [35]. It should be noted that for some of the other candidate lines [shown in red in Figs. 1(a) and 1(c)], somewhat smaller enhancement is seen, which could be attributed to the uncertainties resulting from the lower statistics. Furthermore, similar structures for the implantations per strip (“hit distributions”) corresponding to the 558-, 1766-, and 2906-keV lines can be seen in Fig. 1(d). These distributions differ from those for the representative 1351/1352 \( ^{95}\text{Rh}^{95}\text{Ru} \) and 1415 keV \( ^{96}\text{Pd} \) contaminant lines.

After a careful inspection of the data for all of the nuclei that have been produced in our experiment, we found that the 2906-keV transition could only result from the decay of either \( ^{94}\text{Pd} \) or \( ^{95}\text{Pd} \), for which \( \beta \)-delayed nuclear level schemes are not known. \( Q \)-value considerations imply that the 2906-keV \( \gamma \) ray could originate from the decay of either \( ^{94}\text{Pd} \) to \( ^{94}\text{Rh} \) or \( ^{94}\text{Rh} \) to \( ^{94}\text{Ru} \). This \( \gamma \) ray was not observed in...
the study of the latter decay presented in Ref. [19], although several other high energy γ rays with reasonable intensity were observed, implying that the γ detection efficiency was not a limiting factor. Furthermore, evidence of a prompt-delayed coincidence, using a delay of 0.33 to 1.75 μs, between the 2906-keV γ ray and the known 55-keV transition in 94Rh is found in the present work. However, this evidence is somewhat weak due to the low detection efficiency and high internal conversion coefficient for the 55-keV γ transition. These observations and the appearance of the 2906-keV line in Fig. 1(a) strongly suggest that this transition is associated with the ground-state β decay of 94Pd. This is further supported by the corresponding “hit distributions” and correlation efficiencies [see Figs. 1(c) and 1(d)]. Therefore, we propose a (1⁺) level in 94Rh residing at 2961 keV above the 4⁺ ground state, which decays to the 2⁺ ground state by emitting a 2906-keV γ ray. This (1⁺) ground state is likely to be the same as the (1⁺) ground state reported in Ref. [21] residing at an energy that is 2910 (10) keV above the 4⁺ state. The apparent disagreement in the energies could be due to the differences in technique used in Ref. [21]. In Figs. 1(a) and 1(c), evidence for the 1638-keV γ transition can also be found, though the signature in the CE plot is not very clear. Unfortunately, our statistics in this case do not allow us to establish a coincidence relation with any other (in particular the 55 keV) γ ray. However, noting the evidence for the (1⁺) state at 1670 keV in Ref. [21] and the aforementioned fact that in our experiment the energies might be somewhat different, we propose a (1⁺) state residing at 1693 keV that decays to the (2⁺) state by emitting the 1638-keV γ ray.

We show the level scheme in Fig. 2 (EXP), which was deduced by utilizing our results from the above analysis and from weakly observed γ-γ coincidence relations, the spin-parity assignments from Ref. [21], and shell model calculations (see below). All of the γ rays are placed in the level scheme. Good agreement is found between the current results for 94Rh and those from Ref. [21] except for differences

![Image](https://via.placeholder.com/150)

FIG. 1. (Color online) γ-ray spectra associated with the decay of (a) the 94Pd nuclei, where symbols are used to mark the 822, 846, and 896 (*) and 863 keV (+) lines and (b) all of the nuclei implanted in the active DSSSD. The majority of the lines can be associated with the known decays of nuclei as indicated [35]. New as well as the known γ transitions in 94Rh are marked in red (light). Unidentified peaks are marked in black (dark) only with their energies. (c) The correlation efficiencies CE (multiplied by 1000) deduced from the spectra in (a) and (b). (d) Implantations per strip in the active DSSSD (i.e., hit distributions) corresponding to several γ rays are also shown. See the text for details.

![Image](https://via.placeholder.com/150)

FIG. 2. (Color online) Deduced (EXP) and calculated (GF, FPG, GF-GD) level schemes for 94Rh. Levels up to 4 MeV relevant for the β⁺/EC decay are shown. The lowest two states in EXP correspond to 94m1Rh and 94m3Rh. See the text for details.
in the excitation energies of the levels residing at 1693 \( \left[ \frac{1}{2}^+ \right] \), 2619 \( \left[ \frac{5}{2}^+ \right] \), and 2961 \( \left[ \frac{1}{2}^+ \right] \) keV. As given, we propose that the 1766-keV transition originates from the 2619-keV \( \left[ \frac{5}{2}^+ \right] \) level which we refer to as FPG, also allows the \( \frac{1}{2} \rightarrow \frac{3}{2} \) transitions, while the calculation, which we refer to as FPG, also allows the \( \frac{3}{2} \rightarrow \frac{5}{2} \) transitions, and \( f_5 \rightarrow f_7 \) transitions due to the extended space that also includes the \( \frac{5}{2} \) orbitals at present it is not possible to simultaneously include all of the aforementioned important transitions and carry out completely consistent calculations.

Our calculations show that mostly the \( 1^+ \rightarrow 2^+ \) \( M1 \) transitions are favored due to either the transition strengths or decay-energy considerations. Here, higher values for the subscript \( n \) correspond to the levels with higher excitation energies. As expected from our calculations, the \( \gamma \) decays between the \( \frac{1}{2}^\pm \) states, namely, the 2961 \( \rightarrow 613 \) (2348 keV) and 2619 \( \rightarrow 613 \) (2006 keV) transitions, do not appear in our spectra (cf. Figs. 1 and 2) due to the unfavorable branchings. On the other hand, a \( \gamma \) line corresponding to the 2564-keV \( M1 \) transition from the \( \left[ \frac{3}{2}^+ \right] \) state at 2619 keV to the \( \left[ \frac{5}{2}^+ \right] \) state at 55 keV may be expected but is, however, absent. The calculations indicate that this can be due to another competing decay via the intermediate \( \left[ \frac{5}{2} \right] \) state, i.e., via the \( 1^+ \rightarrow 2^+ \rightarrow 2^+ \) cascade (Fig. 2). This is in line with one of the cascades, with 1766- and 798-keV \( \gamma \) transitions, obtained from our \( \gamma-\gamma \) coincidence data analysis. In the context of observed coincidences, the high level density of \((0–2)^+\) states between 500 and 700 keV in the FPG approach is remarkable, and this could also certainly accommodate cascades, such as those mentioned previously with a sum energy of \( \sim 2564 \) keV. However, we refrain from a detailed evaluation of branching ratios, because of the deficiencies of various shell-model approaches and the limited statistics in our data.

Table I shows the \( B(\gamma) \) values from our work. The sum \( B(\gamma) \) strengths for the first four observed \( 1^+ \) states from our analysis of all the detected \( \gamma \)-ray intensities and from the TAS work [21] are 0.7 (2) and 0.56 (8) (in standard units; see Ref. [37]), respectively. These values are in agreement within the experimental uncertainties. In our analysis, when different decay paths are observed between two possible levels, we assumed that the population of the decaying level is proportional to the sum of the intensities corresponding to the lowest most \( \gamma \) rays in the decay cascades. Our value, 0.7 (2), also corresponds to the total strength \( B(\gamma) \), because of the nonobservation of any additional strength. This value is \( \sim 3 \) times smaller than the experimentally deduced value of \( B(\gamma) = 1.9 (4) \) from Ref. [21]. This conflict can be traced to the pandemonium problem [38] and the unobserved weak cascades in our high-resolution study. In the TAS work, only the previously noted first four states in \( ^{94}\text{Rh} \) were resolved. Thus, in order to account for the remaining two-thirds of the \( GT \) strength, a hypothetical distribution of \( 1^+ \) states (based on a shell-model calculation and empirical interaction in the GF space [22]) was introduced above 3 MeV [21]. In Fig. 2, this is indicated by the shaded area. This indicates that this part of the TAS analysis might be subjected to systematic uncertainties due to the limitations of the models. The \( 1^+ \) states shown in red receive significant \( B(\gamma) \) strengths. As can be seen, these results for the feeding differ significantly between the GF, FPG, and GF-GD approaches.

From our calculations and the \( Q_{EC} = (94^{\text{Pd}} \rightarrow 94^{\text{m1}}\text{Rh} = 6.7 \text{ MeV} \) value [21], we note that the \( B(\gamma) \) strength \( (1.95(5) – 0.56(8) = 1.39(9)) \), which is calculated using the \( B(\gamma) \) values from the TAS work [21] could be distributed over a few \( 1^+ \) states above 3 MeV and, therefore, is somewhat

<table>
<thead>
<tr>
<th>( E_x ) (keV)</th>
<th>( E_\gamma ) (keV)</th>
<th>Feeding (%)</th>
<th>( B(\gamma) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>613</td>
<td>558</td>
<td>67.5 (6)</td>
<td>0.11 (3)</td>
</tr>
<tr>
<td>1693</td>
<td>1638</td>
<td>4.1 (6)</td>
<td>0.02 (1)</td>
</tr>
<tr>
<td>2619</td>
<td>798</td>
<td>18.1 (10)</td>
<td>0.29 (13)</td>
</tr>
<tr>
<td>2961</td>
<td>2906</td>
<td>10.3 (4)</td>
<td>0.27 (14)</td>
</tr>
</tbody>
</table>

Table I. Excitation energies, intensity analyzed \( \gamma \) rays, feeding intensities, and \( B(\gamma) \) values for the four observed \( 1^+ \) daughter states.
fragmented. This would imply low intensities for the γ transitions resulting from the decay of these states. We believe that we did not observe the fragmented GT strength of 1.39(9), because of the limited γ-ray detection efficiency of our setup. This negative result strongly endorses a fragmentation of the B(GT) strength, which could be due to the seniority mixing for these 1+ states arising from the influence of the np interaction (see below).

The total calculated B_T(GT) strengths in GF, FPG, and GF-GD approaches are 0.11, 0.32, and 2.69, respectively. Clearly, the first two approaches do not agree with the experimental situation as they do not include all of the important transitions. As discussed above, the latter two calculations consist of the GF approach, but also allow additional transitions. In order to obtain a realistic estimate, it is required to retain all the important contributions to the strength and avoid any “double counting” of the transitions. In our calculation, we achieved this by subtracting the GF strength from the sum of the FPG and GF-GD strengths. The experimental value of B_T(GT) = 1.95(5) [21] agrees with our calculated value of 0.75² (2.69 + 0.32 − 0.11) = 1.63. Here, we have used 0.75 for the quenching factor of the GT operator [39]. The fact that the B_T(GT) value from the GF-GD calculation is much closer to the experimental value emphasizes the strong role of the γ7/2 orbital. Similar results were also discussed for 94,96,98Pd in Refs. [21,40].

All of the SM calculations have a general feature; namely, they predict small B(GT) strengths into the low-lying states, which are essentially dominated by the π 1g9/2 and the π9/2 → γ9/2 GT transition. This is borne out by the β+/EC decay data of N = 48 isotones [7,21,35]. Even after consideration of the effect from angular momentum re-coupling, the summed strength remains significantly below the extreme single particle estimate (see, e.g., [41], i.e., B(GT; π 1g9/2 → γ9/2) = (110/9)n(π 1g9/2)n(γ9/2), where n and n' are the occupation ratios for π 1g9/2 particles and γ9/2 holes, respectively. This can be understood in terms of the diagonal nature of the odd-tensor part of the GT operator in the seniority scheme [42,43]. The seniority quantum number v is well defined in a pure g9/2 model space. Therefore, the calculations in such a space yield negligible GT strengths for the decay of N = 49, v = v_{ν} + ν_{ν} = 1 (even-odd) and 2 (odd-odd) parent states to their N = 50, v = v_{ν} = 3, 4, and 5 daughter states. This is a clear signature for a seniority conserving interaction. For the low-lying states in nuclei with N ≤ 50, such as those from the present work, an increased seniority mixing is expected due to the influence of the np interaction. This could cause a reduction in the GT strength calculated using a seniority conserving interaction. Therefore, our nonobservation of the 1+ states above 3 MeV in 94Rh due to low values of fragmented B(GT) can be attributed to the effect of the np interaction on the low-lying states, especially on the ground state, in 94Pd. It has been argued that such an effect gives rise to the low-lying structure of 94Pd, which is intermediate to that of 92Pd and 96Pd, which have almost equally spaced and seniority type low-lying level schemes, respectively [6].

In Refs. [12,14], the reliability of the evidence found in Ref. [11] for the direct two proton decay of the 21+ isomeric state in 94Ag was questioned. A hypothetical 2.9-MeV γ-ray was used for the arguments in Ref. [14]. Even though a γ-ray of 2906 keV is observed in the present work, we would like to stress that a possibility for this γ-ray to yield a spurious 1.9-MeV two-proton-like peak in the Si sum spectrum [14] was already discarded in Ref. [44]. At present, neither our observation of the 2906-keV γ-ray nor the new data from the mass measurements [13] can exclude the possibility for a two proton decay of the 21+ isomeric state [1,45–47].

In summary, the low-lying level scheme of 94Rh is deduced by using the observed γ-transitions following the ground-state β-decay of 94Pd in our experiment. The results are discussed and compared with the shell-model calculations performed in three different approaches. A dominant role of the g7/2 orbital is evident and the experimental B(GT) strengths can only be explained with its inclusion. The effect of the np interaction via seniority mixing on GT hindrance is also discussed for the ground state in 94Pd, which strongly suggests that this nucleus resides in a region exhibiting structural transition. Future experiments designed to enhance the yields for the γ-rays following the β-decay of 94Pd with respect to that for γ-rays from other fragments and theoretical interpretations are suggested to gain further understanding into the structure of the observed 1+ states. The observed 2906-keV γ-ray in our work cannot exclude the possibility of a two proton decay in 94Ag.

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