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Beta decay of ^{93}Pd*

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Abstract. The very neutron-deficient isotope ^{93}Pd was produced in fusion-evaporation reactions of a ^{40}Ca beam on a ^{58}Ni target. The reaction products were separated at the GSI Online Mass Separator, using ion sources of the FEBIAD type. The β-decay properties of ^{93}Pd were studied by detecting β-delayed protons and β-delayed γ-rays. The feeding of excited levels in the daughter nucleus ^{93}Rh and the β-decay half-life of ^{93}Pd were determined. The experimental results are discussed in comparison to shell model predictions.

PACS. 21.10.-k Properties of nuclei; nuclear energy levels – 23.40.-s Beta decay – 27.60.+j $90 \le A \le 149$

1 Introduction

Neutron-deficient isotopes in the vicinity of the $N = Z$ line have attracted considerable theoretical and experimental attention over the last years. Among the phenomena of interest are investigations of exotic decay modes, such as β-decay with large Q-values and β-delayed proton emission, and studies of the residual proton-neutron interaction [1]. Experimentally, the $N = Z$ line has been mapped by decay and in-beam spectroscopy up to ^{94}Ag [2]. Moreover, nuclear structure properties of proton-rich isotopes in this area, above all nuclear masses and β-decay half-lives, are important input parameters for investigations in the framework of the astrophysical rp-process. Recent network calculations [3] of the rp-process identified, among other isotopes such as ^{92}Pd and ^{96,97}Cd, the very proton-rich isotope ^{93}Pd$(Z = 46, N = 47)$ as a probable waiting point in the reaction path under X-ray burst conditions.

The doubly-magic nucleus ^{100}Sn is located near the upper end of the $N = Z$ line. Due to the closed core at $N = Z = 50$, large-scale shell model calculations [4] are feasible, thus allowing for a detailed comparison of experimental data and theoretical predictions. Especially the relatively simple β-decay pattern of neutron-deficient isotopes, namely allowed Gamow-Teller (GT) transitions from the $\pi g_{9/2}$ orbit to either the $\nu g_{9/2}$ or the $\nu g_{7/2}$ orbit, have proven to be a rich source of nuclear structure data, see, *e.g.*, [5] for a recent example.

The isotope ^{93}Pd was first identified in high-energy fragmentation reactions [6,7], while a recent half-life measurement of $T_{1/2} = 9.3^{+2.5}_{-1.7}$s was reported in [8]. Excited states in the daughter nucleus ^{93}Rh were studied in an in-beam experiment [9]. In this paper we present the first detailed investigation of the β-decay properties of ^{93}Pd. After outlining the experimental method and discussing the results, the findings will be compared to the predictions of a shell model calculation.

2 Experimental method

The isotope ^{93}Pd was produced in the fusion-evaporation reaction ^{58}Ni(^{40}Ca,αn)^{93}Pd, using beams from the heavy-ion accelerator UNILAC at GSI. The incident energy and intensity of the ^{40}Ca beam amounted to 4.7A MeV and approximately 80 particle nA. The targets consisted of enriched ^{58}Ni with a thickness of 2.8 mg/cm^2. The reaction products were stopped in a graphite catcher inside a FEBIAD-E or FEBIAD-B2C ion source, respectively, and

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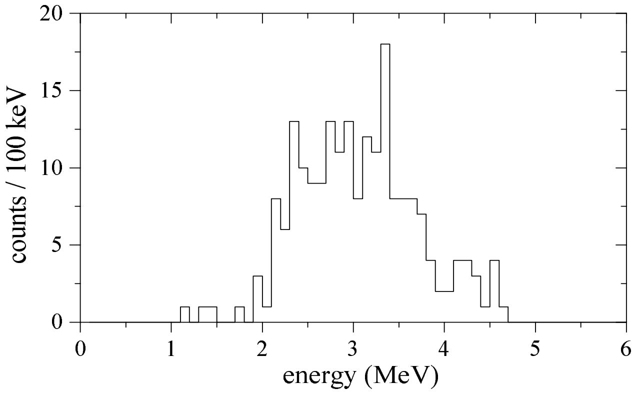

Fig. 1. Energy spectrum of β-delayed protons measured at mass $A = 93$.

separated at the GSI Online Mass Separator. While both sources possess excellent release properties for silver, the latter strongly delays the release of palladium [10], thus allowing for an unambiguous identification of ^{93}Pd, see section 3.1 for details. The mass-separated reaction products were investigated at two different beam lines of the Online Mass Separator. One set-up comprised a $\Delta E-E$ telescope for proton spectroscopy, consisting of two silicon detectors with thicknesses of 22.6 and 732 μm and active areas of 150 and 450 mm^2, respectively. The solid angle covered by the telescope was estimated to be (14.3 ± 2.3)% of 4π, while the energy calibration was carried out with standard α sources, namely ^{148}Gd, ^{239}Pu, ^{241}Am, and ^{244}Cm. The activity was collected on a 29 μg/cm^2 thick carbon foil in front of the ΔE counter; by applying coincidence and anticoincidence requirements between the two detectors, both the investigation of β-delayed and direct proton emission was possible. The emission of β-delayed γ-rays was studied at a set-up involving a moveable tape-collector system. The activity was implanted into the tape and periodically removed, thus suppressing longer-lived contaminants and daughter activities. The collection point was surrounded by a plastic counter for registering positrons and an array of germanium γ-ray detectors. All in all, twelve individual germanium crystals, mounted in one cluster detector [11], one clover [12], and a single-crystal counter, allowed for the detection of β-γ and β-γ-γ coincidences. The whole array covered a solid angle of (10 ± 1)% of 4π. The efficiency of the plastic counter amounted to (85 ± 1)%, while the γ-array possessed a photopeak efficiency of (3.5 ± 0.4)% at a γ-ray energy of 1.33 MeV. Due to the absence of a low-energy γ-ray detector and the low source strength of only about 8 ^{93}Pd atoms/s, the spectroscopy of X-rays released in electron-capture decay or conversion electron emission was not possible.

3 Results

3.1 Beta-delayed proton emission

Apart from ^{93}Pd, where an energy window for the emission of β-delayed protons of $(Q_{EC} - S_P) = (7.4 \pm 0.8)$ MeV is predicted [13] from systematics, ^{93}Rh and ^{93}Ag are also possible precursors for this decay mode at mass $A = 93$. It should be noted that ^{93}Ag is expected to be unbound with respect to direct proton emission from its ground state [4, 14].

Figure 1 shows the spectrum of β-delayed protons recorded at mass $A = 93$. Within a measuring time of 25 hours, 398 events were registered. For part of the time, the $A = 93$ beam was flipped between the collection position in front of the detector system and a beam dump, thus allowing for the measurement of time-differential data. From the ratio of events detected during 3.0 s beam-on and 3.0 s beam-off periods, a half-life of $T_{1/2}^{\beta p} = 0.7^{+0.2}_{-0.1}$s was deduced.

The data presented so far were taken with samples separated with a FEBIAD-E ion source. An alternative measurement with a FEBIAD-B2C source showed a drop in the rate of detected protons by a factor of more than 30. This steep reduction in measured activity is attributed to the hindered release of palladium from this source. The release properties of silver, on the other hand, are practically the same for both sources. From these ion source characteristics, we are able to deduce that the overall contribution of β-delayed protons from ^{93}Ag to the spectrum shown in fig. 1 is smaller than 5%. A significant admixture from the decay of ^{93}Rh can be ruled out by comparing the decay energy $(Q_{EC} - S_P) = (2.5 \pm 0.4)$ MeV predicted for this isotope [13] with the experimental spectrum. Furthermore, the analysis of events in the ΔE detector in anticoincidence to the E detector yielded no events in the energy range up to 1.2 MeV which could be assigned to the emission of protons from the ground state of ^{93}Ag.

Table 1. Transition energies, intensities, half-lives, and coincidence relations for γ-transitions observed at mass $A = 93$. The intensities, determined by neglecting corrections for γ-γ summation and internal conversion, were normalized to the sum of all γ-ray transitions from excited levels to the ground state of ^{93}Rh, see fig. 3.

E_γ (keV)	Intensity (%)	$T_{1/2}$ (s)	Coincidences
239.7	81.3 ± 7.3	1.0 ± 0.3	381.7, 511.0
381.7	24.8 ± 3.1	0.9 ± 0.6	-
621.7	9.6 ± 2.0	-	-
864.1	9.1 ± 2.0	-	-
511.0	-	0.9 ± 0.4	239.7, 381.7, 511.0, 621.7

3.2 Beta-delayed γ emission

Figure 2 shows the sum of the β-gated γ-ray spectra of all germanium detectors. Table 1 summarizes the results obtained within a measuring time of 7.3 hours. Four γ-transitions with energies of 239.7, 381.7, 621.7, and 864.1 keV were found to be coincident with positrons, and showed a grow-in of activity when measured with a collection cycle of 4.8 s. In addition, β-γ-γ coincidences could be observed for the 239.7 and 511.0 keV lines, while the intensities of

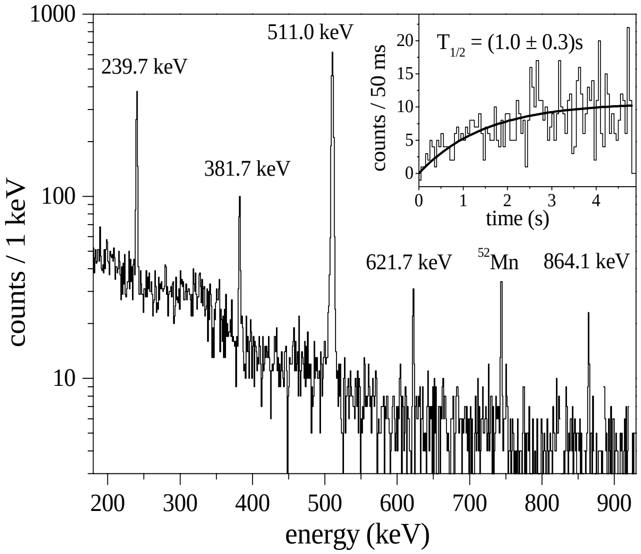

Fig. 2. Beta-gated γ-spectrum measured at mass $A = 93$. The line marked with ^{52}Mn stems from a long-lived contamination produced in a previous experiment. The inset shows the time dependence of the intensity of the 240 keV line along with the result of a fit.

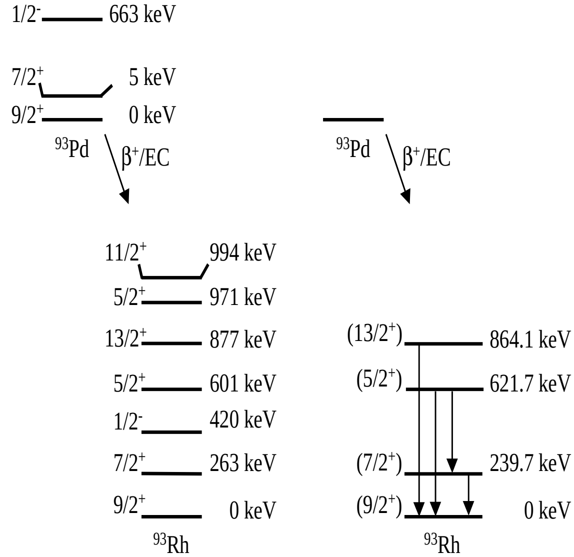

Fig. 3. Comparison of the experimental decay scheme (right) and the corresponding shell model prediction (left).

the other transitions were too low to permit such an analysis. The half-lives were obtained by fitting an exponential grow-in function with a single component to the data. In the case of the 621.7 and 864.1 keV transitions, the low number of counts did not allow for a half-life determination. We infer a half-life for the emission of β-delayed γ-rays of $T^{\beta\gamma}_{1/2} = (1.0 \pm 0.3)$ s by taking the fitted value of the strongest line at 239.7 keV. Due to the good agreement with the half-life deduced from the β-delayed protons we assign the γ-transitions shown in fig. 2 to the decay of ^{93}Pd. Using the coincidence relations listed in Table 1, the decay scheme depicted in fig. 3 was constructed. An upper limit for the branching ratio for the ground-state-to-ground-state decay from ^{93}Pd to ^{93}Rh was inferred from an intensity analysis of the 511.0 keV line. By comparing the number of β-decays, as deduced from the decay scheme shown in fig. 3, to the number of counts in the 511.0 keV transition, we found a surplus of (30±9)% of positron annihilation quanta. This value, which does not include any correction related to the positron-stopping geometry and thus represents a rough estimate only, can be considered as an upper limit for the combined intensity of the ground-state-to-ground-state decay and other transitions where β-delayed γ-rays of ^{93}Pd remained unobserved.

Finally, a half-life $T^{\beta}_{1/2} = (0.9 \pm 0.2)$ s is assigned to the decay of ^{93}Pd by taking the weighted average of the values measured for β-delayed protons and γ-rays. This value is in good agreement with shell model predictions, as described in the following section, but shows an obvious disagreement with the half-life of $T_{1/2} = 9.3^{+2.5}_{-1.7}$s, as reported in ref. [8].

4 Discussion

Proton-rich nuclei in the mass range $A = 86-100$ were recently investigated in a shell model calculation by Herndl and Brown [4]. The authors used, both for valence protons and neutrons, the model space $(1g_{9/2}, 2p_{1/2})$ as well as the effective interaction SLGT0 taken from ref. [15]. We have performed a shell model calculation in the same model space, using the interaction derived by Gross and Frenkel [16], which is largely identical to SLGT0 used in ref. [15] as is fitted to the same body of experimental data. As far as the isotope ^{93}Pd is concerned, the ground-state spin is predicted to be either $9/2^+$ or $7/2^+$. The calculated half-life for the β-decay of the ground state amounts to $T_{1/2} = 1.4$ s [4]. Moreover, a $1/2^-$ state is expected at an excitation energy of approximately 660 keV. Due to the intrinsic uncertainty of the calculation we cannot, however, exclude a smaller excitation energy, thus turning this level into a low-spin isomer with a β-decay branch.

Figure 3 compares the calculated levels in the daughter nucleus ^{93}Rh with the experimental data. Due to the good correspondence of the calculated level energies with the measured transitions and the generally good agreement of shell model calculations in this model space with experiments [4,17], we tentatively assign the spins $9/2^+$, $7/2^+$, $5/2^+$, and $13/2^+$ to the ground state and to the energy levels at 239.7, 621.7, and 864.1 keV, respectively. It should be noted that in in-beam work on ^{93}Rh [9] a γ-ray of 865.9 keV was assigned to an E2 transition from a $13/2^+$ state to ground state. This transition most likely corresponds to the 864.1 keV γ-ray observed in the present work, with the difference originating in the contamination reported in the in-beam work. Finally, we remark that the caution should be applied when deducing the β-feeding of levels in the daughter nucleus ^{93}Rh from the γ-ray intensities listed in Table 1. Due to the large energy window for the β-decay, we expect a significant feeding of highlyexcited states which will decay to low-lying states via γ-transitions with intensities below the detection efficiency of our set-up; compare [5] for a detailed discussion of this problem.

Due to the good overall agreement of the shell model calculation with the experimental data, we attribute the measured β-delayed proton and γ-ray data to the decay of the lowest-lying $7/2^+$ or $9/2^+$ level of ^{93}Pd, which could be the ground state of this nucleus.

The data for β-delayed γ and proton emission represent the first detailed spectroscopic investigation of the decay properties of the isotope ^{93}Pd. Although limited in statistics, a conclusive comparison with the predictions of a shell model calculation allowed for an unambigious identifcation of this isotope. Moreover, the measured half-life will serve as a valuable input parameter for further calculations of the nucleosynthesis of very proton-rich nuclei in the rp-process.

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