Decay Studies of $N \approx Z$ Nuclei From $^{77}$Y to $^{100}$Sn

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Abstract:

Very proton rich nuclei below $^{100}$Sn were produced by fragmentation of a $^{112}$Sn beam at the fragment separator, GSI, Darmstadt. By implanting these ions into a silicon detector stack we were able to determine their halflives and other decay properties. Beside others, we measured the halflives of the rp-process waiting points between $^{80}$Zr and $^{92,93}$Pd and demonstrated a short living transition for the heaviest odd-odd nuclei, $^{90}$Rh, $^{91}$Ag, and $^{98}$In, in agreement with a superallowed Fermi transition. Furthermore we identified two new nuclei, $^{76}$Y and $^{78}$Zr, close to the proton dripline. The results for the halflives are presented.

1 Introduction

The region of nuclei below $^{100}$Sn is interesting for many reasons. Firstly, one can study the rp-process nucleosynthesis, which may lead up to $^{100}$Sn. The rp-process proceeds with a series of (p,$\gamma$) reactions towards the p-dripline until a strong inverse process, like proton decay, prohibits further proton captures [1]. To continue to higher masses, the nucleus has to wait for the much slower $\beta^+$ decay. These nuclei are called waiting point nuclei. As all the mass during the rp-process is concentrated in these waiting points, their total lifetime exclusively determines the flux towards heavier nuclei and the respective isotopic abundances. On the other hand the rp-process path is determined by the proton dripline. A good knowledge of the exact position of the proton dripline and the decay properties of waiting point nuclei is essential for rp-process calculations.

Secondly, the odd-odd $N = Z$ nuclei just below $^{100}$Sn are the heaviest nuclei where one can hope to study pure Fermi beta transitions and to test – in case of sufficient accuracy of the halflives and decay energies – nuclear corrections to the corresponding ft-values.

2 Experiment

Neutron deficient nuclei near $^{100}$Sn have been produced by fragmentation of a 1 A-GeV $^{112}$Sn beam in a beryllium target. The fragments were separated in the $0^\circ$ magnetic spectrometer FRS at GSI, Darmstadt, and identified with detector systems, determining the ions trajectory through the FRS and measuring the energy loss and the time of flight. With our detector set-up we achieved a resolution of $\Delta A = 0.32$ (FWHM) and $\Delta Z = 0.23$ (FWHM). The unambiguously identified
ions (see Fig. 1) were stopped in an implantation detector. The spectra are showing the previously unobserved $Z - N = 2$ nuclei $^{76}$Y (two events) and $^{78}$Zr (one event) and demonstrate the non-observation of $^{81}$Nb.

By decelerating the ions with a variable degrader at the final focal plane, we were able to implant different nuclei in the middle of a silicon detector stack. The implantation zone of this detector consisted of four double-sided silicon strip detectors (64 $\times$ 25 $\times$ 0.5 mm$^3$ with a strip pitch of 0.5 mm on both sides), mounted in a compact stack. The 128 vertical strips were read out individually, the 50 horizontal strips were combined in 16 readout groups corresponding to the beam profile. As a result of the large granularity of 8192 pixel we had a very low trigger rate per pixel and were in addition able to track the decay particles in our detector. The correlation of the implantation position of an identified ion with a decay position permits an efficient background suppression.

Around the implanation zone two 10 mm thick stacks of Si detectors were mounted for the $\beta$-energy measurement. The 10 detectors (60 $\times$ 40 $\times$ 1 mm$^3$, manufactured by Micron) on either side were seven-fold segmented to ensure a good suppression of Compton electrons.

The detector stack was surrounded by a segmented NaI detector and a Ge-Clover detector covering about 80% of the solid angle.
3 Method for determining the halflives

Due to the very low trigger rate per pixel we were able to correlate decays and implantations up to 100 seconds. Therefore we could observe the daughter and even later decay generations as shown in Fig. 2.

![Diagram of decay sequence]

Figure 2: Background free decay spectrum of $^{77}$Y and its daughter nucleus.

The halflives for each isotope were determined by using a maximum likelihood (MLH) [2] method, taking into account the decay of the mother and the daughter nuclei during a fixed correlation time after the implantation. The reliability of our method is shown in Fig. 3 for the case of $^{78}$Y, where we see two different halflives feeding $^{78}$Sr (2.65 min). The results can be compared with measurements at GANIL [55(12) ms] [4] and Argonne [5.8(6) s] [5].

![Graph showing decay rates]

Figure 3: Decay of $^{78}$Y. The short-living Fermi transition and a long living isomer is shown as well as a curve drawn for their halflives resulting from our MLH-analysis. In the logarithmic time scale the exponential decay is transformed into a bell shaped curve with the maximum at the mean lifetime [3].
4 Results

Since decay properties of the rp-process waiting point nuclei are poorly known, we measured the halflives of all waiting point nuclei from $^{80}$Zr up to $^{92,93}$Pd.

For mapping the proton dripline we investigated the possibly proton-unstable nuclei $^{77}$Y and $^{81}$Nb. $^{77}$Y ions could be identified and we observed their decay with a short halflife, consistent with a superallowed beta decay. As mentioned before we identified for the first time $^{77}$Y and $^{81}$Zr, therefore we expect their halflife to be longer than 200 ns, considering the flight time through the fragment separator. From the non-observation of $^{81}$Nb we deduce a halflife shorter than 200 ns.

The 12 implanted $^{77}$Y nuclei decay all via $\beta$-decay, proton emission (if it exists) can only be a small branch.

![Figure 4: Deposited energy in a single detector strip.](image)

Furthermore, we investigated the six cases of odd-odd $N = Z$ nuclei between $^{78}$Y and $^{98}$In. We were able to show that $^{90}$Rh, $^{94}$Ag and $^{98}$In have low lying states (presumably the ground states) decaying by superallowed Fermi transitions. For the three lighter members of this series, $^{78}$Y to $^{86}$Tc, such superallowed Fermi transitions were recently detected at GANIL [4]. Our new data on these nuclei are in good agreement. Furthermore, we observed $\beta$-delayed protons in the decay of $^{81}$Zr, $^{85}$Mo, $^{89}$Ru, $^{93}$Pd as well as in the decay of the long-living isomer of $^{78}$Y (see Fig. 4). Finally we measured the halflives of so far unknown Rh and Tc isotopes near the $N = Z$-line.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Halflife</th>
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<tr>
<td>$^{76}$Sr</td>
<td>$80^{+40}_{-20}$ ms</td>
<td>$^{85}$Mo</td>
<td>$6^{+30}_{-30}$ ms</td>
<td>$^{93}$Rh</td>
<td>$14.6^{+1.4}_{-1.4}$ s</td>
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<tr>
<td>$^{76}$Y</td>
<td>$&gt; 200$ ns</td>
<td>$^{81}$Mo</td>
<td>$4.5^{+1.0}_{-0.8}$ s</td>
<td>$^{92}$Pd</td>
<td>$1.1^{+0.3}_{-0.2}$ s</td>
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<tr>
<td>$^{77}$Y</td>
<td>$57^{+12}_{-12}$ ms</td>
<td>$^{86}$Tc</td>
<td>$51^{+9}_{-7}$ ms</td>
<td>$^{93}$Pd</td>
<td>$1.4^{+0.2}_{-0.2}$ s</td>
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<tr>
<td>$^{78}$Y</td>
<td>$55^{+7}_{-7}$ ms</td>
<td>$^{87}$Tc</td>
<td>$2.4^{+0.2}_{-0.2}$ s</td>
<td>$^{91}$Ag</td>
<td>$29^{+29}_{-10}$ ms</td>
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<td>$^{78}$Y$^{80}$</td>
<td>$5.8^{+0.5}_{-0.5}$ s</td>
<td>$^{88}$Ru</td>
<td>$1.2^{+0.3}_{-0.2}$ s</td>
<td>$^{91}$Ag$^{100}$</td>
<td>$0.5^{+0.2}_{-0.2}$ s</td>
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<tr>
<td>$^{79}$Zr</td>
<td>$&gt; 200$ ns</td>
<td>$^{89}$Ru</td>
<td>$1.5^{+0.1}_{-0.1}$ s</td>
<td>$^{98}$In$^{100}$</td>
<td>$31^{+35}_{-9}$ ms</td>
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<td>$^{79}$Zr</td>
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<td>$^{90}$Rh</td>
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<td>$^{98}$In$^{100}$</td>
<td>$1.2^{+1.2}_{-0.4}$ s</td>
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<td>$^{80}$Zr</td>
<td>$5.4^{+0.9}_{-0.8}$ s</td>
<td>$^{90}$Rh$^{100}$</td>
<td>$1.2^{+0.3}_{-0.2}$ s</td>
<td>$^{99}$In</td>
<td>$3.8^{+1.0}_{-0.8}$ s</td>
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<td>$^{81}$Nb</td>
<td>$&lt; 200$ ns</td>
<td>$^{91}$Rh</td>
<td>$1.9^{+0.2}_{-0.2}$ s</td>
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<tr>
<td>$^{82}$Nb</td>
<td>$49^{+8}_{-6}$ ms</td>
<td>$^{92}$Rh</td>
<td>$6.2^{+0.5}_{-0.5}$ s</td>
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Our results are shown in the table. In some nuclei ($^{78}$Y, $^{90}$Rh, $^{94}$Ag, and $^{98}$In) we were able to identify a long living isomer. The half-life of the isomer is represented by a second time for an isotope. In all cases only statistical errors are given. In the cases of $^{75}$Sr, $^{79}$Zr, and $^{83}$Mo only one nucleus was implanted, therefore the statistical errors are very large.

In an earlier report of preliminary results, an erroneous value for the $^{93}$Pd and $^{92,93}$Rh half-life was given because a part of the daughter decays were included and the background suppression was insufficient in the first analysis.

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References