Decay studies of N≈Z nuclei from $^{78}$Y to $^{102}$Sn


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Abstract. Neutron deficient nuclei near $^{100}$Sn have been produced by projectile fragmentation of a 1 A-GeV $^{112}$Sn beam in a beryllium target. The fragments were separated in the magnetic spectrometer FRS at GSI, Darmstadt. The unambiguously identified ions were stopped in a highly segmented silicon strip detector stack which was designed to measure the halflives and the total energy of emitted particles with very low background and high efficiency. We were able to study $^{102}$Sn in decay spectroscopy for the first time and establish a decay scheme for the daughter nuclide $^{102}$In. With the measurement of the halflife and the Q-value the Gamov-Teller strength could be deduced. Additionally the Q-value of $^{98}$Cd was measured with high precision and we obtained the halflives of $^{101}$Sn, $^{103}$Sn and $^{100}$In and the absolute branching ratio of beta-delayed proton emission of $^{101}$Sn. We report halflives of rp-process waiting point nuclei between $^{80}$Zr and $^{92}$Rh, $^{94}$Ag and $^{98}$In, in agreement with superallowed Fermi transitions. In addition halflives of $^{75}$Sr, $^{77}$Y, $^{79}$Zr, $^{83}$Mo, $^{87}$Tc, $^{91}$Rh, $^{92}$Rh and $^{99}$In were measured. Finally, with our highly efficient identification system we were able to identify two new nuclei, $^{76}$Y and $^{78}$Zr, close to the proton dripline.

INTRODUCTION

One of the regions of the nuclear chart that are currently explored extensively in both experimental and theoretical studies is the region along the N=Z line near and below $^{100}$Sn. On one hand, this is based on the interest to study directly the doubly-magic nucleus $^{100}$Sn, a key nucleus for the investigation of Gamov-Teller beta decay. On the other hand, the nuclei below $^{100}$Sn along the N=Z line are also of interest for precision studies of superallowed Fermi beta decay and for the astrophysical rp-process.

The main goal of the experiment was a precise determination of the Gamov-Teller (GT) strength in the beta decay of the doubly-magic $^{100}$Sn and the neighbouring nuclei $^{102}$Sn and $^{98}$Cd. These nuclei decay dominantly via a pure GT spin flip transition converting a $\pi g_9/2$ proton into a $\nu g_7/2$ neutron. Due to the high Q-values the main part of the GT resonance can be populated in the decay. A measurable quantity suited for comparison with theoretical predictions is the beta transition strenght, defined for a transition into a single final state as:

$$B_{GT} = \frac{6147 \text{ s}}{(g_A/g_V)^2 \cdot f(Z, E_0) \cdot T_{1/2}},$$

with the ratio of the weak coupling constants $g_A/g_V = 1.26$, the Fermi integral $f$ for the beta endpoint energy $E_0$, and the observed halflife. The accurate analysis of decay properties with reference to model predictions eventually allows a major contribution to illuminate the question of the missing Gamov-Teller strength [1]. It might be possible to determine the degree of renormalization of the axial vector coupling constant in nuclei with respect to the free neutron value.

On the other hand, the path of the rapid proton capture synthesis is expected to lead along the N=Z line up to $^{100}$Sn [2]. At the high temperatures expected in neutron star x-ray bursts, nuclei between $^{64}$Ge and $^{100}$Sn may be synthesized.
successively by \((p, \gamma)\) reactions until the proton dripline is reached. For a continuation to heavier masses, nuclei have to decay by the slower beta decay to a daughter nucleus with more neutrons, from which the \((p, \gamma)\) reactions can proceed to heavier nuclei. The beta emitters with longer half-lives are called waiting point nuclei. As most of 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. The path of the rp-process is also determined by the proton dripline. A good knowledge of the exact position of the p-dripline and the decay properties of waiting point nuclei is essential for rp-process path calculations. The rp-process is expected to be responsible for the high solar abundances of nuclei such as \(^{92,94}\text{Mo}\) and \(^{96,98}\text{Ru}\).

Odd-odd \(N=Z\) nuclei are of special interest because of the possible occurrence of superallowed Fermi beta transitions. With their transition strength fundamental aspects of the weak interaction can be tested. The superallowed \(0^+ \rightarrow 0^+\) decays of nuclei from from \(^{14}\text{O}\) up to \(^{54}\text{Co}\) are used [3] to prove the conserved vector current hypothesis and to test the standard model. For these studies, radiative and charge dependent corrections have to be applied leading to a nucleus independent \(F_1\) value. The latter one is connected to the mixing amplitude between the up and down quarks, which is the dominant term of the unitarity relation in the Cabibbo-Kobayashi-Maskawa (CKM) matrix. Although various theoretical approaches for these corrections are in good agreement with each other for nuclei where experimental data are available, the unitarity relation in the CKM matrix fails by more than two standard deviations. For heavier nuclei, where the corrections become more important, there are considerable differences between several predictions. Therefore, measurements would provide a sensitive probe for the correctness of these theoretical estimates.

**EXPERIMENTAL PROCEDURE**

The experiment was performed at the fragment separator facility of GSI at Darmstadt, Germany. A beam of \(^{112}\text{Sn}\) was accelerated to an energy of 1 A-GeV in the heavy-ion synchrotron SIS after 20 injection and cooling cycles. Spills with intensities of up to \(5 \times 10^8\) ions lasting for 4 seconds with a repetition rate of 1 in 14 s were focussed onto a 4 g/cm\(^2\) beryllium target in front of the fragment separator FRS [4]. The experimental setup is sketched in Fig. 1.

The fragments were isotopically separated in the FRS by a combination of magnetic deflection and energy losses caused by 1 g/cm\(^2\) Al degrader inserted after the first 30° deflecting magnet and a 5.5 g/cm\(^2\) Al degrader after the second 30° magnet. Detector systems placed at the central and the final focal plane allowed the determination of the fragment trajectories using position sensitive ionisation chambers, the time of flight between a start and stop plastic scintillator and the energy losses in two ionisation chambers placed at the central and the final focal plane of the FRS. With this setup a mass resolution \(\Delta A = 0.32\) (FWHM) and a nuclear charge resolution \(\Delta Z = 0.23\) (FWHM) was reached.

The unambiguously identified ions were stopped in the center of a stack of highly segmented silicon strip detectors placed at the final focal plane. This \(4\pi\) implantation detector was designed to measure the total energy of emitted \(\beta^+\)-particles and beta-delayed protons with a high efficiency. The inner implantation zone consisted of four double-sided strip detectors. Due to the high granularity of 8192 pixels a position correlation between implantation and following decay with very low background rates (as little as 1/780 per second) could be achieved. For measuring gamma radiation the implantation detector was surrounded by a 6-fold segmented NaI detector covering \(2\pi\) and a Germanium clover detector in close geometry. We determined the halflives and the positron energies for each implanted isotope with a maximum likelihood method taking into account three decay generations as well as background events during a fixed correlation time after the implantation.
RESULTS AND DISCUSSION

Fig. 2 shows the measured fragment yields for each element from Strontium to Indium as function of the measured mass. The spectra show the previously unobserved \( T = -1 \) nuclei \( ^{76}\text{Y} \) (2 events) and \( ^{78}\text{Zr} \) (one event). Due to the good resolution of our identification detector system we assign a \( 3\sigma \) confidence interval to these assignments. In addition Fig. 2 demonstrates the absence of the \( N = Z - 1 \) nuclei \( ^{81}\text{Nb} \), \( ^{85}\text{Tc} \) and \( ^{89}\text{Rh} \), which are probably unstable against proton-decay.

In view of recent predictions for the proton dripline [5, 6] the particle stability of \( ^{78}\text{Zr} \) and even \( ^{76}\text{Y} \) is no surprise. \( ^{81}\text{Nb} \) and \( ^{85}\text{Tc} \) are calculated to have negative proton separation energies [5], but not negative enough to make proton emission the dominant decay channel as we have to conclude from their non-observation.

During a 60 hours run one \( ^{102}\text{Sn} \) could be identified resulting in a production cross section of \( \sigma = 1.8^{+3.2}_{-1.3} \) pb. The decay data of this event together with 6 events observed in 1994 by our group [7] results in a halflife of \( T_{1/2} = 1.0^{+0.54}_{-0.26} \) s and a beta endpoint energy of \( E_{\beta_0} = 3.8^{+0.7}_{-0.3} \) MeV. Due to the low statistic a meaningful comparison between the experimental Gamov-Teller strength and theoretical values it is not yet possible.

With the implantation of 2800 \( ^{102}\text{Sn} \) we were able to study this nucleus in decay spectroscopy for the first time and establish a decay scheme for the daughter nuclide \( ^{102}\text{In} \). Analyzing the correlated beta-decay events with a maximum likelihood method the \( ^{102}\text{Sn} \) halflife was measured as \( T_{1/2} = 3.8 \pm 0.2 \) s. With the knowledge of the halflife it is possible to calculate the probability that a observed event in a decay chain can be assigned to a decay of the mother isotope. Using only decay events with a probability \( p > 0.70 \) for a \( ^{102}\text{Sn} \) decay, 8 gamma transitions could be identified that follow the \( ^{102}\text{Sn} \rightarrow ^{102}\text{In} \) decay (see Fig. 3). In the case of EC decay events it was possible to observe sum lines of conversion electrons of the low energy transitions in the silicon detector. Considering this additional information it is possible to establish a decay scheme which is in consistence with all experimental observations. Due to the low statistics it was not possible to measure \( \gamma-\gamma \)-coincidences. The spin and parity assignments of the levels below the directly fed \( 1^+ \)-states are not rigouros and can be given only in a tentative way based mainly on systematics.

The measured beta\(^+\) spectrum (Fig. 3) was fitted with two components to levels 366 keV apart and with the relative feeding observed in the gamma decay. This determined the endpoint energies to these two levels and also the groundstate decay Q-value as \( Q_{EC} = 5760 \pm 90 \pm 50 \) keV. The summed Gamov-Teller strength of the two individual transitions observed for the \( ^{102}\text{Sn} \) decay is \( B_{GT} = 4.0 \pm 0.6 \). The reference strength value, expected for the \( \pi_{g9/2} \rightarrow \nu_{g7/2} \) decay of \( ^{102}\text{Sn} \) on the basis of the extreme single-particle shell model, is \( B_{GT}^{ref} = 17.8 \), thus leading to a hinderance
factor $h = \frac{B_{\text{ref}}}{B_{\text{GT}}} = 4.45$.

Using the same experimental techniques it was possible to measure the Q-value of $^{98}\text{Cd}$ with high precision ($Q_{\text{EC}} = 5430 \pm 40$ keV). Together with the already known decay data [8] the summed Gamov-Teller strength for the four observed transitions results in $B_{\text{GT}} = 2.9 \pm 0.2$. This result is in agreement with the published value of $B_{\text{GT}} = 3.5^{+0.8}_{-0.7}$ [8].

Regarding the proton dripline we implanted the $N = Z$ nuclei $^{75}\text{Sr}$, $^{77}\text{Y}$, $^{79}\text{Zr}$ and $^{83}\text{Mo}$. We observed their decay with a short halflife, consistent with a superallowed beta decay. The results are listed in Table 1. The large error intervall for $^{75}\text{Sr}$, $^{79}\text{Zr}$ and $^{83}\text{Mo}$ results from an observation of only one event. These nuclei were implanted as a fortunate byproduct in a magnetic setting of the FRS for their neighbouring isotopes due to the geometric extensions of our implantation detector. With 12 $^{77}\text{Y}$ nuclei collected, decaying all via beta decay, a possible proton emission can only be a small branch.

As mentioned in the introduction decay properties of rp-process waiting point nuclei are of great astrophysical importance and necessary for network calculations. Since decay properties of these nuclei are poorly known, we measured the halflives of all waiting point nuclei from $^{80}\text{Zr}$ up to $^{92,93}\text{Pd}$. Our results are listed in Table 1. Furthermore results of other groups and theoretical predictions as used in the network calculations of H. Schatz [2] can be found. In all cases our results are in good agreement with the measurements of other groups (see Table 1). On the other hand, the given results deviate significantly from the theoretical ones, leading to uncertainties in the network calculations. The halflives measured in this work should remove a large part of these uncertainties.

To investigate superallowed Fermi beta decays we studied the six heaviest candidates of N=Z odd-odd nuclei between $^{78}\text{Y}$ and $^{98}\text{In}$. Beside a very fast transition of the mother nuclei in all cases, we observe a long living isomeric state in some cases. Due to a correlation time intervall of 30 s we were able to detect even the decay of the daughter nuclei. With our data we were able to show that $^{90}\text{Rh}$, $^{94}\text{Ag}$ and $^{98}\text{In}$ have low lying states (presumably the ground
states) decaying by superallowed Fermi transitions. For the three lighter members of this series, \(^{78}\text{Y}\) to \(^{86}\text{Tc}\), such superallowed Fermi transitions were recently detected at GANIL [12]. Our new data on these nuclei are in good agreement.

The observation of long living isomeric states for \(^{78}\text{Y}\) and \(^{94}\text{Ag}\) is in good agreement with other measurements at Argonne (\(^{78}\text{Y}\), [13]) and GSI (\(^{84}\text{Ag}\), [14]). As these states are high spin states we expect the \(^{90}\text{Rh}\) and \(^{98}\text{In}\) isomeric states to have a high spin as well. In case of \(^{84}\text{Nb}\) and \(^{86}\text{Tc}\) we did not observe a beta-decaying isomer. But recently a short living \(\mu\) isomer for \(^{86}\text{Tc}\) decaying via a yrast gamma cascade was reported [15]. The measured halflives of the fast and slow transitions of the \(N=Z\) odd-odd nuclei can be found in Table 2.

**REFERENCES**

7. R. Schneider et al., Z. Phys. A348 (1994) 241

**TABLE 1.** Halflives of waiting point nuclei and \(N = Z - 1\) nuclei. Results of other groups \(T^\text{other}\) (references are given) and the theoretical values \(T^\text{th}\) used in the network calculations of H. Schatz [2] are given.

<table>
<thead>
<tr>
<th>nuclide</th>
<th>(T_{1/2}) [s]</th>
<th>(T^\text{other}) [s]</th>
<th>(T^\text{th}) [s]</th>
<th>nuclide</th>
<th>(T_{1/2}) [s]</th>
<th>(T^\text{other}) [s]</th>
<th>(T^\text{th}) [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{80}\text{Zr})</td>
<td>5.3(+1.1)-0.9</td>
<td>4.1(+0.8)-0.6 [9]</td>
<td>6.9</td>
<td>(^{84}\text{Mo})</td>
<td>3.7(+0.7)-0.8</td>
<td>3.7(+1.0)-0.8</td>
<td>3.7(+1.0)-0.8</td>
</tr>
<tr>
<td>(^{88}\text{Ru})</td>
<td>1.2(+0.3)-0.2</td>
<td>0.7</td>
<td>(^{89}\text{Ru})</td>
<td>1.45 (+0.13)-0.13</td>
<td>1.2 (+0.2)-0.2 [10]</td>
<td>1.2 (+0.2)-0.2</td>
<td></td>
</tr>
<tr>
<td>(^{92}\text{Pd})</td>
<td>1.0(+0.3)-0.2</td>
<td>0.9 (+0.2)-0.2 [11]</td>
<td>0.55</td>
<td>(^{93}\text{Pd})</td>
<td>1.0 (+0.2)-0.2</td>
<td>1.0 (+0.2)-0.2</td>
<td></td>
</tr>
<tr>
<td>(^{76}\text{Sr})</td>
<td>80 (+40)-40</td>
<td>77 (+32)-32</td>
<td>6 (+3)-3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^{79}\text{Zr})</td>
<td>80 (+40)-40</td>
<td>83 (+32)-32</td>
<td>---</td>
<td></td>
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</tbody>
</table>

**TABLE 2.** Halflives of \(N=Z\) odd-odd nuclei. The short and long living states are listed and compared with results of other groups.

<table>
<thead>
<tr>
<th>nuclide</th>
<th>(T_{1/2}) [ms]</th>
<th>(T^\text{other}) [ms]</th>
<th>(T_{1/2}) [s]</th>
<th>(T^\text{other}) [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{78}\text{Y})</td>
<td>55 (+9)-9</td>
<td>55 (+12)-12</td>
<td>5.7 (+0.7)-0.7</td>
<td>5.8 (+0.6)-0.6</td>
</tr>
<tr>
<td>(^{82}\text{Nb})</td>
<td>48 (+8)-8</td>
<td>50 (+4)-4</td>
<td>1.0 (+0.3)-0.3</td>
<td>1.0 (+0.3)-0.3</td>
</tr>
<tr>
<td>(^{86}\text{Tc})</td>
<td>59 (+8)-8</td>
<td>47 (+12)-12</td>
<td>0.45 (+0.20)-0.20</td>
<td>0.45 (+0.20)-0.20</td>
</tr>
<tr>
<td>(^{90}\text{Rh})</td>
<td>12 (+5)-5</td>
<td>12 (+2)-2</td>
<td>1.2 (+1.3)-1.2</td>
<td>1.2 (+1.3)-1.2</td>
</tr>
<tr>
<td>(^{94}\text{Ag})</td>
<td>26 (+26)-26</td>
<td>26 (+15)-15</td>
<td>0.42 (+0.05)-0.05</td>
<td>0.42 (+0.05)-0.05</td>
</tr>
<tr>
<td>(^{98}\text{In})</td>
<td>32 (+32)-32</td>
<td>32 (+32)-32</td>
<td>32 (+32)-32</td>
<td>32 (+32)-32</td>
</tr>
</tbody>
</table>

To summarize, we were able to study \(^{102}\text{Sn}\) in decay spectroscopy for the first time and establish a decay scheme for the daughter nuclide \(^{102}\text{In}\). With the measurement of the halflife and the Q-value the Gamov-Teller strength could be deduced.

The heaviest nuclei, where one can hope to study pure Fermi beta transitions are the odd-odd nuclei up to \(^{98}\text{In}\). We studied the six heaviest candidates between \(^{78}\text{Y}\) and \(^{98}\text{In}\). For the first time we observed fast transitions, compatible with superallowed Fermi transitions for \(^{90}\text{Rh}\), \(^{94}\text{Ag}\) and \(^{98}\text{In}\).

We measured halflives of rp-process waiting point nuclei and compared them with theoretical expectations, which are in most cases shorter than the measured values.

We would like to thank the FRS group for their help during our beamtime. This work was supported by BMBF (06TM872 TPI) and SFB 375.