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Decay studies of N $\approx$ Z nuclei from ^{75}Sr to ^{102}Sn

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Abstract. Neutron deficient nuclei near ^{100}Sn have been produced by fragmentation of a $1 \cdot$ A GeV ^{112}Sn beam. The fragments were separated, identified and stopped in a highly segmented silicon strip detector stack. This detector measured the total energy of emitted β^+-particles. γ-radiation was measured with surrounding detectors. The half-lives for many nuclides have been determined for the first time and give important information for the following topics: For the heaviest particle-stable odd-odd nuclei ^{90}Rh, ^{94}Ag and ^{98}In we observed for the first time fast β-decays, compatible with superallowed Fermi transitions and confirmed such decays for ^{78}Y, ^{82}Nb and ^{86}Tc. We have also observed long-lived $T = 0$ states in some of these nuclei. We measured the half-lives of all rp-process waiting-point nuclei from ^{80}Zr up to ^{92,93}Pd. In addition we find the proton drip line nucleus ^{77}Y to decay dominantly via β-decay. To study the Gamov-Teller strength in the β-decay near the doubly magic ^{100}Sn we measured the half-life, β- and γ-spectrum of ^{102}Sn. We propose a level scheme for the daughter nuclide ^{102}In and deduce the Gamov-Teller strength ($B_{\mathrm{GT}} = 4.0 \pm 0.6$). This is one of the largest values known.

PACS. 21.10.Tg Lifetimes – 23.40.Hc Relation with nuclear matrix elements and nuclear structure – 23.50.+z Decay by proton emission

1 Introduction

The region along the $N = Z$ line near and below ^{100}Sn is currently explored extensively in both experimental and theoretical studies. One focus is to study directly the doubly magic nucleus ^{100}Sn, a key nucleus for the investigation of Gamov-Teller β-decay. Other reasons to investigate the nuclei along the $N = Z$ line below ^{100}Sn are precision studies of superallowed Fermi β-decay and input data for calculations of the astrophysical rapid proton capture (rp-) process.

The path of the rp-process is expected to lead along the $N = Z$ line up to ^{100}Sn [1,2]. At the high temperatures expected in neutron star X-ray bursts, nuclei between ^{64}Ge and ^{100}Sn may be synthesized successively by (p, γ) reactions until the proton dripline is reached. For a continuation to heavier masses, nuclei have to undergo β^+-decay towards more neutron-rich nuclei, from where the (p, γ) reaction can go on. Such β^+ 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 strongly determines the flux towards heavier nuclei and the respective isotopic abundances. The rp-process is expected to be responsible for the high solar abundances of nuclei such as ^{92,94}Mo and ^{96,98}Ru. 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.

Odd-odd $N = Z$ nuclei are of special interest because of the possible occurrence of superallowed Fermi β-decay. With their transition strength fundamental aspects of the weak interaction can be tested. The superallowed $0^+ \to 0^+$ decays of nuclei from ^{14}O up to ^{54}Co are used [3] to prove the Conserved Vector Current (CVC) hypothesis and to test the standard model. For these studies, radiative and charge-dependent corrections have to be applied leading to a nucleus-independent Ft-value. From the latter the vector coupling constant G'_{V} in nuclear weak decays is deduced and yields the mixing between the mass eigenstate and the weak-interaction eigenstate of the down quark, *i.e.* the first element of the Cabibbo-Kobayashi-

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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 for the first row of the CKM matrix fails by more than two standard deviations. For heavier nuclei, where the corrections become larger, there are considerable differences among several calculations. Therefore, measurements could provide a sensitive test of these theoretical estimates.

The main goal of the experiment was a precise determination of the Gamov-Teller (GT) strength in the β-decay of the doubly magic ^{100}Sn and the neighbouring nuclei ^{102}Sn and ^{98}Cd. These nuclei decay predominantly 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 β-transition strength, defined for a transition into a single final state as

$$B_{\rm GT} = \frac{6147\,{\rm s}}{(g_{\rm A}/g_{\rm V})^2 \cdot f(Z, E_0) \cdot T_{1/2}}, \qquad (1)$$

with the ratio of the weak coupling constants $g_{\rm A}/g_{\rm V} = 1.26$, the Fermi integral f for the β-endpoint energy E_0, and the observed half-life $T_{1/2}$. The accurate analysis of the decay properties with reference to model predictions eventually allows a major contribution to illuminate the question of the missing Gamov-Teller strength [4]. 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.

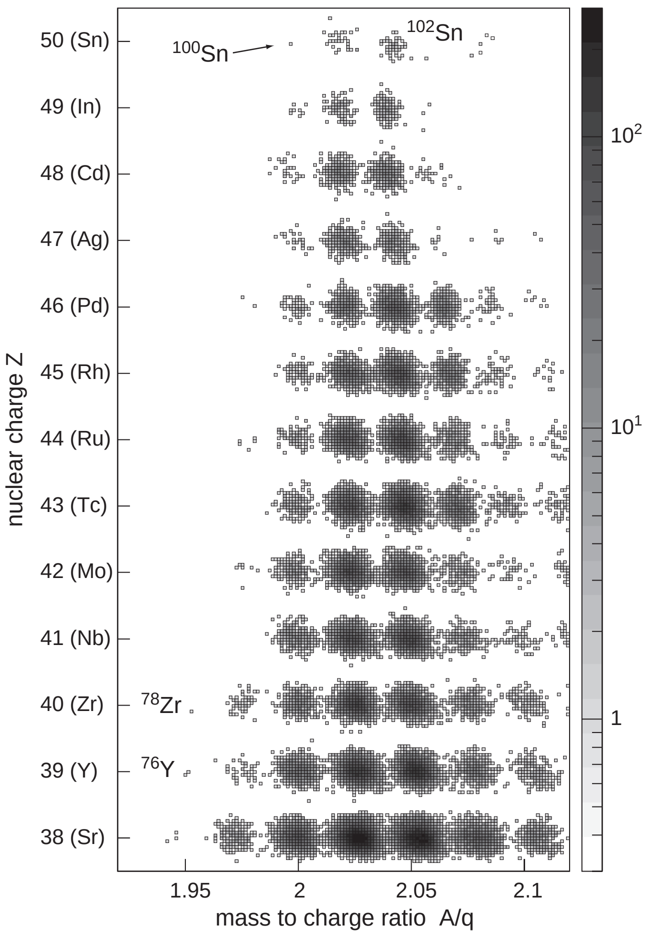

Fig. 1. Fragments identified in many different settings of the FRS. The ions are completely stripped: ionic charge $q = Z$. Note the logarithmic vertical scaling.

2 Experimental details

The experiment was performed at the fragment separator FRS [5] of GSI in Darmstadt, Germany. A beam of ^{112}Sn ions was accelerated to an energy of $1 \cdot$A GeV in the heavy-ion synchrotron SIS after 20 injection and cooling cycles. Spills with intensities of up to $5 \cdot 10^8$ ions every 14 s were focussed onto a 4 g/cm^2 beryllium target.

The fragments were isotopically separated in the FRS by a combination of magnetic deflection and energy loss. 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) were reached. This is demonstrated in fig. 1.

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 4π implantation detector was designed to measure the total energy of emitted β^+-particles and β-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 the following decay with very low background rates (as little as 1 per 780 seconds) could be achieved. For measuring γ-radiation the implantation detector was surrounded by a 6-fold segmented NaI detector covering 2π and a germanium clover detector in close geometry. We determined the half-lives and the positron energies for each implanted nuclide with a maximum likelihood method taking into account three decay generations as well as background events during a fixed correlation time after the implantation.

3 Results and discussion

Figure 1 shows the measured fragment yields, accumulated in many different FRS settings, as a function of the measured nuclear charge Z and the measured mass-to-charge ratio. The spectra show the previously unobserved $N = Z - 2$ nuclei ^{76}Y (2 events) and ^{78}Zr (one event). In addition fig. 1 demonstrates the absence of the $N = Z - 1$ nuclei ^{81}Nb, ^{85}Tc and ^{89}Rh, which are probably unstable against proton-decay.

3.1 rp-process

In view of recent predictions for the proton dripline [6] the particle stability of ^{78}Zr is no surprise. For ^{77}Y and ^{76}Y stability against proton emission was also predicted. For ^{76}Y it is experimentally proven for the first time and for ^{77}Y we could even measure the half-life (see below). For ^{81}Nb and ^{85}Tc we have to conclude that proton emission is the dominant decay channel in agreement with the calculations yielding negative proton separation energies [6].

Of the nuclei near the proton dripline we implanted ^{75}Sr and ^{77}Y. We observed their decay with a short half-life, consistent with the superallowed β-decay. The results are shown in fig. 2. With 12 ^{77}Y nuclei collected, all decaying via β-decay, a possible proton emission can only be a small branch.

As mentioned in the introduction, the decay properties of rp-process waiting-point nuclei are of great astrophysical importance and necessary for network calculations. We measured the half-lives of all waiting-point nuclei (even Z) from ^{80}Zr up to ^{92,93}Pd. Our results are also shown in fig. 2 together with results of other groups and theoretical predictions as used in the network calculations [1]. Now the half-lives of all even-even $N = Z$ waiting-point nuclei except for ^{96}Cd are known. The experimental half-lives are in most cases significantly longer than the theoretical ones. Therefore the time scale for the rp-process may have been underestimated in the network calculations.

3.2 Fermi decay

To investigate superallowed Fermi β-decays we studied the six heaviest candidates of $N = Z$ odd-odd nuclei between ^{78}Y and ^{98}In. A very fast transition of the mother nuclei is observed in all cases and for some of these nuclides a long-living isomer is observed too (see fig. 2). Due to a correlation time interval of 30 s we could also detect the decay of the daughter nuclei. With our data we are 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, ^{82}Nb and ^{86}Tc, such superallowed Fermi transitions were recently detected at GANIL [13]. Our new half-life values for these nuclei are in good agreement.

The observation of long-living isomeric states for ^{78}Y and ^{94}Ag is in good agreement with measurements at Argonne (^{78}Y, [11]) and GSI (^{94}Ag, [12]). As these states are high-spin states we expect the isomeric states in ^{90}Rh and ^{98}In to have high-spin as well. For ^{82}Nb and ^{86}Tc we did not observe a beta-decaying isomer. But recently a short-living μs isomer in ^{86}Tc decaying via a yrast γ cascade was reported [14].

In the superallowed Fermi decay of light nuclei the CVC hypothesis has been proven by showing that the ft-values agree at a level of 10^{-3} after corrections of less than 2% have been applied [3]. Using this value $ft = 3072$ s together with the experimental half-lives $t = T_{1/2}$ and neglecting corrections and unknown branchings, which are small compared with the experimental uncertainties, we can deduce the phase-space factor f and thus the decay Q-values. Since f depends on Q with roughly the 5-th power, the relative error in $Q_{\rm EC}$ is about 5 times smaller than the error in $T_{1/2}$. These values are shown in fig. 3 together with the values extrapolated in the mass table [15] and those deduced from Coulomb displacement energies (CDEs) [16]. For ^{86}Tc we notice a significant deviation of our experimental value from the smooth trend of CDEs. The reason is perhaps, that with the $g_{9/2}$ subshell a new orbital is being occupied or that mother and daughter nuclei have different shapes.

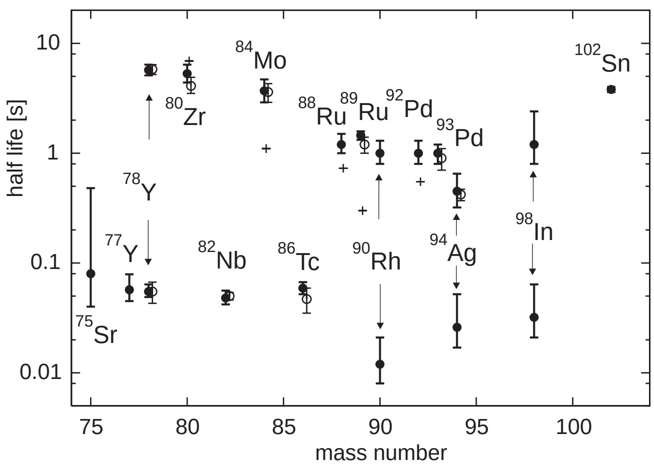

Fig. 2. Results of our half-life measurements (full symbols). They agree well with already known values (open symbols, [7–12]), but are generally longer than theoretical predictions (+ signs) used in rp-process calculations [1].

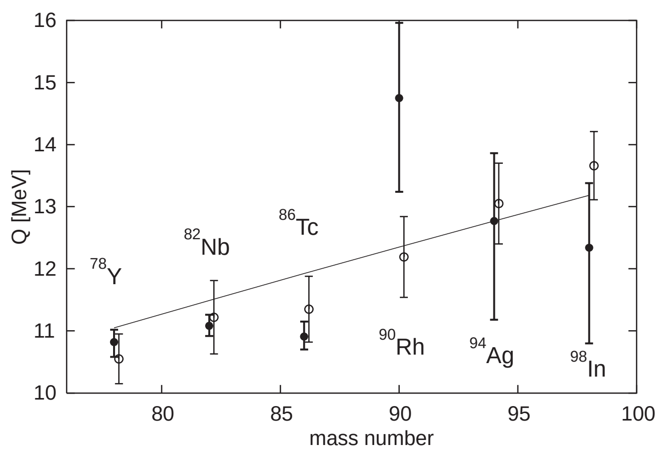

Fig. 3. $Q_{\rm EC}$-values for the observed Fermi decays deduced from the measured half-lives and the constant $ft = 3072$ s (full symbols) compared with those from the Audi and Wapstra extrapolations (open symbols, [15]) and from Coulomb displacement energies (line, [16]).

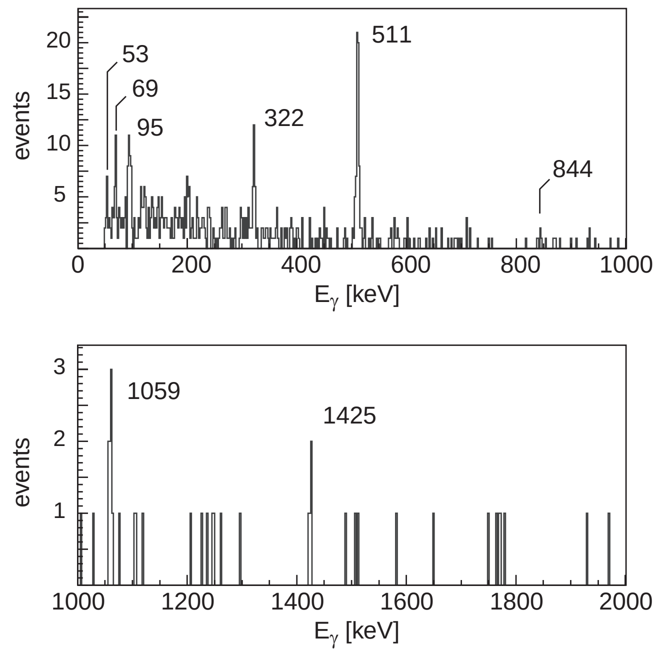

Fig. 4. Measured γ energy spectrum for the ^{102}Sn $\to$ ^{102}In decay. Only decay events which can be assigned to a decay of ^{102}Sn with a probability $p > 0.7$ are shown.

3.3 Gamov-Teller decay

During a run of 60 hours a single ^{100}Sn nucleus could be identified resulting in a production cross-section of $\sigma = 1.8$ pb. The decay data of this event together with 6 events observed in 1994 by our group [17] results in a half-life $T_{1/2} = 1.0^{+0.54}_{-0.26}$ s and a β endpoint energy $E_{\beta_0} = 3.8^{+0.7}_{-0.3}$ MeV. Due to the low statistics a meaningful comparison between the experimental Gamov-Teller strength and theoretical values is not yet possible.

With the implantation of 2800 ^{102}Sn nuclei we were able to study this nucleus in decay spectroscopy for the first time. Analyzing the correlated β-decay events with a maximum likelihood method, the ^{102}Sn half-life was measured as $T_{1/2} = 3.8 \pm 0.2$ s. With the knowledge of the half-life it is possible to calculate the probability that an 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}Sn decay, 8 γ-transitions that follow the ^{102}Sn $\to$ ^{102}In decay (see fig. 4) could be identified. In the case of electron-capture decay it was possible to observe sum lines from conversion electrons of the low-energy transitions in the silicon detector. Considering this additional information and guided by theoretical expectations [18] it is possible to construct a decay scheme which is consistent with all experimental observations: the β-decay feeds two 1^+ states at 1598 keV and 1964 keV with an intensity ratio 70 : 30. From these states γ cascades lead down to the (7^+) ground state.

The measured β^+-spectrum was fitted with two components to levels 366 keV apart and with the relative feeding observed in the γ-decay. This determined the endpoint energies to these two levels and also the ground-state decay Q-value as $Q_{\mathrm{EC}} = 5760 \pm 90 \pm 50$ keV. The first error is that of the endpoint energy, the second is estimated to take care of the uncertainty in the low-energy level scheme of ^{102}In. The summed Gamov-Teller strength of the two individual transitions observed for the ^{102}Sn decay is $B_{\mathrm{GT}} = 4.0 \pm 0.6$. This value is among the largest observed in the nuclear chart. The reference strength value, expected for the $\pi g_{9/2} \to \nu g_{7/2}$ decay of ^{102}Sn on the basis of the extreme single-particle shell model, is $B_{\mathrm{GT}}^{\mathrm{ref}} = 17.8$, thus leading to a hindrance factor $h = B_{\mathrm{GT}}^{\mathrm{ref}}/B_{\mathrm{GT}} = 4.5$.

4 Conclusions

Summarizing we have measured in a single experiment the half-lives of most $N = Z$ and $N \approx Z$ nuclei below ^{100}Sn. Thus, we could contribute to the understanding of the rp-process and of Fermi β-decay. The heaviest $N = Z$ odd-odd nuclei are now all established as superallowed Fermi emitters. It will be possible to test calculations of charge-dependent corrections in good shell model nuclei like ^{98}In, but the production rate of these nuclides has to be increased by a large factor.

For the decay of ^{102}Sn we have for the first time measured the β^+- and γ-spectra as well as the half-life with good precision. The Gamov-Teller strength deduced is one of the largest known, but still quenched strongly compared with the extreme shell model value. Therefore, we can stress again the importance of measuring the Gamov-Teller strength in the ^{100}Sn decay.

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