PROCEEDINGS OF SCIENCE

Alpha decay of ^{109}I and the implications for the rapid-proton capture process

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In an experiment at the Recoil Mass Spectrometer of the HRIBF at ORNL the alpha decay branch of ^{109}I was discovered. The measurement of its decay energy allowed for the indirect determination of the proton separation energy in the daughter nucleus ^{105}Sb. The deduced $S_p(^{105}\mathrm{Sb})$=-356(22) keV is about 130 keV larger than the previously claimed value. The consequences of this measurement for the astrophysical rp-process will be discussed.

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The path followed by the rapid proton capture (rp-) process in a subset of type I X-ray bursts has been predicted to end into a loop around neutron-deficient Sn-Sb-Te isotopes in the vicinity of ^{100}Sn [1]. Here, the presence of an island of alpha emitters and the proximity to the proton drip-line is the main cause for the cyclical nature of the process. The path and energy generation rate of the rp-process termination depend dramatically on the properties of nuclei involved, such as their mass and half-life. In particular the decay properties of the magic tin isotopes and the proton separation energies (S_p) for Z=51 antimony isotopes are critical for the endpoint of the rp-process path. While the half-lives of the nuclei involved are well known experimentally, the same cannot be said for either the mass or proton separation energy. Moreover the most widely used theoretical calculations do not seem to be able to predict with good accuracy the experimental data available in the region [2, 3].
This cycling around the Sn-Sb-Te isotopes generates helium at late times in the X-ray burst, thus enhancing the production of seed nuclei for the rp-process itself through the triple-α reaction. A late boost in energy production would change the shape of the light curve and affect the composition of the burst ashes. Current calculations predict that the cycle forms at ^{105}Sn with proton capture into ^{106}Sb, i.e. where the antimony isotopes become bound enough against proton emission to proceed through double proton capture to ^{107}Te, which closes the cycle with alpha decay back into ^{103}Sn, see Figure 1. The measurement of the S_p value for the lighter ^{105}Sb is therefore crucial in order to determine if the cycle can start already at ^{104}Sn with the reaction sequence ^{104}Sn(p,γ)^{105}Sb(p,γ)^{106}Te(α,γ)^{102}Sn. This scenario would speed up the termination of the rp-process, since ^{106}Te is much more short-lived than ^{107}Te. The S_p value for the exotic ^{105}Sb isotope was reported in a proton emission experiment [4], but this observation has never been confirmed [5, 6, 7, 8]. In spite of that, the S_p(^{105}Sb) has been adopted in widely used mass tables and quoted in many theoretical papers. An alternative way of determining the ^{105}Sb proton separation energy consists in measuring the unknown alpha decay branch of the proton emitter ^{109}I. The proton and alpha decay energies from ^{109}I, combined with the known alpha decay energy of ^{108}Te, provide a direct and independent determination of the S_p(^{105}Sb) (see Figure 1).

The nuclei of interest were produced at the HRIBF facility in the fusion evaporation reaction ^{54}Fe(^{58}Ni,p2n)^{109}I. The reaction products were separated according to their mass-to-charge ratio (A/Q) through the Recoil Mass Spectrometer (RMS) and only those with A/Q=109/27 and 109/28 were implanted into the detection set-up positioned at the focal plane. The set-up consisted in a position-sensitive microchannel plate detector (MCP) to identify the incoming ions, followed downstream by a double-sided silicon strip detector (DSSD), into which the recoiling ions were implanted, surrounded by veto detectors to suppress escaping particles. The preamplifier signals from all the detectors were read by Digital Signal Processing-based electronics (XIA-DGF) [9] that recorded the time and energy of each event for off-line analysis. The decay events detected in the DSSD detector were software correlated in space and time with the implanted A=109 ions.

The energy spectrum of decay events following the implantation of an ion within 400 μs is displayed in Figure 2. Three peaks can be identified in the plot: the two lower energy transitions at 3107 and 3317 keV correspond to the known alpha decays of the mass contaminant ^{109}Te and of the ^{109}I proton-decay daughter ^{108}Te, respectively. The higher energy peak at 3774(20) keV is assigned

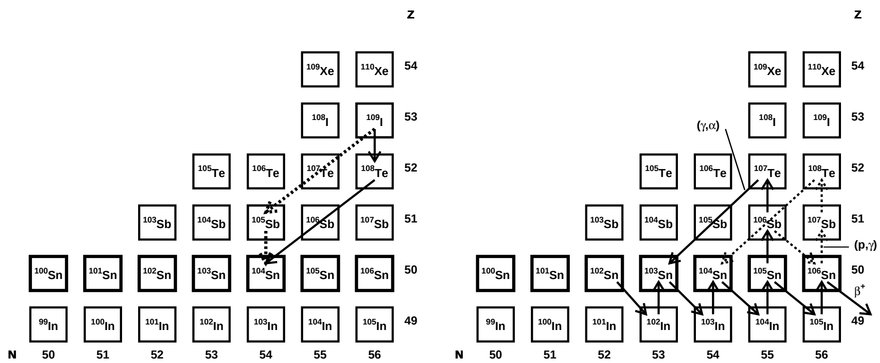

Figure 1: Portion of the chart of nuclei above ^{100}Sn. Left panel: the isotopes of interest are highlighted. Solid arrows correspond to known decay modes, while dashes arrows to those predicted . See text for details. Right panel: the predicted path followed by the rp-process as predicted in [1] is depicted, as well as the decays of interest. See text for details.

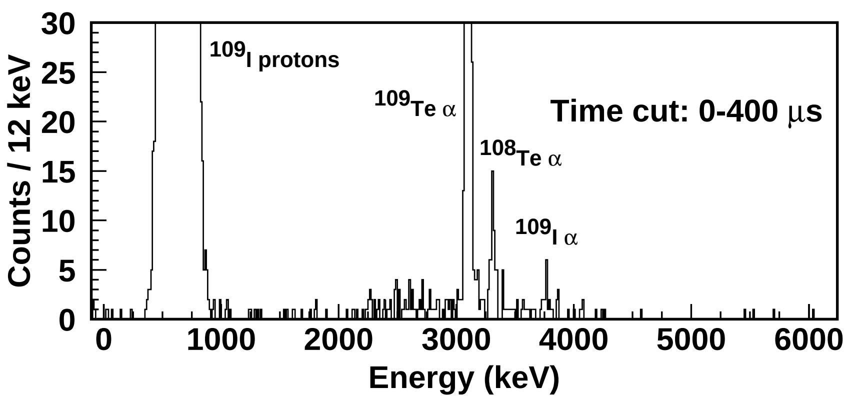

Figure 2: Energy of particle-decay events following the implantation of an ion within 400 μs. See text for details.

to the hitherto unknown alpha-decay branch of ^{109}I [10]. This energy corresponds to a Q-value for alpha decay Q_α=3918$\pm$21 keV. This allows the indirect determination of the Q-value for proton emission from ^{105}Sb as Q_p=356$\pm$22 keV, hence S_p=-Q_p=-356$\pm$22 keV. The new Q_p(^{105}Sb) value is about 130 keV lower than the previously claimed value of 491$\pm$15 keV, therefore excluding the possibility of observing direct proton emission from the ground state of ^{105}Sb. With these new values, the mass excess for ^{105}Sb is corrected to -64023$\pm$64 keV, if the new Q_p(^{105}Sb) [10] and mass excess of ^{104}Sn [11] are applied.

In Figure 3 the S_p values for odd-Z isotopes above ^{100}Sn are plotted. Odd-even effects on the S_p are clearly evident in Figure 3; based on the assumption that these effects carry on for lighter nuclei, we can infer a lower limit for S_p(^{104}Sb) to be equal to the lower value of S_p(^{105}Sb), i.e. S_p(^{104}Sb)>-378 keV. The latter implies a lower limit on S_p(^{108}I) of 474 keV, see Figure 3.

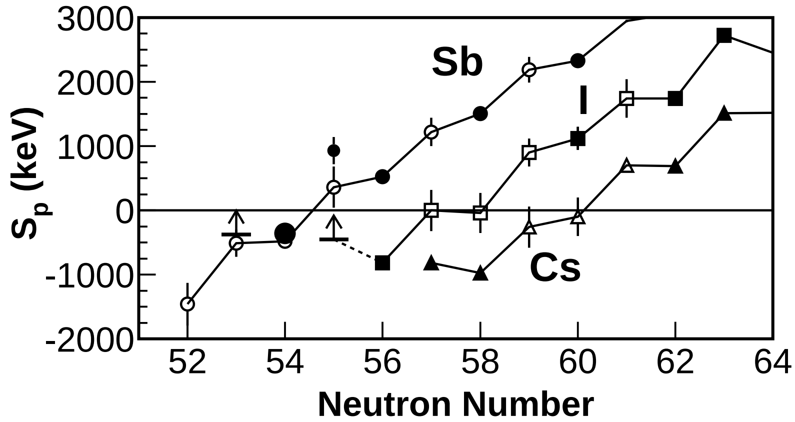

Figure 3: Systematics of proton separation energies for odd-Z isotopes above the doubly magic nuclide ^{100}Sn. Filled symbols stem from experimental values while open symbols are values from extrapolations [12]

Network calculations using a one-zone X-ray burst model [1] were performed. The branching into the Sn-Sb-Te cycle was calculated as a function of the S_p values for (p,γ) capture reactions on $^{103-105}$Sn. The results are shown in Figure 4. It is evident from it that S_p values larger than 500 keV would be needed for a significant Sn-Sb-Te cycle to be established. These calculations show that with the new $S_p(^{105}$Sb) the formation of the Sn-Sb-Te loop at ^{104}Sn can be excluded. The formation of the cycle as early as at ^{103}Sn would be possible if odd-even effects in $S_p(^{104,105})$Sn are very strong and/or the reaction rate is greatly underestimated. An experiment to measure $S_p(^{104}$Sb) with a similar method was carried on at the same facility. The data are currently under analysis [13].

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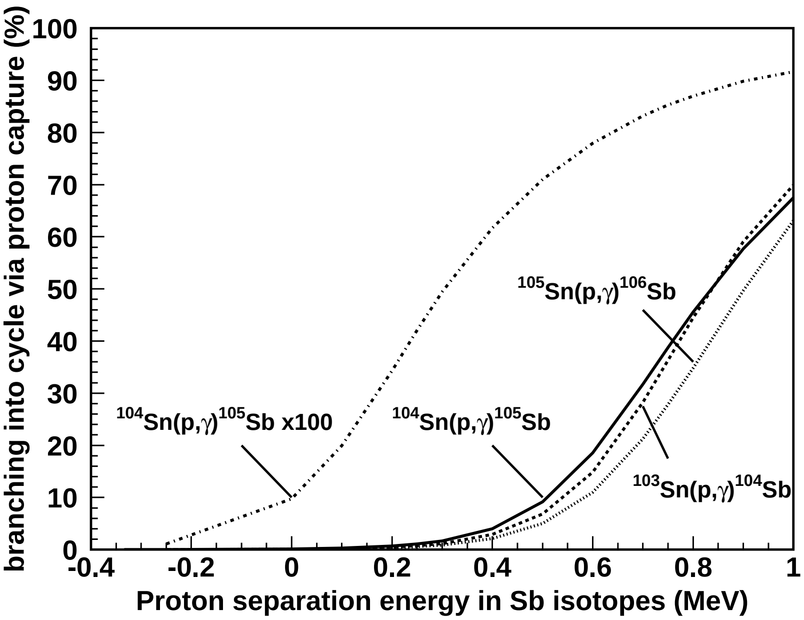

Figure 4: Branching of the rp-process reaction flow into the Sn-Sb-Te cycle at various tin isotopes as a function of the proton separation energy in the respective antimony isotope. The dash-dotted line corresponds to ^{104}Sn when the reaction rate ^{104}Sn(p,γ) is increased by two orders of magnitude.

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