The rp-process and new measurements of $\beta$-delayed proton decay of light Ag and Cd isotopes

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Recent network calculations suggest that a high temperature rp-process could explain the abundances of light Mo and Ru isotopes, which have long challenged models of p-process nuclide production. Important ingredients to network calculations involving unstable nuclei near and at the proton drip line are $\beta$-halflives and decay modes, i.e., whether or not $\beta$-delayed proton decay takes place. Of particular importance to these network calculation are the proton-rich isotopes $^{96}$Ag, $^{98}$Ag, $^{96}$Cd and $^{98}$Cd. We report on recent measurements of $\beta$-delayed proton branching ratios for $^{96}$Ag, $^{98}$Ag, and $^{98}$Cd at the on-line mass separator at GSI.

1. THE QUEST FOR THE P-NUCLEI

The p-process elements, proton-rich nuclei heavier than iron that cannot be produced by neutron-capture (r- and s-processes), are among the least abundant elements in the cosmos. Their synthesis has been modelled as an rp-process $[^3]$, a series of $(p,\gamma)$ reactions on existing r- and s-process seeds in a hot hydrogen rich environment, or a $\gamma$-process $[^4]$, which creates proton-rich nuclei by photodissociation reactions, $(\gamma,p)$, $(\gamma,n)$ and $(\gamma,\alpha)$, thought to take place in type II supernovae. This $\gamma$-process requires temperatures of the order of $T_9 = 2 – 3$, starts from r- and s-process seed nuclei and runs on timescales of order a second. It appears to explain the abundance of heavy p-nuclei ($A > 108$) quite

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well (for shortcomings of the \(\gamma\)-process and further references, see e.g. \[3\]), but always severely underproduces the lighter p-nuclei \((A \leq 108)\) by factors of the order of 10 to 100.

Some of the lighter p-nuclei, specifically \(^{92}\text{Mo}\), \(^{94}\text{Mo}\), \(^{96}\text{Ru}\) and \(^{98}\text{Ru}\), are much more abundant than their heavier (and lighter) counterparts. If these are produced by the rp-process (see \[4\,5\]; recent reviews given by \[6\] and \[8\]), high temperatures (of the order \(T_9 = 1\)) and hydrogen richness \((\rho Y_p\) of the order \(10^3\) to \(10^4\) \(g\ cm^{-3}\)) are required.

Accreting neutron stars or white dwarfs in binary systems and Thorne-Żytkow objects have been suggested as possible sites for the rp-process \[5,9\]. In the neutron star scenario, hydrogen rich material flows from the partner (usually a red giant) to the neutron star and reaches high enough temperatures during the accretion process. In a Thorne-Żytkow object, a neutron star is merged with a red giant. There will be a strongly convective hydrogen-rich environment at high temperatures directly above the neutron star. A recent study \[10\] assuming a pulsed rp-process appears to be capable of producing substantial amounts of light p-nuclei, especially the important and difficult to create Mo and Ru isotopes. This study provides the incentive to determine experimentally the decay modes of some of the progenitors of \(^{96}\text{Ru}\) and \(^{98}\text{Ru}\), namely \(^{96}\text{Ag}\), \(^{98}\text{Ag}\) and \(^{98}\text{Cd}\).

Another recent investigation \[3\] found that, in a new kind of p-process in the neutrino-driven wind following the delayed explosion of a supernova type II, some light p-nuclei may actually be coproduced with r-process isotopes. This process would take place in addition to the usual \(\gamma\)-process, which would account for the heavier p-nuclei. However, little \(^{94}\text{Mo}\) and \(^{96,98}\text{Ru}\) are synthesized in this process.

2. THE EXPERIMENT

The abundances of the Mo and Ru isotopes produced in network calculations depend sensitively on the decay modes of the progenitors. While \(^{96}\text{Cd}\) has not yet been identified, only half-lives and \(\gamma\)-ray properties have been established for \(^{96}\text{Ag}\) \[11,12\], \(^{98}\text{Ag}\) \[11\] and \(^{98}\text{Cd}\) \[13\]. In this experiment, we have re-investigated the decay properties of these nuclides, including \(\beta\)-delayed proton decays. A 58Ni beam (5.9—6.7 MeV/u, \(\approx 40\) particle nA) from the GSI UNILAC accelerator interacted with a production target of \(^{50}\text{Cr}\) (for \(A = 96, 98\)) and 58Ni (for an \(A = 114\) calibration run) in a FEBIAD-B2-C ion source \[14\]. The reaction products were mass analyzed using the GSI on-line mass separator.

The unique design of the mass separator allowed three setups to be used in parallel (with different masses selected). Setup (a) allowed implantation of the selected isotope onto a tape, which was then transported into a measuring station with a HP-Ge \(\gamma\)-detector and a \(\Delta E-E\) silicon detector telescope for protons. Setup (b) consisted of two identical silicon detector telescopes. The beam could be switched between them, and beam implantation into thin foils in close geometry allowed measurement of growth and decay of proton activity. Setup (c) featured a \(\beta\)-telescope made of two plastic scintillators. The beam was implanted onto a tape directly in front of the measuring station.

With these setups, the \(\beta\)-delayed proton decay rates, \(b_{\beta p}\), of a given nucleus can be obtained in the following four ways: (i) both proton and \(\gamma\)-rates obtained at setup (a); (ii) proton rate from (b), and mass-separated beam intensity from \(\gamma\)-measurement at (a); (iii) proton rate from (b), and mass-separated beam intensity from \(\beta\)-measurement at (c); (iv) proton rate from (b), and mass-separated beam intensity from (c).
In addition to providing a continuous beam, the FEBIAD-B2-C ion source can be operated in bunched mode\(^4\). Some ions with sufficiently long half-lives, e.g. \(^{98}\text{Ag}\), can be collected in a cold pocket, thus suppressing Ag relative to Cd by a factor of \(\sim 10-20\) ("Cd anti-bunch"). Subsequent heating of the cold spot can release substantial quantities of the stored ion species, enhancing Ag over Cd by a factor of \(\sim 100\) ("Ag bunch").

3. RESULTS

A mass 114 beam was used to calibrate each setup independently, based on the known decay of \(^{114}\text{Cs}\)\(^5\). The four methods described above gave consistent \(b_{\beta p}\)-values, and the weighted average was in good agreement with literature (Table 1).

| Isotope | Production rates (s \(\cdot\) 10 particle nA\(^{-1}\)) | \(b_{\beta p}\)-delayed proton branching ratios (\%) |
|---------|---------------------------------|---------------------------------|
|         | Beam Protons This work Literature |
| \(^{96}\text{Ag}\) | 2.9(8) a 0.11(2) c 3.7(9) e | 8.0(23) [11] 11.9(26) [12] |
| \(^{98}\text{Ag}\) | (6.4\(\pm\)2.5\(\times\)10\(^{-4}\) d | (1.1\(\pm\)0.5\(\times\)10\(^{-3}\) f |
| \(^{98}\text{Cd}\) | > 1.2 b < 3.05 \(\times\)10\(^{-4}\) d | < 2.5 \(\times\)10\(^{-2}\) g |
| \(^{114}\text{Cs}\) | 11.8(16) a 1.1(2) c | 8.7(13) e 7(2) [13] |

\(a\) Weighted average from setups (a) and (c). \(^b\) From setup (a). \(^c\) Weighted average from setups (a) and (b). \(^d\) From setup (b). \(^e\) Weighted average from methods (i) to (iv). \(^f\) Weighted average from methods (ii) and (iii).

For the mass 96 measurements, the ion source was operated in continuous beam mode. The observed protons were assigned to the decay of \(^{96}\text{Ag}\), since its production cross section is predicted to be much larger than that of \(^{96}\text{Cd}\). Also, odd-odd nuclei such as \(^{96}\text{Ag}\) are expected to have larger \(b_{\beta p}\)-values than neighboring even-even nuclei such as \(^{96}\text{Cd}\) due to the combined action of larger decay-energy window and enhanced \(\beta\)-feeding of higher-lying (4qp) states. See Table 1 and Fig. 1.

In the measurement of mass 98, Ag was bunched. The release time window was only 1.5 to 2.0 seconds over a total cycle period of 81 to 85 s. A total of 8 protons was measured in setup (b) over a period of about 8.5 hours. The corresponding Cd anti-bunch measurement resulted in no protons. All 8 protons were therefore assigned to \(^{98}\text{Ag}\). For \(^{98}\text{Cd}\) Table 1 reports a 1 \(\sigma\) upper limit.

The apparent discrepancy of the new \(b_{\beta p}\)-value for \(^{96}\text{Ag}\) with literature may be due to the fact that different production reactions (\(^{58}\text{Ni} + ^{50}\text{Cr}\) in this experiment, \(^{40}\text{Ca} + ^{60}\text{Ni}\) in [11,12]) may result in a different population of the ground state and isomeric state of \(^{96}\text{Ag}\), both of which may undergo \(\beta\)-delayed proton decay.

In conclusion, the present experiment shows that \(\beta\)-delayed proton branching ratios of \(^{96}\text{Ag}\), \(^{98}\text{Ag}\) and \(^{98}\text{Cd}\) are small, and thus the abundances of \(^{96}\text{Ru}\) and \(^{98}\text{Ru}\) are directly related to the abundances of their progenitors in rp-process production of Ru.

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Figure 1. (a) $^{96}\text{Ag}$ $\beta$-delayed proton energy spectrum. (b) Time distribution of $\beta$-particles from $^{96}\text{Ag}$. The fit includes $^{96}\text{Ag}$, $^{96}\text{Pd}$ (daughter activity) and background. (c) Time distribution of $\beta$-activity from $^{98}\text{Ag}$. The fit includes $^{98}\text{Ag}$ and background.

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