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Mass Measurements of Proton-Rich Nuclides in the Vicinity of ^{92}Ru and ^{93}Rh for νp-process Models

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One of the long-standing questions in our understanding of the origin of the elements is the significant underproduction of light-p nuclei such as ^{92}Mo and ^{94}Mo by models of nucleosynthesis in various astrophysical scenarios. The recently proposed νp-process [1], which occurs due to the interaction of the neutrino wind with the proton-rich ejecta of core collapse supernova explosions, is a process which could resolve the underproduction of ^{92}Mo and ^{94}Mo. The final abundances of these two isotopes as well as any others synthesized by the νp-process depend directly on the values of the proton separation energies, S_p, along the νp-process reaction path; the S_p value of ^{93}Rh is thought to be especially critical to the relative production of ^{92}Mo and ^{94}Mo [2]. Due to the absence of mass measurements in this region $S_p(^{93}$Rh) and many of the other required S_p values were not well known. Recent mass measurements performed with the Canadian Penning Trap mass spectrometer have reduced uncertainties in the S_p values of many of the proton-rich nuclei between Mo and Pd including $S_p(^{93}$Rh) by factors of as much as 60. These measurements and the resulting implications for both the νp-process path and the ^{92}Mo/^{94}Mo abundance ratio will be discussed.

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1. Introduction

The production of light p-nuclei, the nuclei on the proton-rich side of the valley of stability between $74 < A < 100$ not made by either the s or r processes, has never been well understood. Of these, ^{92}Mo and ^{94}Mo are the most underproduced by current nucleosynthesis models. These two nuclides are made by the proton capture (p,γ) reactions of the rp process in type-I x-ray bursts, but due to the large gravitational potentials of neutron stars very little material is expected to be ejected into the interstellar medium [3, 4]. Core-collapse supernova explosions provide a mechanism for recycling nuclides produced into the interstellar medium, however a process consisting of only (p,γ), (γ,p) and β-decay reactions has no chance of producing ^{92}Mo and ^{94}Mo due to the fact that there is only a ~ 10 second window for this type of nucleosynthetic process to occur [5] and an earlier nuclide along the process path, ^{64}Ge, has an effective lifetime against these reactions of up to 30 seconds [6, 7]. Some p-nuclei can be produced through photodisintegration reactions on heavy seed-nuclei from the s or r processes but, while this reproduces the heavy p-nuclei abundances quite well, the light p-nuclei, especially ^{92}Mo and ^{94}Mo, remain underproduced [8].

The νp process, thought to occur in the inner ejecta of core-collapse supernovae, has been shown to produce some quantity of both ^{92}Mo and ^{94}Mo [1, 9]. The presence of the neutrino wind and the resulting $p(\bar{\nu}_e,e^+)n$ reactions in this proton-rich environment create a residual number of free neutrons. These free neutrons allow (n,p) and (n,γ) reactions to occur, providing a mechanism for this primarily (p,γ)-based process to bypass ^{64}Ge as its effective lifetime with respect to (n,p) at 2 GK is 0.25 sec. Due to these n-capture reactions, the νp-process path is particularly sensitive to proton separation energies S_p of the nuclides involved as they determine whether p-capture or n-capture reactions are the dominant path of destruction of a given nuclide. As this process occurs among proton-rich unstable nuclei there are large uncertainties associated with the required S_p values of many of these nuclides; prior to this work and other recent measurements [10] the masses of the nuclides along the νp-process path between Mo and Pd had not been known.

2. Measurements

The proton-rich nuclides presented here were produced in fusion-evaporation reactions using beams from the Argonne Tandem Linear Accelerator System (ATLAS) at Argonne National Laboratory. The reaction products are focused into one of two gas catchers, the second of which, a large gas-catcher able to withstand higher beam intensities was installed in the fall of 2006. The ions are thermalized in the volume of purified He gas and are extracted through a combination of gas flow, RF, and DC fields. The ions are injected into a Radio Frequency Quadrupole (RFQ) ion guide which further cools the ions and transports them to a small potential well where they are accumulated and periodically ejected towards subsequent traps. Another addition to the earlier CPT system, described in ref. [12], is a gas filled, cylindrical Penning trap located in a 2.5 T magnet and used to separate the ions of interest from other isobars. The ions are next transported to a gas-filled linear RFQ trap where multiple bunches of ions are accumulated and prepared for transfer to the precision Penning trap for measurement. The layout of the CPT system can be seen in figure 2.

Ion confinement in the CPT is provided by a combination of magnetic and electric fields. Radial confinement is provided by a 5.9 T homogeneous magnetic field whereas confinement along

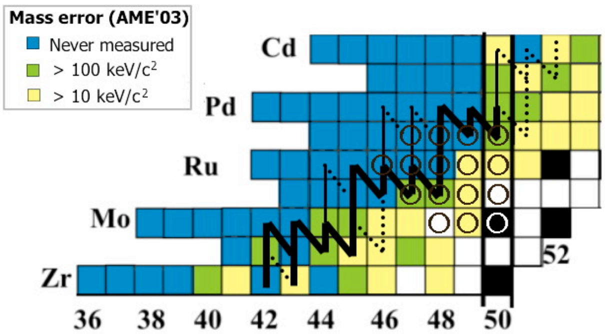

Figure 1: Shown are both the expected νp-process path [2, 9] as well as the current mass knowledge in this region. The legend for the mass error as given by the 2003 Atomic Mass Evaluation [11] is included in the figure. The primary nuclear flows are indicated by thick black lines, secondary flows by thin black lines and tertiary flows by dotted lines [2]. Mass measurements presented in this paper are indicated by open circles.

the axis of the magnetic field is provided by an axially-harmonic electric potential generated by voltages applied to the electrodes of the Penning trap. The ring electrode of the Penning trap is divided into four quadrants as the application of a quadrupole RF field applied to the ring electrode can resonantly excite the cyclotron motion of the ions in the trap when the applied frequency corresponds to the cyclotron frequency, ω_c, of the ions [13, 14]. As $\omega_c = qB/m$, given that the charge state of the ion (q), and the highly stable, homogeneous magnetic field in the Penning trap (B) are known, a precise measurement of the frequency at which this resonant excitation occurs allows for a precise determination of the ion mass m.

A time-of-flight (TOF) measurement technique [15] is used to determine ω_c. Orbital energy imparted to the ions by the applied excitation is converted to axial energy in the fringe field of the magnet, resulting in a shorter TOF to a microchannel plate detector above the trap. Consective bunches of ions are subjected to different applied frequencies and a value for ω_c is obtained by determining at which frequency the minimum in the TOF spectrum occurs. To acquire a mass value from the frequency measurement we also measure ω_c of a very well-known mass. For these measurements, hydrocarbons such as $^{12}C_7{}^1H_8{}^+$ and $^{12}C_7{}^1H_9{}^+$ were used as calibrants. Given that all ions measured were singly charged, the unknown mass is then determined from the ratio (R) of the cyclotron frequencies of the unknown and calibrant ions as follows: $m = R(m_{cal.} - m_e) + m_e$ note that the electron mass, m_e, must be added in order to obtain the mass of the neutral atom.

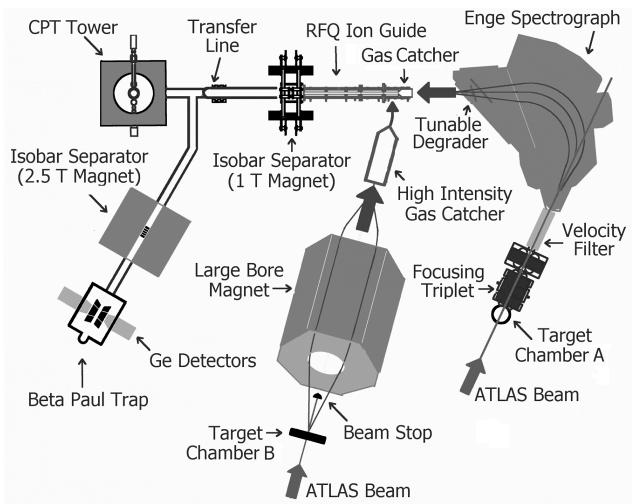

Figure 2: CPT system layout. Target chamber B, the large bore magnet and the high intensity gas cell were added in September of 2007. Prior runs used target chamber A and its associated beamline.

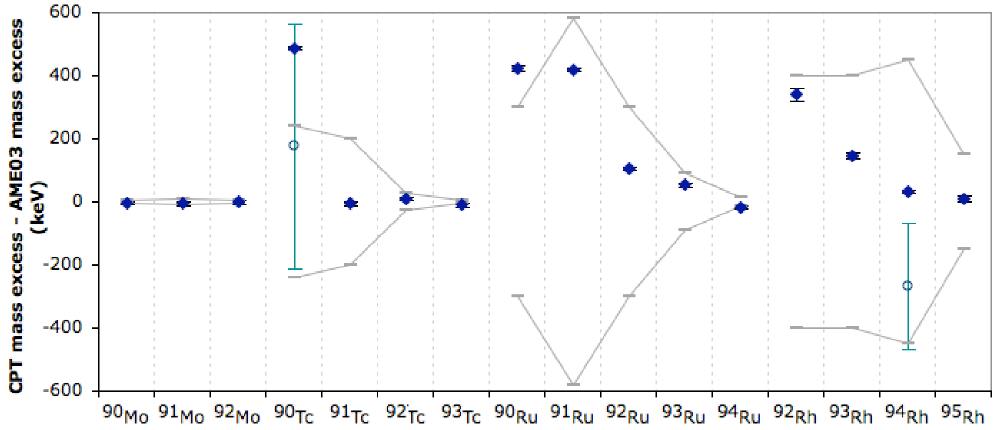

Figure 3: The differences between experimentally measured mass excesses and the values from the 2003 Atomic Mass Evaluation (AME03) [11]. Data points indicated by open circles are values in the cases where we may have measured a nuclide in its isomeric state and not its ground state. The connected data points show the limits of the AME03 uncertainty.

3. Results

To allow for better precision in the determination of the νp-process path the masses of 16 proton-rich, unstable nuclides around $A = 92$ have been measured with the CPT. The resulting mass excesses and S_p values have been compared to those from the 2003 Atomic Mass Evalutation [11] and are shown in figures 3 and 4 respectively. The Nuclear Data Sheets indicate that only ^{90}Tc [16], ^{91}Mo, ^{91}Tc, ^{91}Ru [17], ^{93}Tc, ^{93}Ru [18], ^{94}Rh [19] and ^{95}Rh [20] have isomers with lifetimes long enough to affect our results. A further examination of level scheme studies carried out with the same fusion evaporation reactions (a ^{40}Ca beam on a ^{58}Ni target) indicate that only ^{90}Tc and ^{94}Rh might have been measured in their isomeric state. The ground-state mass excesses which would result from a mass measurement of either of these isomeric states are indicated by open circles in Fig. 3. Points corresponding to the S_p values that would result if these measurements were of isomeric states are indicated by open circles in Fig 4. The isomeric energy levels and uncertainties are taken from the NUBASE evaluation [21].

It was determined by Fisker *et al.* [2] that the S_p value of ^{93}Rh is the most critical in determin-

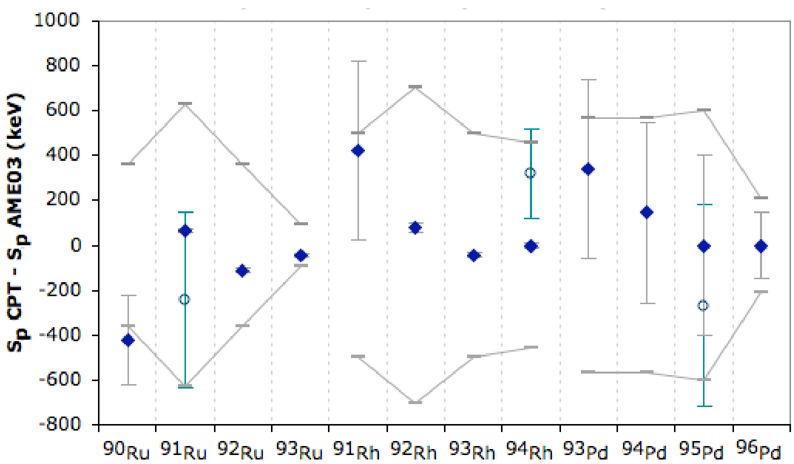

Figure 4: S_p values lying along the νp-process path that result from the above mass measurements. Data points indicated by open circles show S_p values which would result if the mass measurements of ^{90}Tc and ^{94}Rh are of isomeric states. The connected data points show the limits of the AME03 uncertainty.

ing the final νp-process ^{92}Mo/^{94}Mo abundance ratio and that if the νp process were to create the solar ^{92}Mo/^{94}Mo abundance ratio then $S_p(^{93}\text{Rh})$ would have to be 1.64 ± 0.1 MeV. As the masses of ^{92}Ru and ^{93}Rh had never been measured the current value of 2.05 ± 0.50 MeV is based on the extrapolated masses from the 2003 Atomic Mass Evaluation (AME03) [11]. The $S_p(^{93}\text{Rh})$ value determined from our mass measurements of ^{92}Ru and ^{93}Rh is 2.007 ± 0.009 MeV [22]. This agrees with the $S_p(^{93}\text{Rh})$ value from the AME03 [11] of 2.05 ± 0.50 MeV, but is well outside the range of the astrophysically predicted value of $S_p(^{93}\text{Rh}) = 1.64 \pm 0.1$ MeV given by Fisker *et al.* [2]. This discrepancy implies that though the νp process is capable of producing ^{92}Mo and ^{94}Mo, it does not produce them in the relative abundances needed to explain the observed solar ^{92}Mo/^{94}Mo abundance ratio. Unless there are conditions in the inner core-collapse ejecta of supernovae which are not yet well understood, or new revelations with regards to the nuclear data in this region, it seems that there must be yet another process or astrophysical site involved in the production of ^{92}Mo and ^{94}Mo.

References

[1] C. Fröhlich *et al.*, Phys. Rev. Lett. **96**, 142502 (2006).

[2] J. L. Fisker, R. D. Hoffman, and J. Pruet, arXiv:0711.1502v1 [astro-ph].

[3] H. Schatz *et al.*, Phys. Rep. **294**, 167 (1998).

[4] N. N. Weinberg, L. Bildsten, and H. Schatz, Astrophys. J. **639**, 1018 (2006).

[5] J. Pruet, S. E. Woosley, R. Buras, H.-T. Janka, and R. D. Hoffman, Astrophys. J. **623**, 325 (2005).

[6] J. A. Clark *et al.*, Phys. Rev. C **75**, 032801(R) (2007).

[7] P. Schury *et al.*, Phys. Rev. C **75**, 055801 (2007).

[8] M. Arnould and S. Goriely, Phys. Rep. **384**, 1 (2003).

[9] J. Pruet, R. D. Hoffman, S. E. Woosley, H.-T. Janka, and R. Buras, Astrophys. J. **644**, 1028 (2006).

[10] C. Weber *et al.*, Phys. Rev. C, (Accepted 08 Oct 2008), arXiv:0808.4065 [nucl-ex].

[11] G. Audi, A. H. Wapstra, and C. Thibault, Nucl. Phys. **A729**, 337 (2003).

[12] J. A. Clark *et al.*, Phys. Rev. Lett. **92**, 192501 (2004).

[13] G. Bollen, R. B. Moore, G. Savard, and H. Stolzenberg, J. Appl. Phys. **68**, 4355 (1990).

[14] M. König, G. Bollen, H.-J. Kluge, T. Otto, and J. Szerypo, Int. J. Mass Spectrom. Ion Processes **142**, 95 (1995).

[15] G. Gräff, H. Kalinowsky, and J. Traut, Z. Phys. **A297**, 35 (1980).

[16] E. Browne, Nucl. Data Sheets **82**, 379 (1997).

[17] C. M. Baglin, Nucl. Data Sheets **86**, 1 (1999).

[18] C. M. Baglin, Nucl. Data Sheets **80**, 1 (1997).

[19] D. Abriola and A. A. Sonzogni, Nucl. Data Sheets **107**, 2423 (2006).

[20] T. W. Burrows, Nucl. Data Sheets **68**, 635 (1993).

[21] G. Audi, O. Bersillon, J. Blachot, and A. H. Wapstra, Nuclear Physics **A729**, 3 (2003).

[22] J. Fallis *et al.*, Phys. Rev. C **78**, 022801(R) (2008).

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