Mass measurements along the rp- and r-process paths

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Abstract

The rp- and r-processes are responsible for the creation of a large fraction of the heavy nuclides. The paths followed by these processes depend critically on the masses of the nuclides involved. Recent measurements at the CPT mass spectrometer have allowed the successful determination of the mass of the critical waiting point nuclides along the rp-process. Improvements to the CPT injection system have also allowed measurements to be extended to neutron-rich isotopes close to the r-process path.

1 Introduction

There is direct evidence, everywhere around us, for the wide variety of elements present in our universe today. Big Bang nucleosynthesis, however, produced initially only the lightests elements, mostly hydrogen, helium and some lithium. Subsequent processing of this initial seed material was required to form the heavier nuclides. Quiescent burning in stars does not reach temperatures large enough to produce by fusion of charged particles elements heavier than the iron region. To obtain most of the heavier elements, more 'explosive' events such as novae, X-ray bursts, or supernovae are required.

A typical environment for such events is a binary star system consisting of a neutron star and a gas giant. As the neutron star accretes hydrogen and helium from its companion, the gravitational pressure on the material ignites the fusion process, creating elements in a similar fashion as the sun. If the stellar surface is sufficiently hot, 'breakout' reactions can occur [1]. At this time, the creation of heavier elements is possible through the rapid fusion of abundantly-available protons and nuclides formed from the initial fusion reactions. This rapid proton-capture process is referred to as the rp-process [2]. The masses of the nuclides involved are critical to the understanding of the rp-process. They determine the balance between the proton capture reactions, and the competing photodisintegration reactions in the intense gamma-ray flux present at these temperatures. When the latter dominates, the rp-process stalls until the subsequent β-decay of the nuclide. If this nuclide has a β-decay lifetime large enough to significantly slow down the overall process then it is referred to as a waiting-point nuclide. The masses of these waiting-point nuclides are critical in determining the final abundance of the elements and the light-curve profiles and energy generation of X-ray bursts. For temperatures of the order of 10^9 K which occur on the surface of these stellar environments, these reactions occur at or below the Coulomb barrier and the rates depend critically on the proton separation energy and hence the masses of the nuclides involved. Mass accuracy of typically a few tens of keV/c^2 is required along this path. This accuracy can be obtained for weakly produced isotopes by an ion trap mass spectrometer such as the Canadian Penning Trap (CPT) mass spectrometer at Argonne. It has been shown that the critical (not well determined experimentally) waiting point nuclides on the rp-process are ^{68}Se and ^{64}Ge and we have therefore concentrated our efforts on these candidates.

For the even heavier nuclides, charged particle capture becomes difficult because of the increased Coulomb barrier and processes involving a neutral particle such as neutron capture are required. The heaviest nuclides are therefore believed to be produced mainly by two processes: a slow neutron capture scenario, the so-called s-process which is well understood, and a more violent rapid neutron capture process, the r-process, which is thought to occur in type II supernova or neutron star merger scenarios. This latter process proceeds very far from stability and depends critically on the neutron separation energy, and hence the mass, of the involved nuclides. No Coulomb barrier is present for neutral particle capture so that the accuracy required is lower, say about 100 keV/c^2. These nuclides are however much more elusive and actually most cannot yet be synthesized in the laboratory. To better predict the r-process path it is therefore important to obtain reliable mass information around the probed neutron-rich region. Nuclides close to this region can be made accessible by spontaneous fission and we have performed a number of measurements in the barium and lanthanum region to assess the validity of current mass extrapolations in this region.

These measurements have been performed at the CPT mass spectrometer at Argonne and will be presented below after a brief description of the setup.

2 The CPT mass spectrometer

The CPT mass spectrometer [3] can be used to measure the masses of both stable and unstable nuclides, and its versatile injection system can accept and prepare ions from numerous sources depending on the best production mechanism for the isotopes of interest. In the on-line configuration, (see fig. 1) the unstable nuclides are created in nuclear reactions on a rotating target by heavy-ion beams from the ATLAS accelerator facility at Argonne National Laboratory. The recoil products from these fusion-evaporation reactions are collected by a magnetic triplet and focused at the entrance of a gas-filled magnetic spectrometer where they are separated. A velocity filter is located between the triplet and magnetic spectrometer to deflect the primary beam and stop it from entering the magnetic spectrometer. At the focal plane of the spectrometer, the recoil ions enter a gas catcher system [4] through a HAVAR window and are stopped in 150 Torr of purified helium gas. The thermalized ions are then delivered by a combination of gas flow and electric fields to a series of three radio-frequency quadrupole (RFQ) structures separated by small apertures. This system enables the ions to be guided towards a linear radio-frequency trap where the ions are accumulated as the helium gas is pumped away. Periodically, they are ejected in a bunch and transferred to the CPT.

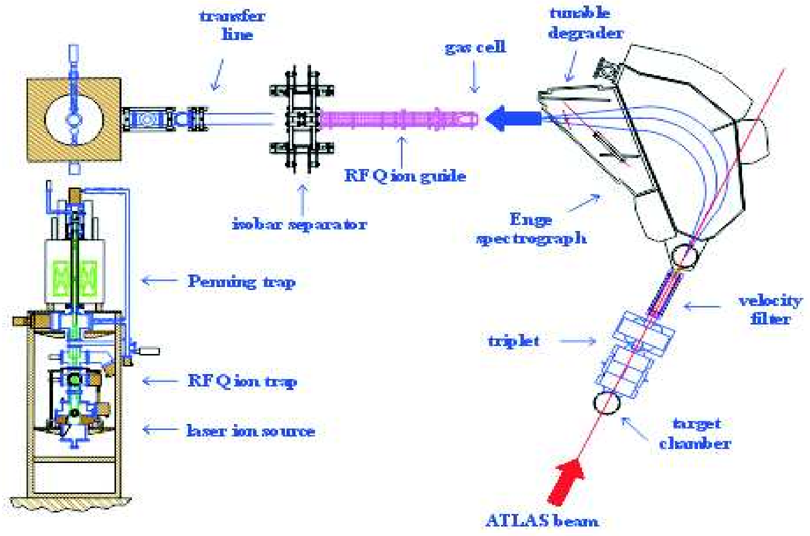

Fig. 1: Overview of the CPT mass spectrometer and its injection system

The ion bunches created in this way are first injected into a radio-frequency linear trap where they are cooled by collisions with helium buffer gas. The time-of-flight between the injection system and the linear trap is used to remove contamination from neighbouring masses. When a sufficient number of ions are accumulated in the linear trap, the ions are ejected and transferred to the high-precision Penning trap centered in a 5.9 Tesla superconducting magnet. The cooling step before injection in the measurement trap ensures that ions are always injected into the Penning trap with the same initial properties.

Ions of charge q and mass m subjected to a magnetic field B undergo cyclotron motion, the frequency of which is described by $\omega_c = \frac{qB}{m}$. Thus, singly-charged ions experiencing the same magnetic field undergo this cyclotron motion with a frequency that is only dependent on their mass. Masses of unknown nuclides can then be determined by comparing the experimentally-determined cyclotron frequency to that obtained from a reference mass.

Ions inside the Penning trap are confined radially by the magnetic field and are confined axially by a quadrupole electric field in which a positive potential is applied to the hyperbolic endcaps of the trap with respect to the intermediate ring electrode of hyperbolic cross-section. The motions of the ions in such a configuration can be described by three eigenfrequencies, ω_+, the reduced cyclotron motion, ω_-, the magnetron motion, and ω_z, the axial motion. The cyclotron frequency is related to the eigenfrequencies in the trap by ${\omega_c}^2 = {\omega_z}^2 + {\omega_-}^2 + {\omega_+}^2$ and $\omega_c = \omega_+ + \omega_-$. Determination of the cyclotron frequency is made possible by subjecting the ion motions to a quadrupole RF field at frequency $\omega_+ + \omega_-$ and detecting the resonance by a TOF technique as described in [5]. The reduced cyclotron motion can be determined in a similar fashion with in this case a dipole RF field at frequency ω_+ used to excite the ion motions. Selective removal of unwanted ions captured in the Penning trap is therefore possible by increasing their reduced cyclotron amplitude until they are lost.

There has been a continuous effort to improve the overall transfer efficiency and reduce the number of unwanted contaminants that reach the measurement Penning trap. The injection system for the CPT mass spectrometer has been recently modified by the addition of an other Penning trap located after the injection system. Ion bunches are purified in this trap using a resonant cooling technique that centers only ions of precisely the right mass [6]. This get rids of most molecular contamination present at the same mass as the isotope of interest and provides better conditions for measurements in the final trap.

For the investigation of isotopes along the astrophysical rp-process, the nuclides were produced and studied on-line. All steps described above were used. In the case of neutron-rich isotopes, the magnetic spectrometer was bypassed and a ^{252}Cf source was installed in front of the gas catcher HAVAR window. ^{252}Cf has a 3% spontaneous fission decay branch and the fission products have enough energy to go through the window and stop in the gas. The efficiency of the CPT and its injection system is large enough to allow a measurement of even weak channels of the 3% spontaneous fission yield and over 20 neutron-rich isotopes were measured this way over the last year.

3 Results

Mass measurements of two important waiting-point nuclides, ^{64}Ge and ^{68}Se, and neighbouring isotopes have been completed recently at the CPT mass spectrometer. A total of 16 days of 'beamtime' from the ATLAS facility was required. This time was divided into four experimental 'runs' in the months of August, September, and October of 2002 and January, 2003. In the first two experiments, a 220 MeV beam of ^{58}Ni struck 1 mg/cm^2 carbon targets to create the desired nuclide ^{68}Se. The masses of other nuclides created in this reaction, notably ^{68}Ge and ^{68}As, were also measured. The last two experiments were used to measure the mass of ^{64}Ge, the resulting TOF spectrum is shown in Figure 2. In this case, a 200 MeV ^{54}Fe beam was incident upon the carbon targets. The analysis of the ^{68}Se data is almost completed yielding a preliminary value of m = 67941798 +/- 35 u and a preliminary value for the mass of ^{64}Ge is 63941653 +/- 34 u.

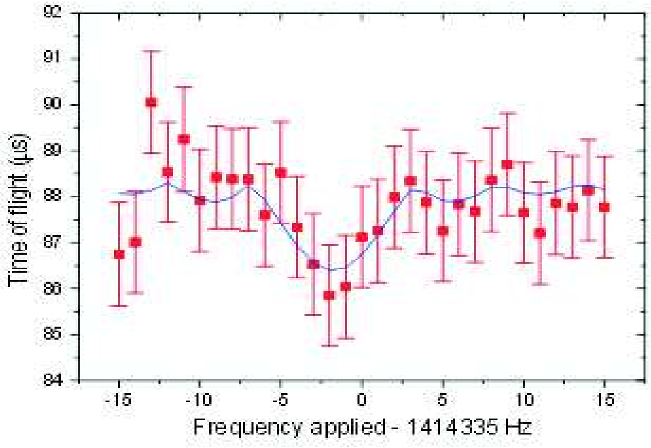

Fig. 2: Time-of-flight resonance for ^{64}Ge.

On the opposite side of stability, the masses of 20 neutron-rich nuclides were measured using a ^{252}Cf source to produce the isotopes of interest. The very preliminary results of these measurements are shown in figure 3. We find excellent agreement with the Audi-Wapstra tabulations/extrapolations [7] for the cases of the lighter barium isotopes which were previously measured at ISOLTRAP but find significant disagreement for the more exotic cases which were either measured by less reliable methods or not previously measured. The disagreements are not random in nature but clearly steer in one direction. We have performed the required systematic checks and conclude that possible systematic shifts in our data are at least an order of magnitude smaller than the discrepancy observed with the tabulated data. A more detailed look at the existing litterature will be performed to try an isolate the source of the erroneous data (in the standard approach of beta-endpoint measurements, a mass far from stability is linked to many other masses and the culprit can be hard to identify).

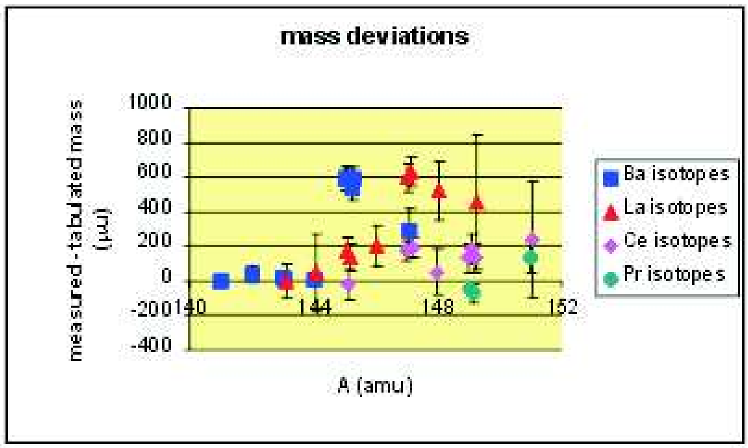

Fig. 3: Measured masses for neutron-rich nuclides compared to tabulated/extrapolated values

4 Summary

Masses of nuclides are critical to the understanding of the astrophysical rp- and r-processes. Particularly important are the masses of the waiting-point nuclides. The mass accuracy required for both processes is easily obtained with the CPT mass spectrometer, and its novel injection system provides a means to efficiently transfer the desired nuclides from the production target to the Penning trap. Recent on-line experiments have been successful in obtaining the masses of two critical waiting-point nuclides, ^{68}Se and ^{64}Ge. The large total efficiency of the system also allows one to measured isotopes produced in spontaneous fission of ^{252}Cf and preliminary results of measurements on 20 neutron-rich isotopes are reported here. They show agreement with previous precision measurements close to stability but significant discrepancy when going further from stability. The fact that calculations of the r-process path are based on extrapolations even further from stability clearly indicates the need for more data in this region. These measurements on neutron-rich isotopes will continue at the CPT as will measurements along the rp-process that will now concentrate on the termination region.

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