B. PHYSICS OF TRAPPED IONS

The trapping of atoms and ions and the measurements on nuclei in traps continues to grow in importance in our group. The Canadian Penning Trap has now become a rich source of new measurements, both for astrophysics and for weak interaction physics. The Advanced Penning Trap is under construction, with a goal to studying weak interactions in calendar year 2004. The laser atom trap is now inline and made its first measurements on radioactive ions. Finally, our studies of the dynamics of trapped ions continue. These lines of research can only grow as they are key techniques for future studies, both at ATLAS and at facilities like RIA, the Rare Isotope Accelerator,

b.1. Continuing the Mass Measurements of Nuclides along the rp-Process Path using the Canadian Penning Trap Mass Spectrometer

(J. P. Greene, G. Savard, N. D. Scielzo, D. Seweryniak, I. Tanihata, W. Trimble, B. J. Zabransky, Z. Zhou, A. F. Levand, B. F. Lundgren, J. A. Clark,* A. A. Hecht,† J. C. Wang,* B. Blank,‡ F. Buchinger,§ J. E. Crawford,§ S. Gulick,§ J. K. P. Lee,§ G. D. Sprouse,|| K. S. Sharma,¶ and Y. Wang¶)

An x-ray burst is believed to result from a thermonuclear runaway occurring on the surface of an accreting neutron star. Network calculations used to describe the timescale of the event, the energy released, and the resulting nuclide abundances are strongly dependent upon the masses of the nuclides involved. Particularly important are the masses of "waiting-point" nuclides that can hinder the rapid proton capture process (rp-process) until their subsequent β-decay.

The Canadian Penning Trap (CPT) mass spectrometer performed many mass measurements along the rp-process path as shown in Fig. I-13. The mass measurements of two potentially critical waiting-point nuclides, ^{68}Se and ^{64}Ge, were first reported last year. The analysis of ^{68}Se is now complete and it was found the effective lifetime of ^{68}Se, or equivalently the delay in the rp-process due to ^{68}Se, is between 29 and 34 seconds, almost equal to the half-life of ^{68}Se.[1] With its 64-second half-life, ^{64}Ge could significantly delay the rp-process as well. However, our measured mass for this nuclide suggests that the delay is at most a few seconds.

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

[2] G. Audi *et al.*, Nucl. Phys. **A729**, 337 (2003).

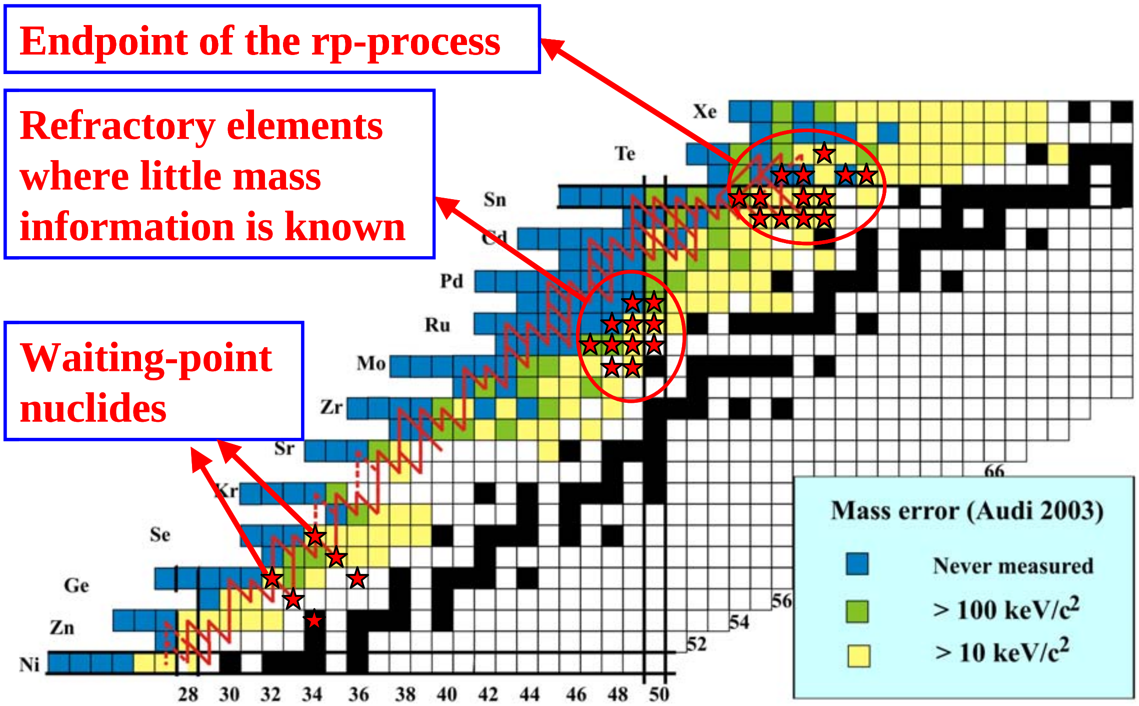

Fig. I-13. A section of the chart of the nuclides with the rp-process path indicated by red lines. The uncertainties in the masses of the proton-rich nuclides given by the 2003 Atomic Mass Evaluation[2] are color coded according to the legend. Each star represents a mass measurement made by the CPT.

Continuing along the rp-process path, especially in the vicinity of the proton-rich Ru, Rh, and Pd nuclides, little mass information is known. In fact, the masses of most of these isotopes have never been measured before. The differences between our results and the recent 2003 Atomic Mass Evaluation[2] (AME) for 10 nuclides in this region are shown in Fig. I-14. The pink lines indicate the precision of the masses as quoted in the AME and the data points represent our measurements with statistical uncertainty. Our measurements greatly improve the precision and are in agreement with the AME. For two nuclides, ^{90}Tc and ^{91}Tc, the resolution used for the measurements was insufficient to resolve the ground state from the known long-lived low-lying isomeric state. We plan to repeat the measurements with sufficient resolution to clearly resolve these two states. Future experiments with the CPT will extend the mass measurements of refractory elements closer to the rp-process path where no data currently exists.

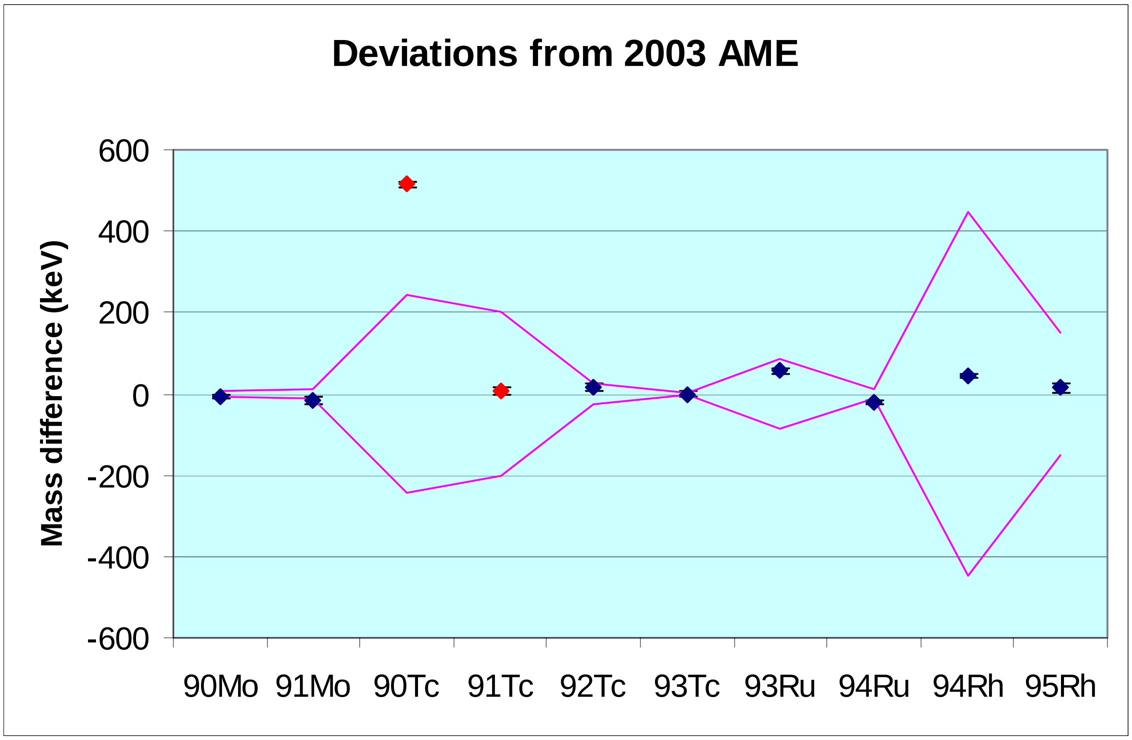

Fig. I-14 Plotted are the differences between our results and those of the latest 2003 Atomic Mass Evaluation (AME). The data points represent our measurements with statistical uncertainty and the pink lines represent the uncertainties from the AME. The two data points indicated in red may have a mixture of both ground and isomeric states.

The endpoint of the rp-process path was calculated to reach the Sb, Sn, and Te region and occurs during the cooling phase of the x-ray burst. The Te isotopes are known ground state alpha emitters, and as such, establish a cycle between the proton captures into the Te isotopes and the alpha emission of the Te isotopes themselves. Our mass measurements of 13 nuclides in this region will be used to verify this alpha-cycling process that is expected to be responsible for the rp-process termination.

Precision mass measurements in a Penning trap require a pure sample of ions in the trap. Any contaminants may overwhelm the weakly produced isotopes of interest and affect the measured cyclotron frequency. All of the measurements of the aforementioned nuclides were only possible because of the 1 T isotope separator installed in July of 2002. Future measurements will require higher mass resolution in the isotope separator to resolve ground and long-lived isomeric states, and will therefore benefit from the installation of the new superconducting 7 T isobar separator to be installed in the fall of 2004.

b.2. Mass Measurements of Light Fission Fragments of ^{252}Cf with the CPT

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The Canadian Penning Trap (CPT) was used to perform precise mass measurements of short-lived nuclides produced either on-line using the ATLAS facility or off-line from fission fragments of ^{252}Cf. After the recent successful measurements of 26 heavy fragments of ^{252}Cf, we initiated a measurement program for the light fragments. To date, 9 neutron-rich Ru, Mo, Tc and Rh isotopes were measured with accuracy on the order of a few tens of keV. When compared with the Atomic Mass Evaluation (2003), the mass precision of ^{108}Ru, ^{107}Mo and ^{107}Tc obtained with the CPT are improvements by a factor of 5, 3, and 3 respectively.

When compared to the heavy fragments, there are some additional challenges in measuring the light fragments. First, the stopping efficiency of the light fragments in the gas cell is about 3 times lower. The average activity yield for the strong fission branches (>1%) is only about 100 counts/min, while in the heavy part it is about 300. This means a longer data-acquisition time is required to obtain the same statistical precision. Second, the contaminants are closer in mass to the activity, which require a higher mass resolving power of the isobar separator and finer isobaric cleaning in the CPT. Most of the measured heavy fragments were doubly charged, with m/q around 70; the light fragments extracted from the gas cell are singly charged ions, which have m/q around 110. Since the mass resolving power of the Penning trap is inversely proportional to the mass to charge ratio, it is relatively more difficult to measure the light fragments with the same precision as the heavy fragments.

Several improvements to the performance of the CPT system were made to counteract these effects. To improve the light fragment stopping efficiency in the gas cell, the 4.2-mg/cm^2 Au degrader was replaced by a 5.8-mg/cm^2 thick one. The power supply driving the isobar separator magnet was replaced by one with better regulation which now provides a more stable magnetic field. A booster pump was installed in front of the isobar separator to increase the cooling water pressure for that magnet to 250 PSI and hence provide much improved cooling to that compact high-power magnet. As a result, the magnet can now operate at the nominal 1 Tesla field, where it delivers a more homogeneous field, without the ohmic heating inducing excessive outgassing in the vacuum chamber. With these measures, the mass resolving power of the isobar separator was improved from 500 to 1000 at mass 100, and 800 to 3000 at mass 20. A programmable logic controller (PLC) unit is now in use to control the vacuum system, ands provides much better protection for the gas cell window. And finally, a 500 μCi ^{252}Cf fission source is in preparation to replace the present source, which has a strength of about 40 μCi. These improvements will allow us to extend the mass measurements to a wider range of light fragments in the near future.

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b.3. Ordering and Temperature in Radiofrequency Ion Traps (J. P. Schiffer)

Some time ago simulations were carried out to better understand the behavior of plasmas confined in radiofrequency traps.[1] In that study it was found that if a plasma was cooled to an ordered state, the kinetic energy in the rf motion, which can be 5-6 orders of magnitude more than the energy corresponding to the temperature, converted into random thermal energy only very slowly – in less than ~ 10^{12} rf periods for a sufficiently cold system.

However, when the ion cloud in the simulation was warmer, this conversion (the coupling of the periodic motion from the confining field into random motion) occurred faster, and this 'rf heating' increased quadratically with temperature. The reason for such a T^2 dependence is not understood.

Radiofrequency traps can work with a variety of rf wave forms. In the work of Ref. 1 it was assumed to be sinusoidal. In order to explore whether the behavior was similar for other wave forms, a simulation is carried out where the rf containing field is a square wave rather sin(ωt). A cold ordered state was achieved in this system and the self-heating (the above coupling of the periodic motion into thermal energy) appears to be much smaller. Above a certain temperature however, there is a rapid onset, and the coupling appears to rise in a more complicated fashion than a T^2 dependence as is shown in Fig. I-15. The simulations require considerably computing time and therefore proceed slowly, but additional work is planned.

[1]J. P. Schiffer *et al*., Proc. Natl. Acad. Sci. **10**, 1073 (2000).

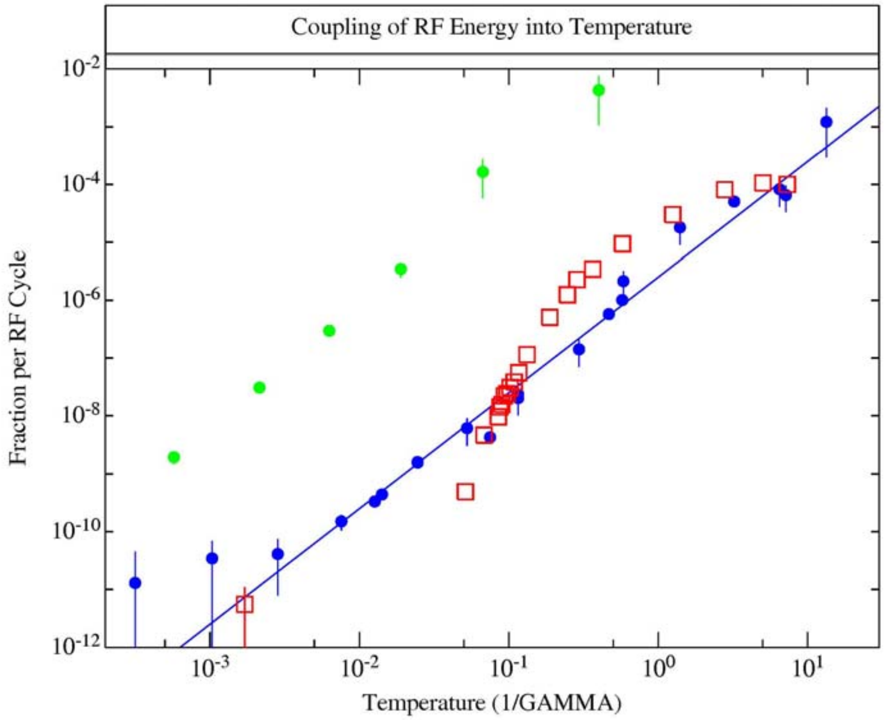

Fig. I-15. This plot shows the fraction of the energy in the periodic rf motion that is mixed into random (thermal) energy per rf cycle, as a function of temperature. The simulations that had been obtained for sinusoidal rf confinement of 1000 ions and published in Ref. 1 are shown as blue and green circular dots, for two different values of the ratio of the rf frequency to the plasma frequency. The blue line represents a quadratic temperature dependence normalized to the blue data set. The red squares show the preliminary results for the same quantity from a simulation where the confining rf field is a square wave – the statistical uncertainties from the simulations have not yet been fully estimated.