PROCEEDINGS OF SCIENCE

Time-of-flight Mass Measurement of Neutron-rich Nuclei

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Astrophysical calculations often require accurate masses of exotic nuclei. In many cases nuclear masses are critical in obtaining a reliable understanding of observational data. The time-of-flight method provides a way to measure the masses of nuclei far from the valley of beta stability with sufficient precision to address questions of stellar nucleosynthesis and nuclear structure in general. Recently such a time-of-flight experiment has been performed at the National Superconducting Cyclotron Laboratory (NSCL) where significant progress has been made on the neutron-rich side of stability in the argon to iron region. We expect to make advances in understanding nuclear structure in the region and nucleosynthesis occurring in accreted neutron star crusts.

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1. Time-of-Flight Method

The time-of-flight method exploits our knowledge of the equation of motion of a charged particle through a magnetic system. Equating the Lorentz force with zero-electric field with the centripetal force, it is apparent that the rest mass (m_0) of a particle with charge q is proportional to the magnetic rigidity ($B\rho$) and time-of-flight (TOF) along a flight path of length L_{path},

$$m_0 = \frac{TOF}{L_{path}} \frac{q(B\rho)}{\gamma}. \tag{1.1}$$

Thus, a precise measurement of time-of-flight and magnetic rigidity yields a precise mass measurement. In practice, due to insufficient knowledge of systematic effects, the TOFs of several nuclei, including those with known mass, are measured simultaneously to result in a calibrated TOF-m_0 relationship [1, 2, 3].

2. Experimental Set-up

Recently a time-of-flight mass measurement (similar to the one described in [3, 4]) has been performed at the National Superconducting Cyclotron Laboratory with the use of the S800 spectrograph, as seen in Figure 1. Neutron-rich nuclei in the silicon to zinc region were produced by fragmenting a ^{82}Se beam on a beryllium target of one of two thicknesses. The thin target produced more stable nuclei required for calibration masses, where the thick target produced the more exotic nuclei of interest. Time-of-flight was measured between the extended focal plane of the A1900 fragment separator [5] and the S800 focal plane. Magnetic rigidity was measured at a dispersive focus at the entrance of the S800 spectrograph [6]. Magnetic elements in the beam-line were tuned such that the time-of-flight of a nucleus depended mostly on its mass to charge ratio (m_0/q), with a slight momentum dependence remaining. We were able to quantify the momentum dependence of the time-of-flight with our magnetic rigidity measurement.

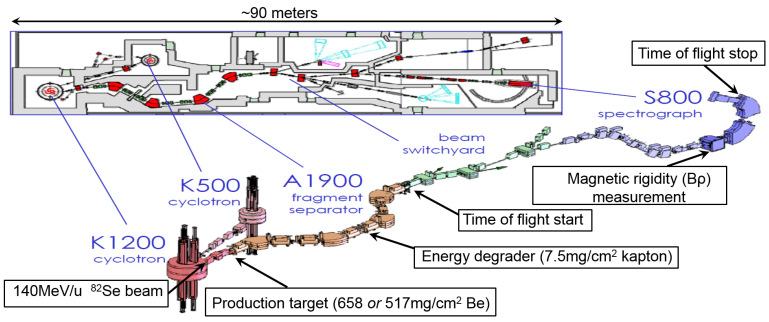

Figure 1: Experimental set-up for TOF mass measurement at the NSCL.

3. Detectors

BC418 fast timing scintillators from Saint Gobain Crystals [7] coupled to Hamamatsu [8] R4998 photomultiplier tubes provided timing signals for the time-of-flight measurement. Intrinsic

timing resolution of this combination was ∼30 picoseconds. The magnetic rigidity of individual ions was determined by measuring their position at the dispersive focus prior to the S800 spectrograph. For this purpose a 1500 Å gold foil backed by 70 μg/cm^2 mylar was placed in the path of the beam, causing electrons to be emitted from the foil by passing ions, as seen in Figure 2. The electrons were guided towards the surface of a microchannel plate detector (MCP) equipped with a resistive back-plane from Quantar Technology [9] via magnetic and electric fields. This technique had the result that the electron-impact position on the microchannel plate detector would directly correspond to the ion-impact position on the foil [10]. The microchannel plate detector amplified electrons which reached its surface, resulting in an avalanche of electrons that reached its back-plane. Electrons drifted to the four corners of the back-plane, allowing for a position determination with a resolution of ∼0.45 mm. The measured *TOF* vs dispersive MCP position was ∼40 ps/mm, which corresponds to ∼120 ns/T.m. After performing the rigidity correction, the timing resolution was ∼75 ps.

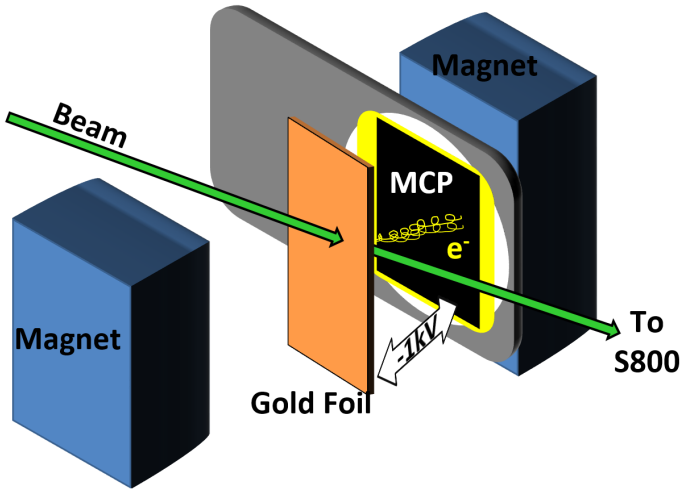

Figure 2: Position sensitive microchannel plate detection system at the dispersive focus.

4. Analysis

The analysis procedure consists of correcting isotopes' timing distributions for their momentum-dependence, as seen in Figure 3, obtaining a relationship between momentum-corrected time-of-flight and mass for nuclei of known mass, and ultimately using this relationship to obtain masses for all measured nuclei.

The time-of-flight versus microchannel plate dispersive position (*TOF*vs*MCPx*) trend was fit for each isotope of sufficient statistics. In a second step another fit was performed to arrive at a global equation for parameters of the *TOF*vs*MCPx* trend, which was used for the rigidity correction of all isotopes in order to minimize the impact of systematic effects. This drastically narrowed the time-of-flight distribution of each isotope, as seen in Figure 3.

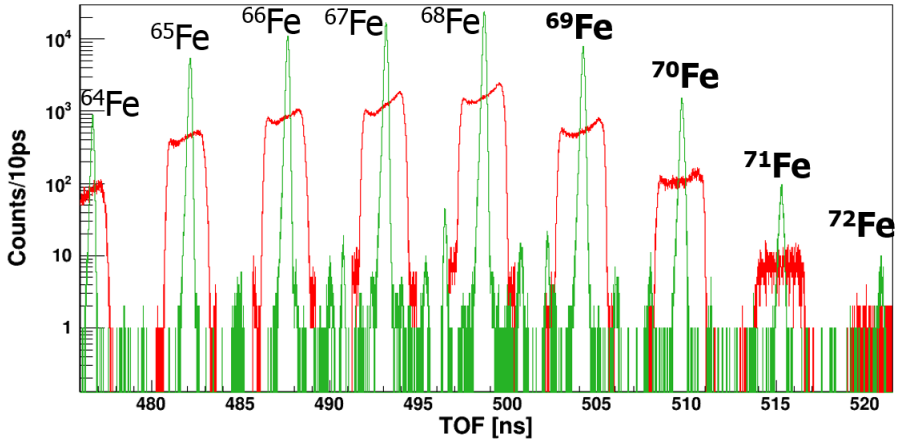

Figure 3: Time-of-flight distributions for the iron isotopes observed in this experiment before (red) and after (green) the momentum correction. Isotopes with unknown literature masses [11] have bold labels.

The relationship between mass and time-of-flight was calibrated via a fit to measured nuclei with a well-known literature mass, e.g.:

$$m/q = f(TOF,Z) = a_0 + a_1 * TOF + a_2 * TOF^2 + a_3 * Z + a_4 * Z^2 + a_5 * TOF * Z + a_6 * Z^4. \quad (4.1)$$

A systematic uncertainty was added in to the statistical uncertainty of each nucleus involved in the mass fit until $\chi^2_{red} \sim 1$ was obtained;

$$\chi^2 = \Sigma_{calibrants} \frac{((m/q)_{literature} - f(TOF,Z))^2}{(\sigma_{literature})_i^2 + (\sigma_{statistical})_i^2 + (\sigma_{systematic})^2}, \quad (4.2)$$

$$where (\sigma_{statistical})_i^2 = \left(\frac{\partial f(TOF,Z)}{\partial TOF}\right)^2 * \sigma_i^2(TOF). \quad (4.3)$$

5. Preliminary Results

Several neutron-rich nuclei with unknown masses have been observed in our time-of-flight experiment, as seen in Figure 4. The time-of-flight mass measurement analysis is currently in its final stages. A precise mass-fit has been obtained for nuclei in the argon-iron range, where reference mass nuclei are reproduced within ~400 keV with the absence of systematic trends, as seen in Figure 5. In addition, we found no systematic dependencies on the production target thickness, rigidity correction method, PID-cut, timing signals, and mass-fit function chosen. Based on these results we conclude that our mass fit can be reliably extrapolated to unknown masses.

Acknowledgments

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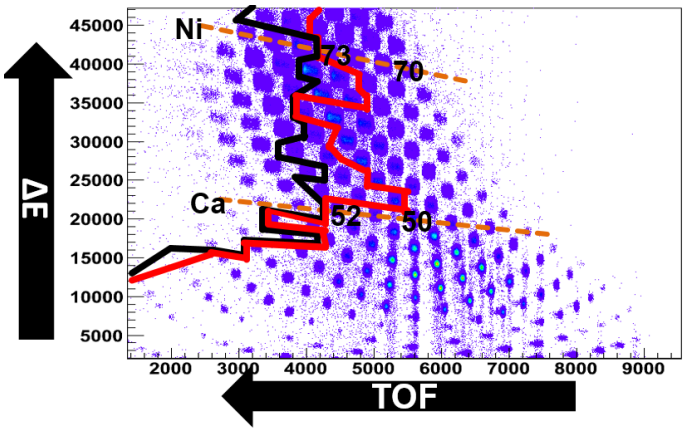

Figure 4: Particle identification (PID) plot for the recent time-of-flight mass measurement performed at the NSCL. Nuclei left of the black line have an unknown experimental mass as of the 2012 Atomic Mass Evaluation [11]. Nuclei right of the red line have a mass experimentally known to better than 200 keV as of the 2012 Atomic Mass Evaluation.

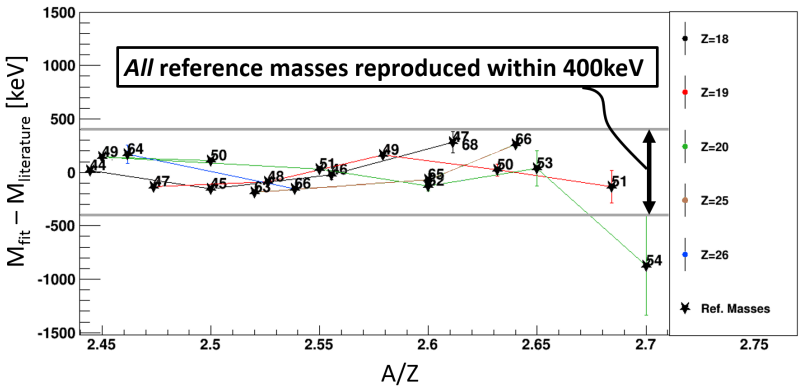

Figure 5: Fit residuals between reference nuclei and the $m_0(TOF)$ relationship. Reference nuclei, nuclei with literature mass uncertainties less than 100 keV [11] and no known isomers with half-lives longer than 100 ns [12], were all fit within 400 keV (within their 1σ uncertainties) with an absence of any systematic trends.

References

[1] Z. Meisel and S. George, *Time-of-flight mass spectrometry of very exotic systems*, *IJMS* **349-350**, 145 (2013).

[2] M. Matoš et al. *Time-of-flight mass measurements of exotic nuclei*, *NIMA* **696**, 171 (2012).

[3] A. Estradé *Time-of-flight Mass Measurements of Neutron Rich Isotopes at the NSCL*, *Michigan State University PhD Thesis*, (2010).

[4] A. Estradé et al. *Time-of-Flight Mass Measurements for Nuclear Processes in Neutron Star Crusts*, *PRL* **107**, 172503 (2011).

[5] D.J Morrissey et al. *Commissioning the A1900 projectile fragment separator*, *NIMB* **204**, 90 (2003).

[6] D. Bazin et al. *The S800 spectrograph*, *NIMB* **204**, 629 (2003).

[7] http://www.crystals.saint-gobain.com/, *Accessed 10 September 2014*.

[8] http://www.hamamatsu.com/, *Accessed 10 September 2014*.

[9] http://www.quantar.com/, *Accessed 10 September 2014*.

[10] D. Shapira, T.A. Lewis, & L.D. Hullett, *A fast and accurate position-sensitive timing detector based on secondary electron emission*, *Nucl.Inst.Meth. A* **454**, 409 (2000).

[11] G. Audi et al. *The Ame2012 atomic mass evaluation*, *Ch.Phys.C* **36**, 12, 002 (2012).

[12] G. Audi et al. *The Nubase2012 evaluation of nuclear properties*, *Ch.Phys.C* **36**, 12, 1157 (2012).