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Project Title: Time-of-flight experiments for nuclear structure and astrophysics

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Abstract: Neutron-rich isotopes are atomic nuclei with a large neutron excess compared to their stable counter parts. Their study provides essential information to understand the properties of the nuclear interaction, and to model nuclear processes in extreme astrophysical environments where neutron-rich isotopes drive the chains of nuclear reactions. Experimentally, these unstable isotopes are difficult to study because of their short half-lives and low production yields at particle accelerator laboratories. The TOF-Bρ technique is a mass measurement technique specialized for experiments with fast beams of short-lived radioactive isotopes. In this project we used the technique for two experiments performed at the National Superconducting Cyclotron Laboratory to measure new masses of isotopes in the region of ^{112}Mo and ^{46}S. The experiments at the NSCL were complemented by the development of new timing radiation detectors and experimental techniques to improve the performance and reach of mass measurements on neutron-rich isotopes.

Overview

The main goal of the project was to measure masses of neutron-rich nuclei using the time-of-flight (TOF) Bρ technique (TOF-Bρ) in experiments at the National Superconducting Cyclotron Laboratory (NSCL) [1]. With this technique the nuclear mass can be determined by measuring the time it takes the atomic nuclei to travel between two locations in a magnetic beamline (their TOF) and simultaneously measuring their momentum per unit of electric charge (Bρ). These quantities are related to the nuclear mass by the equation of motion of the ions in the beamline of the accelerator laboratory. The TOF-Bρ technique is well adapted to fast ion beams produced by fragmentation reactions, as those at the NSCL, that can efficiently reach very unstable isotopes. The typical mass resolution obtained with the technique is of the order of 100 keV/c^2. As a complement to these experiments, we developed plans for measurements with Penning trap spectrometers that will provide additional high-resolution nuclear mass data.

In support of the mass measurements, a second goal of the project was an upgrade of the radiation detectors used in the TOF-Bρ experiments to measure the time-of-flight of the beam ions. Improving the TOF resolution had been identified as a key step to improve the uncertainty of the mass measurement technique, and it would also allow better identification of the beam particles in experiments with heavy isotopes. The TOF detectors used in previous experiments had a resolution of 30 ps, and the objective of the development program culminated within this project was to reduce it to 10 ps or better. The detector development work was performed in facilities at Central Michigan University (CMU).

Mass measurement experiments

The TOF-$B\rho$ mass measurement experiments performed in this project used an experimental setup at the S800 spectrometer beamline of the NSCL [1], shown in Figure 1. A beam of neutron-rich isotopes was produced by fragmentation reactions in a beryllium production target. The beam ions were then transported through the S800 beamline where the TOF was measured by timing detectors placed approximately 60 meters apart. The $B\rho$ was measured by tracking the beam position with a micro-channel plate detector located in the target position of the S800 beamline, where the beam ions were dispersed in momentum (the S800 is operated in dispersion matched mode). The identification of the ions in the beam was completed by measuring their energy loss and total kinetic energy with the detectors at the final focal plane of the S800. The nuclear mass is obtained by calibrating the experimental setup with the TOF and tracking information measured for the ions in the beam that have previously well-known masses (usually those not as neutron-rich as the target isotopes).

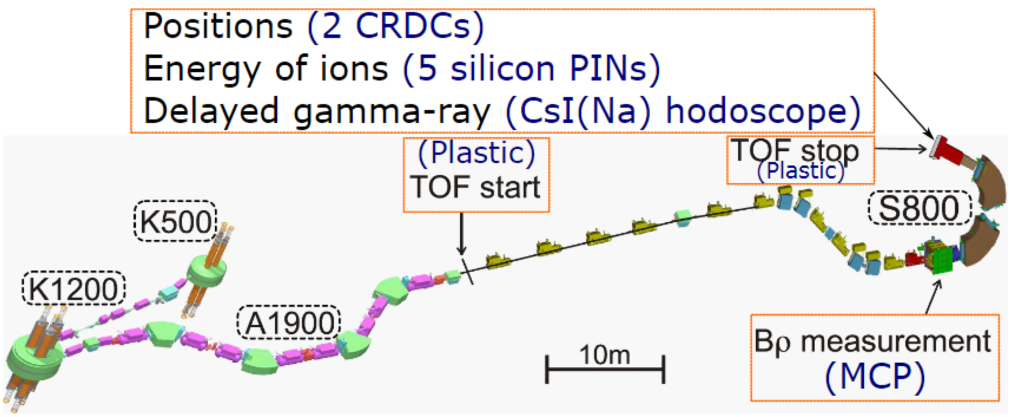

Figure 1: Experimental setup for TOF-$B\rho$ mass measurements at the NSCL [1]. A beam of neutron-rich isotopes is produced by reactions at the start of the A1900 beamline. The TOF is measured from the *TOF start* position at the end of the A1900 to the *TOF stop* position at the focal plane of the S800 spectrometer. The magnetic rigidity ($B\rho$) is measured by a tracking detector in the S800 dispersive plane location.

Experiment E12022: *Verification of shape transition for neutron-rich nuclei for 65<N<75 and mass measurements in the same region.* This experiment was performed at the NSCL in 2018 with the goal of measuring the nuclear mass of neutron rich isotopes near ^{112}Mo (atomic number Z=42), in the region of neutron number N=70. Theoretical models show significant differences in the prediction of nuclear masses for these isotopes. The nuclear mass data is important to understand the astrophysics processes that synthesize heavy chemical elements in explosive stellar environments, like core-collapse supernovae.

During this project we completed the data analysis of the experiment, resulting in a first measurement of the nuclear masses of ^{104}Y and ^{112}Mo, and a new measurement for ^{106}Zr and ^{115}Tc (a manuscript is in preparation). Another important accomplishment of the experiment was being able to perform a measurement with such heavy beams (previous measurements where in nickel and lighter isotopes). This was possible due to new detectors added to the experimental setup (a stack of silicon detectors for total kinetic energy measurement), and analysis techniques developed during this project. These included using the *Gaussian Mixture Model* technique to evaluate the probability for each beam ion to be in a given ionization state, and adjust accordingly their use in the mass calibration and evaluation. The measurement used our newly developed timing detectors that improved the mass resolution to $\frac{\delta m}{m}=1\times10^{-4}$ (sigma).

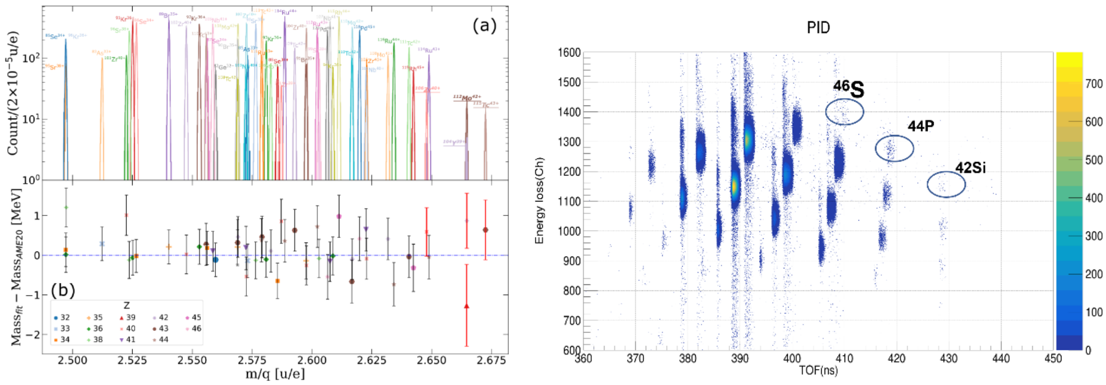

Figure 2: Left) The top panel shows the time-of-flight spectra for the isotopes in the beam in NSCL experiment E12022, in the region of ^{112}Mo. The bottom panel shows the residuals of the mass calibration fit, with the newly measured masses showed in red. Right) Particle identification spectra (TOF vs energy loss) for NSCL experiment E18009, with the isotopes of interest highlighted by the ellipses.

The uncertainty of the measured masses, of the order of 700 keV/c^2, was dominated by the low statistics collected for the isotopes of interest (Figure 2). The uncertainty is too large to place strong constraints on the theoretical models that predict the evolution of nuclear masses in this region of isotopes. However, the intensities of isotope beams are expected to be significantly higher at the Facility for Rare Isotope Beams (FRIB), which replaced the NSCL with a new linear accelerator, so experiment E12022 was an important first step to extend our TOF-Bρ mass measurements to isotopes with atomic number larger than Z=30.

<u>Experiment E18009: *Evolution of the N=28 shell closure around sulfur*.</u> The goal of this experiment was to measure for the first time the mass of ^{46}S, ^{44}P, and ^{42}Si. These nuclear masses are important to understand the nuclear structure of isotopes with N=28 neutrons, which correspond to a *magic number* of neutrons in a closed shell configuration for the occupation of neutron energy levels. The nuclear masses, in particular that of ^{42}Si, are also important for models of nuclear reactions in the crust of neutron stars in binary star systems. Such neutron stars can accrete material from their companion star. As the accreted material sinks towards the interior of the star, nuclear reactions can become a significant heat source that must be precisely quantified to interpret some of the astronomical data from these binary star systems.

The experiment was prepared and performed in 2020 at the NSCL. The experiment ran successfully, with collected statistics for the isotopes of interest matching the predicted beam intensities (Figure 2). The data analysis is ongoing as the main project for a PhD student supported by the award.

<u>FRIB Experiments.</u> During the project we worked on the development of new ideas for TOF-Bρ mass measurement experiments at the Facility for Rare Isotope Beams (FRIB). This newly commissioned facility significantly upgrades the beam intensities and experimental opportunities available at the NSCL laboratory that it replaced. Two proposals for TOF-Bρ measurements with

the S800 spectrometer were submitted to the first Program Advisory Committee (PAC) meeting in 2021 (A. Estrade was spokesperson for a measurement in the ^{40}Mg region). Neither was accepted due to the high competition for beamtime in the first FRIB PAC, but the development of revised proposals continued in the last year of the project.

Experiment I289: *Mass measurement of neutron-rich Cl and P isotopes with JYFLTRAP*. During the project we identified an opportunity to produce isotopes in the region between the N=20 and N=28 closed neutron shells with a new beam production setup under development at the JYFL Accelerator Laboratory in the University of Jyvaskyla (Finland). The isotopes would be produced by multi-nucleon transfer reactions and stopped in a cell filled with helium gas. They would then be transported as a low-energy beam to a Penning trap spectrometer (JYFLTRAP) for a precise mass measurement. The measured masses can provide information on the structure of isotopes in the region between N=20 and N=28. They would also be important data to improve the calibration of the TOF-Bρ setup for NSCL experiment E18009, previously discussed.

This development initiated a new collaboration with the IGISOL group of the JYFL Accelerator Laboratory. The work involved calculating the yields of light isotope beams produced through multinucleon transfer reactions and estimating the efficiency to stop them in the new gas cell setup at IGISOL. As a result, we developed experiment proposal I289 (A. Estrade, O. Beliuskina et al), whose beam request was partially approved by the Program Advisory Committee of the facility. The experiment is planned for 2023 and will aim to demonstrate the proposed beam production method, as well as optimizing the experimental setup for the beams of the Cl and P isotopes of interest.

Development of Timing Detectors

The radiation detectors used for the time-of-flight measurement in TOF-Bρ experiments are based on timing scintillators connected to fast photomultiplier tubes. The detectors are placed on the path of the beam ions, and convert the scintillation light produced by the interaction of the beam into a fast electronic pulse. The detector design used in the initial campaign of experiments at the NSCL was upgraded to a model that increased the number of photomultiplier tubes to four per detector. During the project we completed the characterization of this new detector, demonstrating that it can reach timing resolution as low as 7.5 ps (sigma), with a uniform response that maintains a resolution below 10 ps over the full area of the scintillator. We also demonstrated that the new design provides information on the position of interaction of the beam at the 1 mm level. Results are described in detail in [2].

The second development project focused on the electronics used to read out and record the signals from the timing detectors, and on testing methods to correct systematic uncertainties in the timing measurement (from the *timing walk* effect). We tested a CAEN D742 switched-capacitor digitizer as the electronic module to acquire data from the TOF detectors, and developed data analysis code to compare a number of different algorithms to correct the *timing walk* (e.g. different implementations of the constant fraction discriminator technique using the digitized waveforms). The results showed that the D742 digitizers performs well acquiring the signals from fast scintillator detectors, with a resolution comparable to the electronics currently used in TOF-Bρ experiments. We also showed that using digitized waveforms can effectively reduce *walk* effects. Details are discussed in [3]. The use of the CAEN D742 module in future experiments will be considered in discussions with the FRIB facility.

Astrophysics reaction network calculations

The experimental work of the project was complemented by computational work to model X-ray bursts in accreting neutron stars. These are one of the main observable phenomena in neutron star binary systems. The hydrogen-rich material accreted onto the neutron star surface can burn in a thermonuclear runaway process, which is observed as a short increase of the X-ray luminosity. The details of the X-ray bursts are very sensitive to the chain of nuclear reactions, involving very unstable isotopes, that power them. In the project we coupled a set of existing reaction network codes to be able to run fast calculations for the nuclear process up to the ignition of an X-ray burst and the burst itself. The codes are then used to identify the uncertain nuclear reaction rates that have the largest effect on the model results. The details of the calculations are discussed in [4]. The project is part of the work of the CMU PhD student supported by the award.

Education and training

An important objective of the proposal was training and education of early career researchers in nuclear physics, to help strengthening the STEM workforce in the US. The project partially supported a postdoctoral researcher, who focused on the data analysis of experiment E12022 and the development of the timing detectors for time-of-flight measurements. The PhD student supported by the award is leading the analysis of experiment E18009 and working on the X-ray burst sensitivity study. A Master of Science student focused on the timing detectors work using the CAEN D742 digitizer. The student is currently a Physics PhD student in another US institution. We offered summer research projects for undergraduate students at Central Michigan University. One undergraduate project was the implementation and testing of a fine position control for the laser test setup of the detector lab at CMU, and a second one involved simulations of multinucleon transfer reactions and of the IGISOL gas stopping cell that were used for proposal I289 at JYFL Accelerator Laboratory. Of the two undergraduate students that participated as summer research assistants, one is currently in a MS program in computer science and the other is in the process of applying to graduate programs in Physics and Astrophysics.

References

[1] Z. Meisel et al, *Nuclear mass measurements map the structure of atomic nuclei and accreting neutron stars*, Phys. Rev. C 101, 052801 (2022). https://doi.org/10.1103/PhysRevC.101.052801

[2] K. Wang et al, *Plastic scintillation detectors for time-of-flight mass measurements*, Nucl. Inst. and Meth. A 974, 164199 (2020). https://doi.org/10.1016/j.nima.2020.164199

[3] K. Wang et al, *Investigation of a digitizer for the plastic scintillation detectors of time-of-flight mass measurements*, Nucl. Inst. and Meth. A 1027, 166050 (2022). https://doi.org/10.1016/j.nima.2021.166050

[4] I. Sultana et al, *Sensitivity Study of Type-I X-ray Bursts to Nuclear Reaction Rates*, EPJ Web of Conf. 260, 11040 (2022). https://doi.org/10.1051/epjconf/202226011040