Mass Measurements with Penning Traps and Reaction Q-values

Knowing the precise values of nuclear masses is vital for certain astrophysical processes, as well as for tests of the standard model. There are multiple ways to measure these masses accurately and precisely. The Penning trap is one of the most precise apparatus currently used. Penning traps take advantage of the relationship between the nucleus's cyclotron frequency, ω_c, and its mass when it is placed in a magnetic field: $\omega_c = qB/m$. By determining the nucleus's ω_c in a well known magnetic field via the time-of-flight (TOF) technique, the mass of the nucleus can be determined to within a few hundred eV using the mass of a well known nucleus or molecule for calibration [1].

As an alternative to the Penning trap, there are several other methods that can be used to determine nuclear masses, such Q-value measurements of a reaction, which take advantage of other well-known nuclear masses involved in the reaction to determine the mass excess of the nucleus in question. While this may not always be as precise as Penning trap measurements due to systematic errors, masses can be determined to within a few keV or better and do not require such complicated apparatus.

We have undertaken a series of experiments to measure masses in the A = 20 to 32 range, which are important for testing standard model physics as well as nuclear astrophysics. The Canadian Penning Trap (CPT) at Argonne National Lab was used to measure the mass of ^{31}S, which formerly had an uncertainty of 1.5 keV. The nucleus was produced using the ^{3}He(^{32}S,^{31}S)α reaction with a stable ^{32}S beam impinging on a ^{3}He gas cell. The reaction products were focused by a large solenoid and then stopped in a gas catcher. After being ejected the ^{31}S ions of interest were cooled, bunched, and separated from the other reaction products. Once the ^{31}S ions reached the Penning trap, they were subjected to an excitation frequency near the cyclotron frequency, ω_c, which increased the radial energy of the ions. After a specified time the ions were ejected from the trap and the radial energy was converted into axial energy as the ions moved through the field gradient. The ions were then detected by a micro-channel plate (MCP) detector and the time of flight (TOF) was measured. This time will be at a minimum when the excitation frequency is equal to ω_c, as that is the frequency which results in the most radial energy. The mass of the ion was therefore measured by scanning frequencies around ω_c and finding the minimum TOF (Figure 1). Using this method we were able to determine the mass of ^{31}S to within 400 eV.

Using the Q3D magnetic spectrograph at the Technische Universität München, high precision Q-value measurements were made to determine the mass excesses of ^{20}Na, ^{24}Al, ^{28}P, and ^{32}Cl. The masses and excited states of all these nuclei are important for various reactions in novae nucleosynthesis. High precision Q-value measurements of the ^{20}Ne(^{3}He,t)^{20}Na, ^{24}Mg(^{3}He,t)^{24}Al, ^{28}Si(^{3}He,t)^{28}P, and ^{32}S(^{3}He,t)^{32}Cl reactions were used to determine the mass excesses of the resulting nuclei. The relatively well-known ^{36}Ar(^{3}He,t)^{36}K reaction was used for calibration, as the mass of ^{36}K was recently measured to 0.39 keV with a Penning trap [2]. A ^{3}He^{2+} beam impinged upon ion-implanted targets of ^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, and ^{36}Ar from University of Washington. The tritons from the (^{3}He,t) reaction were momentum analyzed in the Q3D spectrograph and detected at the focal plane by a gas proportional counter, which was backed by a scintillator. This produced spectra of the ground states and low-energy excited states of the residual nuclei of interest (Figure 2), which when calibrated with the well-known ^{36}Ar(^{3}He,t)^{36}K reaction, will lead to the mass excesses of ^{20}Na, ^{24}Al, ^{28}P, and ^{32}Cl with a precision of ~1 keV. Though quite different from Penning trap measurements, both techniques are capable of yielding high-precision mass measurements, which are useful for astrophysical reaction rates, as well as other areas of physics, such as tests of the standard model [3].

[1] J. Clark *et al*., Nucl. Instrum. Methods Phys. Res., Sect. B **204**, 487 (2003).
[2] C. Yazidjian *et al*. Phys. Rev. C **76,** 024308 (2007).
[3] C. Wrede *et al*., *in preparation.*

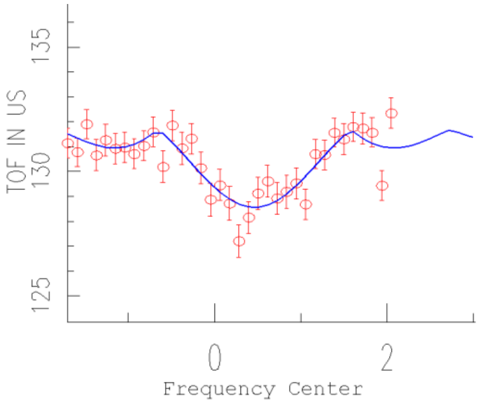

Figure 1: Time of flight as a function of frequency for the ^{31}S mass measurement. The minimum of the spectrum occurs at the cyclotron frequency.

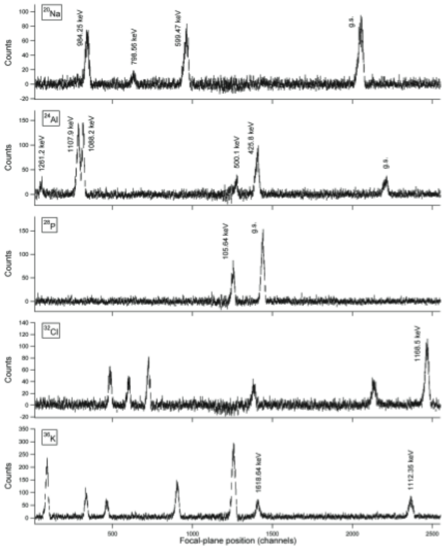

Figure 2: Spectra of tritons detected at the focal plane of the Q3D from the ^{20}Ne(^{3}He,t)^{20}Na, ^{24}Mg(^{3}He,t)^{24}Al, ^{28}Si(^{3}He,t)^{28}P, ^{32}S(^{3}He,t)^{32}Cl, and ^{36}Ar(^{3}He,t)^{36}K reactions. Excitation energies shown are from the literature.

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