Measurement of $^{17}$F + p reactions with ANASEN

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Abstract. Reactions involving radioactive nuclei play an important role in stellar explosions, but those reactions involving short-lived nuclei have only limited experimental information available due to currently limited beam intensities. Several facilities are aiming to provide greater access to these unstable isotopes at higher beam intensities, but more efficient and selective techniques and devices are needed to properly study these important reactions. The Array for Nuclear Astrophysics Studies with Exotic Nuclei (ANASEN), a charged particle detector designed by Louisiana State University (LSU) and Florida State University (FSU), was created for this purpose. ANASEN is used to study the reactions important in the αp- and rp-processes with proton-rich exotic nuclei, providing essentially complete solid angle coverage through an array of 40 silicon-strip detectors backed with CsI scintillators, covering an area of roughly 1300 cm². ANASEN also includes an active gas target/detector in a position-sensitive annular gas proportional counter, which allows direct measurement of (α,p) reactions in inverse kinematics. The first in-beam measurements with a partial implementation of ANASEN were performed at the RESOLUT radioactive beam facility of FSU during the summer of 2011. They included stable beam experiments and measurements of the $^{17}$F(p,p)$^{17}$F and $^{17}$F(p,α)$^{14}$O reactions which are important to understanding the structure of $^{18}$Ne and the $^{14}$O(α,p)$^{17}$F reaction rate. The performance of ANASEN and initial results from the $^{17}$F studies will be presented.

1. Motivation

The most common stellar explosions in the galaxy are novae and x-ray bursts. These events occur in binary star systems, where matter rich in hydrogen and helium accretes from a main-sequence star to its compact partner and ignites in a thermonuclear runaway. In order to understand and correctly model such phenomena, many nuclear reaction rates must be known, especially (p,γ) and (α,p) reactions involving proton-rich nuclei. These critical reactions occur at relatively low energies and are governed by resonant properties near the particle threshold. In the case of (p,γ) reactions in novae, typically only a few distinct resonances dominate the reaction rate. However, for (α,p) reactions occurring in x-ray bursts, the temperatures and level densities are generally higher, and resonances also can decay to many excited states. While the statistical model is generally applicable in such cases, the reliability of such models at lower energies is uncertain.

Direct studies of the important reactions are preferred, but indirect studies of the important resonance properties can generally be realized with much less intense beams. Indirect studies can be
particularly helpful to identify the most important resonances that can be addressed in the future by direct measurements. The Array for Nuclear Astrophysics Studies with Exotic Nuclei (ANASEN) is a charged-particle detector array designed for direct measurements of (α,p) reaction rates using an active gas target, and for indirect studies of resonance properties through scattering and transfer reactions [1, 2].

2. Array Components
ANASEN uses a position-sensitive proportional counter surrounding the beam axis to enable an active-target mode. Silicon-strip detectors (manufactured by Micron Semiconductor) surround the proportional counter in a barrel configuration with 3 rings of 12 rectangular Super X3 and annular QQQ3 detectors at forward angles form the cap of the barrel. Below in figure 1 is a SolidWorks representation of the inner pieces of ANASEN beside a photo of the assembly.

![Solidworks (left) and photo (right) representation of ANASEN.](image)

The Super X3’s are double-sided, segmented, 75mm x 40.3mm x 1mm silicon-strip detectors. The back segments are used to determine the energy of particles independent of position to a resolution of typically about 50-70 keV, which is limited in part by the electronics. Comparison of signals from the four front horizontal resistive strips with the full energy measurement provides position resolution of about 1.5mm along the beam axis. The forward angles are covered in quadrants by QQQ3 detectors with an outer radius of 98mm. Each detector has 16 radial front rings, and 16 annular back segments, all of which are non-resistive.

All detectors in the array are backed by trapezoidal-shaped 2-cm thick CsI(Tl) crystals (manufactured by SCIONIX), to ensure that the full energy is measured for all particles. There are two different geometries, both types read by two 18mmx18mm pin-diodes, and providing a typical energy resolution of roughly 8%. With the first geometry, one CsI(Tl) detector completely backs one Super X3 detector. The second geometry allows for four CsI(Tl) detectors to back each QQQ3 detector.

To allow direct measurements of (α,p) reactions, ANASEN includes a gas target capability. When using a gas target, the beam will pass through a thin window and enter a gas-filled recirculating (flow) chamber. In this mode, ANASEN can use helium gas (with a small component of a quenching agent) as a target and detection medium simultaneously. The position-sensitive proportional counter extends along the beam axis for 43 cm. There are five rings of wires. The inner and outer rings are used to prevent electrons produced outside of the detection region from interfering with the signal. The middle
ring holds 19 anodes, each separated by a cathode. The remaining two rings are cathodes that help create the independent trapezoidal detection regions of the proportional counter. Figure 2 shows the electric field simulation for the proportional counter configuration of five rings of wires. The 19 carbon-fiber anode wires, 4 kΩ/cm, are equally spaced 3 cm from the beam axis. The position of the traveling particle is determined by charge division method using the signal from both ends of each anode.

With the combination of proportional counter, silicon detectors, and CsI(Tl) detectors, there are roughly 800 channels of electronics in the full configuration of ANASEN. To deal with this high channel count in a cost effective manner, ANASEN utilizes Application-Specific Integrated Circuits (ASICs) HINP16C designed by Washington University [3]. Each HINP16C chip handles the pulse-shaping, timing, triggering, and digitization of 16 channels of data. The system as a whole has 2 ASICs HINP16C chips per board, with 16 boards in the system, handling up to 512 channels. External preamplifiers are used to optimize the resolution and dynamic range. We developed a 72-channel preamplifier system for the silicon detectors based on the Indiana University’s LASSA preamplifier chip; with a gain of 27 mV/MeV and a 30 ms fall time that matches the shaping of the HINP16C [4].

In addition, a heavy ion recoil detector was developed as an auxiliary detector for experiments measuring inverse mechanics. Recoiling ions at forward angles and with relatively high energies penetrate through a thin Mylar window into an additional chamber attached downstream of ANASEN that forms a gas proportional counter. This counter is fixed at $\Theta_{\text{lab}} = 0^\circ$ and can provide coincidence detection of heavy ions with high efficiency for some reactions, though most effectively when a solid target is used that fixes the location of the reaction vertex. The gas in the heavy ion gas ionization chamber can be independently controlled from that in the ANASEN active-target. The chamber itself holds ten pairs of alternating anode and cathode planes oriented perpendicular to the beam axis. We have also developed circuit board anodes that provide independent x and y position of the heavy ion. Each circuit board provides 34 independent signals with 4 mm spacing. Two circuit boards along with eight additional anodes are processed using the 72-channel preamp system and ASICs developed for the silicon array.

3. Commissioning and $^{17}$F+p Experiment

ANASEN targets measurements with radioactive ion beams at the ReA3 facility at the National

![Figure 2: Electric Field Calculation for the Proportional Counter.](image)

![Figure 3: Energy (keV) vs $\Theta_{\text{lab}}$ (radians) showing the p’s and $\alpha$’s detected by the S2 silicon telescope.](image)
Superconducting Cyclotron Laboratory [5] and the REOLUT facility at FSU [6]. The initial assembly, testing, commissioning, and first experiments with ANASEN were performed at FSU. We first tested the performance of the electronics with an annular (S2) double double-sided segmented silicon detector telescope and a first implementation of the heavy ion detector by measuring the $^{17}\text{O}(p,\alpha)^{14}\text{N}$ reaction. Beams of $^{17}\text{O}$ from the tandem accelerator at FSU bombarded solid polyethylene (CH$_2$)$_n$ targets at four different beam energies between $E_{cm}=1.8-3.0$ MeV. The silicon detectors were calibrated with a $^{228}$Th source before and after the experiment. All the different reaction channels were clearly separated by kinematics with the silicon strip detectors (shown in Fig. 3), and the better than 5% Z resolution through the heavy ion recoil chamber (shown in Fig. 4). During the experiment, the $^{17}\text{O}$ and $^{14}\text{N}$ was clearly distinguishable and the elastic and inelastic scattering was easily resolved, even with the elastic scattering 10 times stronger than the inelastic.

Given the encouraging results from the $^{17}\text{O}$ measurement, we then switched to a $^{17}\text{F}$ beam from RESOLUT to simultaneously study the $^1\text{H}^{(17}\text{F},p)^{17}\text{F}$ and $^1\text{H}^{(17}\text{F},\alpha)^{14}\text{O}$ reactions. This experiment studied the structure of $^{18}\text{Ne}$ and the time inverse of $^{14}\text{O}(\alpha,p)^{17}\text{F}$ reaction that is the first reaction in the $\alpha p$ process in X-ray bursts. A 55 MeV beam of $^{17}\text{F}$ with an intensity of about $10^5$ ion/s bombarded a thick (2 mg/cm$^2$) polypropylene target. The S2 double-sided segmented silicon-strip detector telescope detected p’s and α’s at $\theta_{lab}=9.5-28^\circ$, covering a relatively large solid angle of interest. The purity of the beam was typically about 70% or better, and the elastic scattering events were easily identified by coincidence between the fluorine in the heavy ion recoil chamber and the protons in the silicon telescope. The center of mass energy for each event was calculated from the measured angle and the energy of the light particle in the silicon telescope, and an excitation function reconstructed. Figure 5 shows the $^{17}\text{F}+p$ elastic scattering yield versus proton center of mass energy (MeV) for $\theta_{cm}=137^\circ$ with a preliminary R-Matrix fit. Evidence for 2 resonances is seen in the elastic scattering excitation function in the region around $E_{cm} \approx 2.3-2.5$ MeV, which corresponds to the most interesting region of excitation energy in $^{18}\text{Ne}$ for the $^{14}\text{O}(\alpha,p)^{17}\text{F}$ reaction. However, additional analysis is required to determine the statistical significance of this observation and to extract resonant properties for the states. We also observed $^{17}\text{F}(p,\alpha)^{14}\text{O}$ through this experiment, but only a total of roughly 80 events over the entire excitation function. While analysis is still in progress, the statistics are likely not going to be sufficient to draw strong conclusions about possible low energy resonances for this reaction.
4. Summary

The first (α,p) reaction was measured using active target mode of ANASEN in a test experiment with a stable 14N beam on helium gas with a 1% mixture of CO2. Protons and alpha particles were easily identified by their energy loss in the proportional counter. Figure 6 shows the 14N(α,p)17O gs excitation function reconstructed from the energy in the silicon array and the trajectory reconstructed from the position in the silicon and in the proportional counter. This excitation function was obtained in 6 hours of beam time and beam intensities of 5x10^5 ion/s. It is important to note that this complete excitation function was measured simultaneously with a center of mass energy resolution of roughly 70 keV. The next step with ANASEN is to perform the first direct study of 14O(α,p)17F directly with a helium gas target.

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