Study of alpha decay branches in ^{19}Ne via the ^{21}Ne(p,t)^{19}Ne reaction

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The ^{15}O(α,γ)^{19}Ne reaction is the main reaction controlling breakout of the hot CNO cycle into the rapid proton capture process (rp-process). As such, it is one of the most important reactions determining nucleosynthesis in the rp-process (and related proton capture processes), as well as astronomical observables such as X-ray burst light curves [CYB16]. As a result, experimentally determining the rate of this reaction at the relevant stellar temperatures (~0.2 – 3 GK) is a major goal of nuclear astrophysics.

It is now well established that the ^{15}O(α,γ)^{19}Ne reaction rate at relevant temperatures is completely dominated by the resonance at E_x = 4.033 MeV (E_{res} = 0.505 MeV, $J^{\pi} = 3/2^+$) [DAV02]. To date, attempts to measure the strength of this resonance directly, e.g. using a recoil separator and ^{15}O rare-isotope beam, have been hindered by low beam intensities. A successful direct measurement would require 10^{10} pps or greater ^{15}O beam intensity at an energy of ~0.160 MeV/nucleon. Current world-best intensities at the appropriate energy are limited to around 10^6 pps, and even next-generation facilities such as FRIB + ReA-3 may well not achieve this intensity. As a result, indirect measurements remain the main prospect for experimentally determining the stellar rate of this key reaction.

The strength ($\omega\gamma$) of the 4.033 MeV resonance in ^{19}Ne is completely determined by its alpha partial decay width, i.e., $\omega\gamma \simeq 2\Gamma_\alpha$. The alpha decay branch of this state is extremely small, which makes its observation challenging. To date, the most widely accepted upper limit on the alpha width is $\Gamma_\alpha <$ 0.011 meV, resulting in a branching fraction of $< 9 \times 10^{-4}$ [DAV02]. That limit was established in an experiment populating the 4.033 MeV state using the ^{21}Ne(p,t)^{19}Ne reaction at E = 43 MeV/nucleon. The (p,t) reaction selectively populates the 4.033 MeV state, which is predominately a two-neutron hole state. Outgoing ^{15}O recoils from alpha decay were selected in a magnetic spectrometer and used to establish alpha decay in coincidence with tritons, which were also detected and momentum analyzed in the spectrometer. That experiment was statistics limited, in part due to measuring tritons emitted at backward center-of-mass angles, where the (p,t) cross section is not maximized. The present project aims to improve upon the previous measurement by using the same measurement technique as [DAV02] but instead measuring forward-angle tritons using a stack of 1.5 mm thick Si detectors placed at forward laboratory angles.

Previous work on this project was focused on simulations, which determined that the resolution of the Si stack detectors was sufficient to separate the 4.033 MeV state (gated on t-alpha coincidences) from neighboring background states, as well as procuring a new scattering chamber and detectors for the measurement. Subsequently, in June 2020, we performed a test run using a 40 MeV/nucleon ^{21}Ne beam from the K500 cyclotron, to commission the Si stack detectors (coupled to the MDM spectrometer) and characterize background scattering rates in both the Si detectors and the spectrometer focal plane. A key discovery during this test was that an initial halo of the ^{21}Ne beam causes rates in the forward-angle Si detectors to be too large to run at the required beam intensity of 10^8 pps. The halo was successfully eliminated using a ~5mm diameter collimator placed upstream of the CH_2 reaction target. With the collimator in place, rates in the Si detector were manageable, demonstrating that this portion of the system is suitable for the real experiment.

A second focus of the test was establishing heavy-ion particle identification at the MDM focal plane, using the upgraded Oxford detector [SPI19], and determining rates of scattered ^{21}Ne beam incident on the focal plane detectors. Fig. 1(a) demonstrates that clear element separation was achieved in the experiment using signals from the detector's DE anode plate vs. residual energy loss in a thick scintillator. The locus of oxygen recoils, which will be gated on in the real experiment, is clearly separated from the neon beam and other elements.

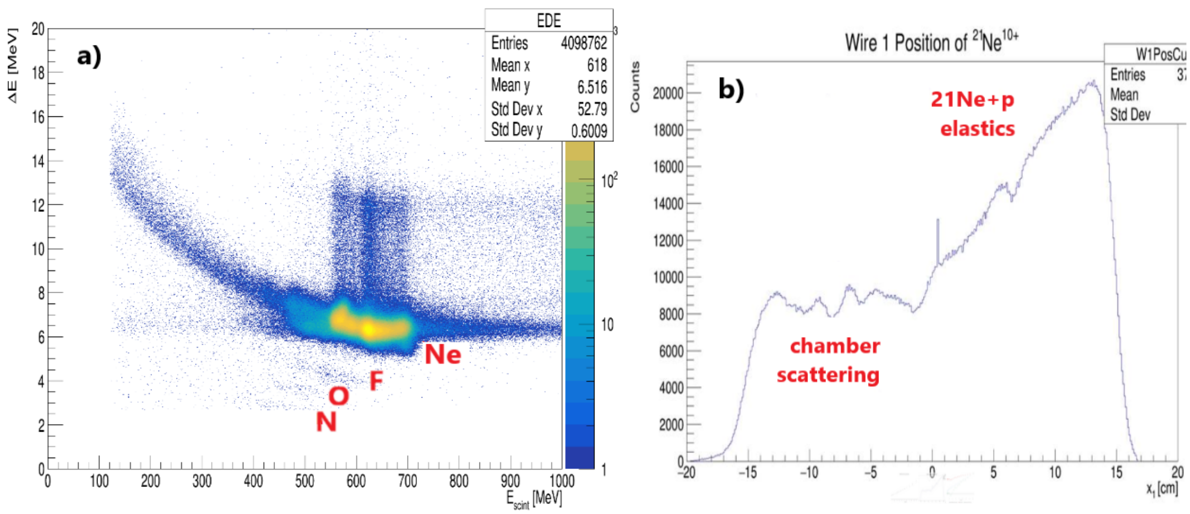

Fig. 1. a) Particle identification spectrum using signals from the DE anode vs. energy loss in a thick plastic scintillator. b) Dispersive (x) position of ^{21}Ne ions at the focal plane, showing two components of the ^{21}Ne background.

A major problem identified during the test experiment was the substantial presence of scattered ^{21}Ne beam in the focal plane. During the test run, the scattered beam rates were too large to run at the optimal beam intensity, since the position-sensitive avalanche wires of the Oxford detector are limited to incident rates below 5,000 pps. We made substantial progress at identifying the source of this background during analysis of the offline test-run data. As shown in Fig. 1(b), the background has two components. The first is backward-angle ^{21}Ne+p elastic scattering from the reaction target. The resulting ^{21}Ne ions have a magnetic rigidity that overlaps with the positive-x (high rigidity) side of the focal plane, with intensity increasing as +x position increases. This is responsible for the increasing intensity seen on the right side of the plot. While this background source is unavoidable, it can be eliminated or reduced by blocking some or all of the right-hand side of the detectors.

The second background source evidently arises from scattering in the vacuum chamber and produces a roughly uniform distribution across the focal plane. RAYTRACE ion-optics calculations, in combination with the observed test-run data, have been used to determine that this background most likely arises from scattering in the "blocker box" approximately 35 cm upstream of the Oxford detector entrance window. The blocker box contains two thick metal plates on linear drives, allowing some or all of the focal plane detectors to be blocked from beam. According to RAYTRACE, the unreacted ^{21}Ne beam reaches the physical edge of the detector volume approximately in this detector box, which contains numerous scattering surfaces. A straightforward solution to removing this component is to simply remove the blocker box (a second, more simple metal plate can still be used to block the high-rigidity side of the spectrometer as necessary). With the blocker box removed, the unreacted ^{21}Ne ions will instead impinge normal to a flat surface, just outside the detector window. This should effectively block both the unreacted beam and any scattering products resulting in the chamber.

Next steps for this project are to perform a second test run, tentatively slated for August 2021. This run will examine the change in focal plane rates with the blocker box removed. It will also commission a new detector system, combining a newly built position-sensitive PPAC detector with a fast plastic-slow plastic phoswitch detector. The new detector is expected to provide the required DE-E particle identification signals, along with position signals from the PPACs. Crucially, both the PPACs and the phoswitch detectors are very fast, with counting rates $>10^4$ pps possible. This will allow the necessary high beam currents to be run even with substantial ^{21}Ne scattering rates in the focal plane.

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