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A new technique for measuring astrophysically important (α,p) reactions

K. Y. Chae[*], [†] **D. W. Bardayan, C. D. Nesaraja, M. S. Smith**
Oak Ridge National Laboratory, USA
E-mail: kchae@ornl.gov

S. H. Ahn, A. Ayres, A. Bey, K. L. Jones, S. T. Pittman
University of Tennessee, Knoxville, USA

M. E. Howard, P. D. O'Malley
Rutgers University, USA

R. L. Kozub
Tennessee Technological University, USA

M. Matoš, B. H. Moazen
Louisiana State University, USA

W. A. Peters
Oak Ridge Associated Universities, USA

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Studying (α,p) reactions of astrophysical interest with radioactive beams presents serious challenges because of the difficult nature of the target. We have developed a new approach for the measurement of (α,p) reactions using heavy ion beams in inverse kinematics and have measured the ^{4}He(^{19}F,^{1}H)^{22}Ne reaction as a demonstration. ^{19}F beams were used at the Holifield Radioactive Ion Beam Facility (HRIBF) tandem accelerator in Oak Ridge National Laboratory (ORNL) to bombard a large scattering chamber filled with ^{4}He gas. Recoiling protons from the reactions were detected by the large area annular silicon strip detector array (SIDAR). The ^{19}F(α,p) and ^{19}F(α,p') excitation functions were measured over the energy range of $E_{c.m.}$ ~1-2.1 MeV, demonstrating the viability of the technique.

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[*]Speaker.
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1. Introduction

The αp-process, which consists of series of (α,p) and (p,γ) reactions, plays a crucial role in understanding the synthesis of heavy elements in explosive type I x-ray bursts. The αp-process provides breakout of the CNO cycle and enables the rp-process which converts light element fuel into heavy elements from Fe-Ni up to Cd-Sn within a few seconds. Most of the important (α,p) reactions, however, have never been experimentally determined in the laboratory. These measurements are challenging requiring the use of radioactive beams bombarding helium targets in inverse kinematics.

There have been a few previous studies of (α,p) reactions with radioactive beams [1, 2]. These studies typically used thick windows to contain the gas and therefore had to distinguish events of interest from large background rates produced by reactions on the windows. It is unclear the extent that these backgrounds affected the interpretation and analysis of the data, but later studies [3, 4] contradicted the published results in both cases. To avoid these types of backgrounds and to provide the sensitivities necessary, new and better techniques need to be developed to study (α,p) reactions on radioactive beams. A technique that avoids the use of thick windows is the subject of this manuscript.

As an initial demonstration, the ^{19}F(α,p)^{22}Ne reaction was chosen in part because it is believed to play crucial role in destroying ^{19}F in asymptotic giant branch (AGB) and Wolf-Rayet (WR) stars [5]. A recent study by Ugalde *et al.* [6] has substantially improved our understanding of the reaction, but the reaction rate is still uncertain due to the lack of experimental data.

2. Experimental Setup

The chosen technique was to bombard a large scattering chamber filled with ^{4}He gas at pressures of up to 9 Torr. The pressure in the scattering chamber was monitored continously using a MKS Absolute Capacitance Baratron rated to 1 mTorr accuracy and was regulated to better than $\pm$3% during the experiments. Differential pumping was used to maintain good vacuum upstream of the chamber. The differential pumping system was originally designed for the windowless gas target developed at the HRIBF [7] but was later modified for placing large silicon detector arrays in the gas [8]. In order to contain the ^{4}He gas in the large scattering chamber, a 5mm diameter aperture was used at the entrance of the chamber. This aperture was chosen in order to allow the beam to pass through it. The size of the beam spot was $\sim$3mm. Upstream of the target, residual gas was pumped out by roots mechanical pumps at the first pumping stage and turbomolecular pumps at the other pumping stages. The compressed ^{4}He gas from the various pumping stages was injected into a newly built gas recirculator to be purified and pumped back into the scattering chamber. A residual gas analyzer was used to check the purity of the gas and only very low levels of contaminants were found. The purity of the recycled ^{4}He gas was estimated to be greater than 99.99% during the runs. Nonetheless, the gas volume was flushed every 4 hours to ensure purity.

We have tested the technique by measuring the ^{19}F(α,p)^{22}Ne and ^{19}F(α,p')^{22}Ne* reactions using ^{19}F beams over the range of E_{beam} = 6-12.3 MeV. The energy loss of the beam in the active area of the gas target was $\sim$200 keV. Recoiling protons from the ^{19}F(α,p)^{22}Ne and ^{19}F(α,p')^{22}Ne* reactions were detected by a large area annular silicon strip detector array, SIDAR [9]. The SIDAR

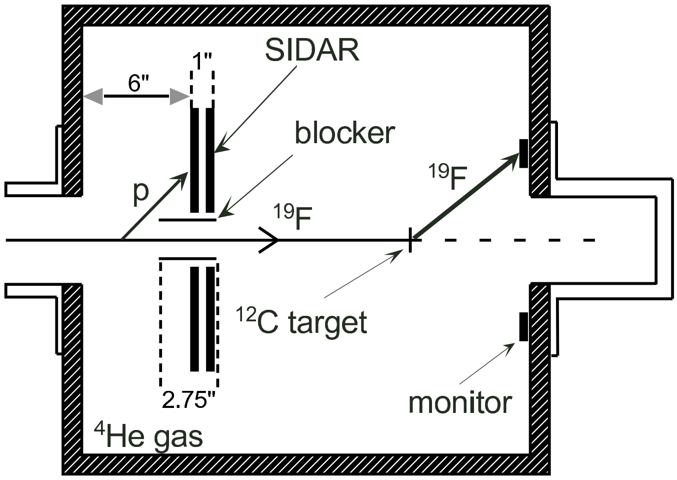

Figure 1: A schematic diagram of the experimental setup is shown.

was configured in ΔE-E telescope mode (100μm thick ΔE detectors backed by 1000μm thick E detectors) for particle identification. The SIDAR was placed approximately 165mm from the entrance of the chamber. Elastically scattered α particles at large angles ($\theta_{ab} \geq 70°$) were blocked by a hollow cylinder at the center of the array. The unreacted beam passed through the center of the SIDAR and impinged on a 50μg/cm^2 thick carbon foil. ^{19}F particles scattered off carbon were detected by two silicon surface barrier detectors which were mounted at the end of the chamber for beam current normalization. A schematic of the experimental setup is shown in Figure 1.

3. Data Analysis and Preliminary Results

Protons from the (α,p) and (α,p') reactions were detected by the SIDAR. A typical particle identification plot is shown in Figure 2. The intense group is from the ^{19}F(α,p')^{22}Ne* reaction and the fainter group is from the ^{19}F(α,p)^{22}Ne reaction. A state in the compound nucleus ^{23}Na (^{19}F + α) can decay into either the ground state of ^{22}Ne via the (α,p) channel or the first excited state located at E_x = 1.274 MeV via the (α,p') channel. As shown in the Figure, the (α,p) and (α,p') reaction channels are clearly separated owing to different reaction Q-values.

Identified protons were gated for each reaction channel and processed event by event for reconstructing the (α,p) reaction vertex. The angle between the beam axis and the detected proton was calculated as [10]

$$\cos\theta = \frac{A}{\sqrt{E_b E_p}}\left[B^2 E_p - B\left(m_Y Q + (m_Y - m_X)\,E_b\right)\right],$$

where E_b is the beam energy, E_p is the energy of the detected proton, Q is the reaction Q-value, and m_X and m_Y are the masses of the beam (^{19}F) and the heavy recoil from the reaction (^{22}Ne), respectively. A and B are defined as,

$$A = \frac{1}{2\,(m_Y + m_p)\,\sqrt{m_X m_p}},$$

$$B = m_Y + m_p,$$

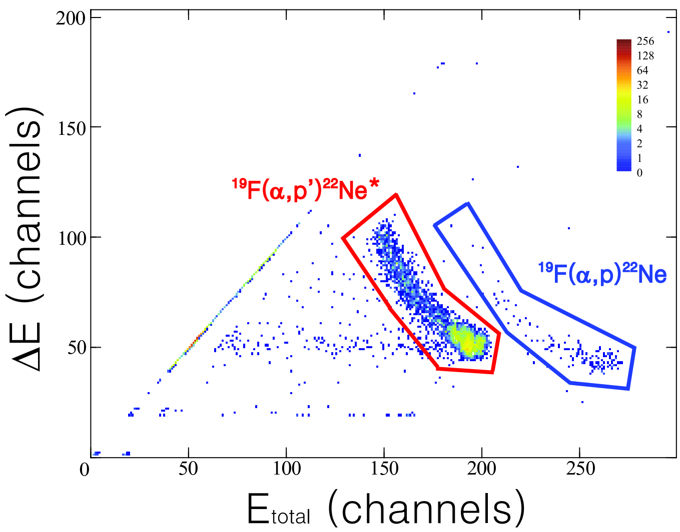

Figure 2: (Color online) ΔE vs ΔE+E plot is shown. The intense group is from the $^{19}F(\alpha,p')^{22}Ne^*$ reaction and the fainter group is from the $^{19}F(\alpha,p)^{22}Ne$ reaction. Two reaction channels are clearly separated owing to different reaction *Q*-values.

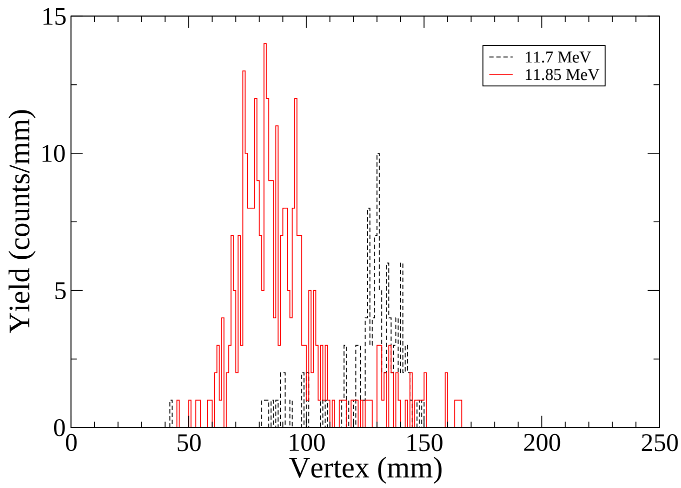

Figure 3: (Color online) The reaction yield versus the distance from the reaction vertex to the plane of SIDAR plot is shown for E_{beam} = 11.85 MeV (solid red curve) and 11.7 MeV (dotted black curve).

where m_p is the proton mass.

The reaction yield versus the distance from the reaction vertex to the plane of SIDAR plot is shown in the Figure 3. The solid red curve and the black dotted curve represent the reaction vertices at E_{beam} = 11.85 MeV and 11.7 MeV ($E_{c.m.}$ = 2.062 MeV and 2.036 MeV), respectively. A preliminary excitation function for the $^{19}F(\alpha,p')^{22}Ne^*$ reaction is shown in Figure 4. The measured excitation functions for the $^{19}F(\alpha,p)^{22}Ne$ and the $^{19}F(\alpha,p')^{22}Ne^*$ reactions are still under analysis.

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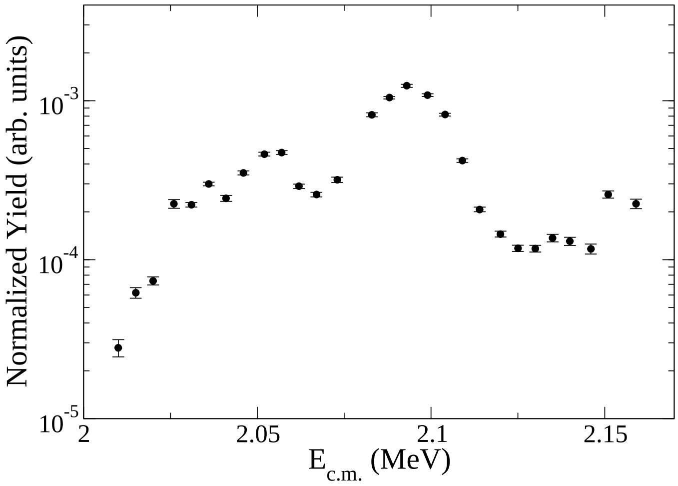

Figure 4: A preliminary excitation function for the $^{19}F(\alpha,p')^{22}Ne^*$ reaction is shown.

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