Work toward measuring transfer reaction particle correlations to improve stellar models

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The $^{12}C(\alpha,\gamma)^{16}O$ reaction in stellar nucleosynthesis is considered one of the most important aside from the triple-α process as it directly impacts the $^{12}C/^{16}O$ ratio and the properties of stars past helium burning [1]. Even after decades of research, however, the uncertainty associated with the reaction cross section at stellar energies remains large due to difficulties with direct measurements and the presence of two dominant multipolar contributions. Estimation of the cross section via extrapolation is currently the only viable technique which proceeds using models constrained by resonance properties of ^{16}O. As a result, a comprehensive understanding of $^{16}O^*$ as a function of the excitation energy is needed for accuracy.

One of the most significant uncertainties is that associated with the relative contributions of the E1 and E2 transitions for excitation energies near the stellar regime. Conventional measurements of this ratio often make use of the angular correlation technique, in which the two are disentangled by measuring the transition intensity at an angle with respect to the de-exciting residue where the E2 contribution is zero. Generally, the de-exciting residue is measured near zero degrees in the center-of-mass, resulting in cylindrical symmetry for the emission pattern. This simplifies the correlation, which is often necessary for small acceptance instruments, such as spectrometers. With the proper apparatus and reaction, however, a more comprehensive measurement of the correlation can be performed.

Indirect methods, such as the α-transfer technique, are often used to supplement the direct reaction. In the context of this work, (^{7}Li, t) has been investigated. The resulting reaction is a "mirror" of the true (α, γ), and as a result, reaction properties can be extracted similarly. The full process studied is an inverse kinematic α-transfer between ^{12}C and ^{7}Li with coincidence measurements made between the triton, α, and ^{12}C following de-excitation of the $^{16}O^*$.

A test experiment of the aforementioned reaction was conducted at 15 MeV/u with the Forward Array Using Silicon Technology (FAUST) and an added annular S3 silicon detector; the details of this, in addition to preliminary simulations, are given in [2]. A ^{12}C beam was supplied from the TAMU CI K150 cyclotron and impinged upon a ~5 μm metallic Li foil with an intensity such that the highest rate seen by the innermost forward detectors in FAUST averaged 300 Hz; this was maintained for approximately two days. Following the experiment, preliminary calibrations were performed, and the data of interest were extracted using the techniques detailed in [2]; the α-^{12}C relative energy spectrum from this experiment is shown in Fig. 1. In this plot, the relative energies of the α and ^{12}C detected in relevant events were calculated as if originating from a de-exciting $^{16}O^*$. The distribution is largely featureless within statistical error except for the clear excess at $E_{rel.}$ = 3.2 MeV which corresponds to the E* = 10.36 MeV state in ^{16}O.

The original intent of this work was to investigate relative energies less than 3.0 MeV, but as can be seen, the population of these energies is low. To continue the preliminary analysis, attention was turned

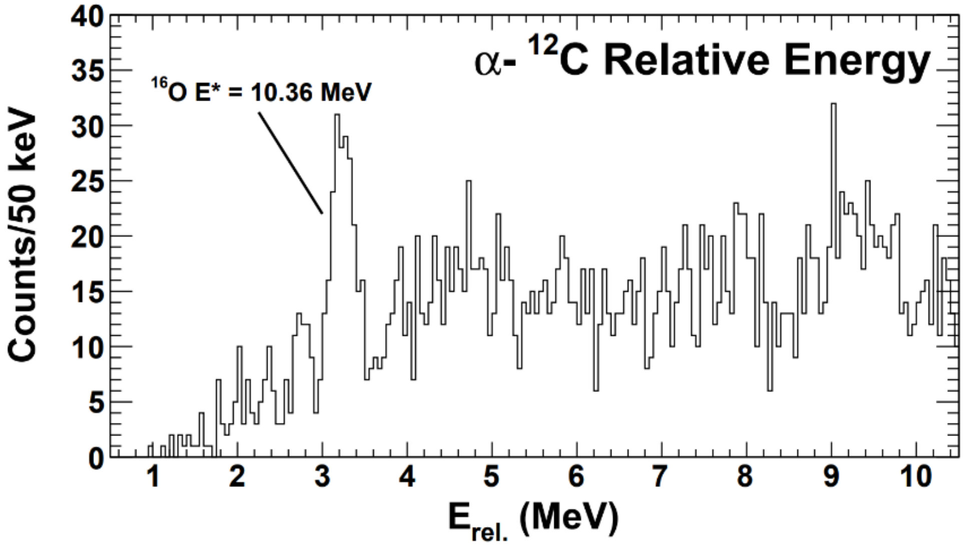

FIG. 1. α-^{12}C relative energy spectrum. The spectrum is largely featureless within statistical uncertainty, except for the excess at $E_{rel.}$ = 3.2 MeV corresponding to the E* = 10.36 MeV state in ^{16}O.

to the E* = 10.36 MeV state. First, with experimental data in hand, estimating yield with a lower beam energy became possible. Using the reaction code FRESCO [3], integrated cross sections for the 10.36 MeV state were calculated using optical model parameters (OMPs) from literature [4]. This information is summarized in Fig. 2a; each red point corresponds to a cross section calculated using OMPs extracted from data at the corresponding beam energy. However, with so few points for a broad span, the cross sections for intermediate energies were also calculated. These are given by the black points, and the lines connecting them to the red points indicate which OMPs were used for the associated calculation. As can be seen, the differing OMPs may yield cross sections differing by as much as a factor of three, but a general trend is clear. Comparing the cross sections for the 10.36 MeV population at 15 MeV/u (~180

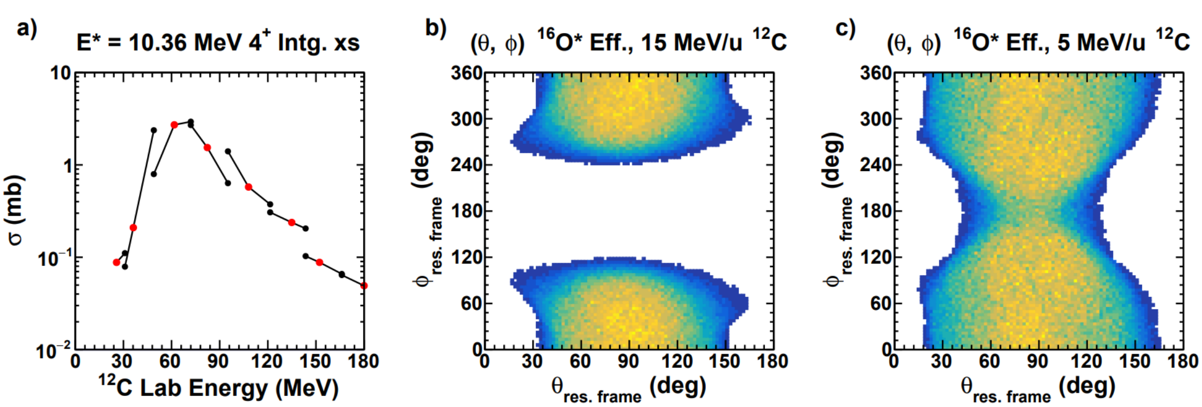

FIG. 2. Summarized simulation results. a) FRESCO integrated cross section calculations for the E* = 10.36 MeV ^{16}O* state as a function of incident ^{12}C beam energy. The Q4 2023 experiment was conducted at 180 MeV. b) (θ, φ) detection map for simulated isotropic decay of ^{16}O* in the frame of the ^{16}O with a ^{12}C beam energy of 15 MeV/u. c) Same as b), but at 5 MeV/u.

MeV TKE) and the maximum (~6.0 MeV/u, ~72 MeV TKE), the optimized yield boost is roughly a factor of 60. This is estimated to increase to about 150-200 once folding in detection efficiency (see below).

Reducing the beam energy leads to two closely related problems. The original energy was chosen such that ^{12}C elastic scatter would punch through the ~300 μm silicon detectors, as stopping in the detector causes significant damage; with a corresponding punchthrough energy of ~11.2 MeV/u, energies near or less than this result in a large amount of stopping. Additionally, reducing the beam energy results in an increase in the elastic scatter cross section at a given lab θ; reducing to the "ideal" energy of 6.0 MeV/u results in a factor of six increase to the cross section. The only solution to mediate this problem, aside from using a different instrument for the measurement, is to transition to thinner silicon detectors. This has been considered as an avenue, although no progress has been made on this front at the time of writing.

To begin preparing to make the final angular correlation measurement, the phase-space simulation originally used for coincidence and yield estimations [2] was configured to include breakup correlations in the frame of the decaying $^{16}O^*$. The simplest configuration, isotropic decay, was first simulated to estimate detection efficiency in preparation for the true measurement. Through this simulation, however, it was discovered that FAUST is kinematically insensitive to a large portion of the α-^{12}C (θ, φ) map at 15 MeV/u; this can be seen in Fig. 2b. This figure shows the detected (θ, φ) map from isotropic decay (source $\theta \propto \sin(\theta)$, source $\varphi \propto$ const.) of the $^{16}O^*$; FAUST is insensitive for decays near φ = 180°. This corresponds to in-plane or near-in plane emission of the α toward the beam axis, often missing FAUST acceptance. The detection efficiency improves with decreasing beam energy, however, as the magnitude of the Lorentz boost becomes smaller, and the transverse "pop" becomes relatively larger. To illustrate, the (θ, φ) map for isotropic decay at 5 MeV/u is also provided in Fig. 2c. In this regime, FAUST becomes sensitive for decays near φ = 180°, as the relative energy "kick" for in-plane emissions is now proportionally large enough to send the particle to the other side of the array for detection.

Based on the results of the (θ, φ) simulations detailed in Fig. 2, it is hypothesized that the lower energy states that were not populated in Fig. 1 were simply kinematically inaccessible at 15 MeV/u but might become measurable at lower energies. Follow-up simulations to confirm this are to be performed in the near future. It is important to note that losing sensitivity to the full (θ, φ) is not entirely problematic; preliminary simulations extracting a sample density matrix using only the sensitive region corresponding to Fig. 2c were successful with as little as 25,000 entries. However, having the intermediate region is critical; a sensitivity map analogous to Fig. 2b is insufficient for extraction of the matrix elements.

Due to the beam energy and yield requirements, alternate reaction mechanisms for probing this with FAUST are being investigated. Alternate α-transfer candidates, as well as inelastic excitation mechanisms have been considered, but nothing has been definitively decided at the time of writing.

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