Determining ANCs relevant for the $^{12}C(\alpha,\gamma)^{16}O$ reaction

E.A. Harris,[1,2] G.V. Rogachev,[1,2] G. Chubaryan,[1] C. Hunt,[3] E. Koshchiy,[1] Z. Luo,[1,2]
C.E. Parker,[1] K. Rao,[4] M. Roosa,[1,2] A. Saastamoinen,[1] and D.P. Scriven[1,2]
[1]*Cyclotron Institute, Texas A&M University, College Station, Texas 77843*
[2]*Department of Physics & Astronomy, Texas A&M University, College Station, Texas 77843*
[3]*Facility for Rare Isotope Beams, Michigan State University, East Lansing, Michigan, 48824*
[4]*Department of Physics & Astronomy, Rice University, Houston, Texas, 77005*

The $^{12}C(\alpha,\gamma)^{16}O$ reaction is often considered one of the most important reactions in nuclear astrophysics. This reaction determines the absolute abundance of ^{12}C and ^{16}O in our universe and has a large influence on the later stages of stellar evolution. However, direct measurement of radiative α-capture on ^{12}C at the relevant astrophysical energy is not possible with current experimental methods. This is because the Gamow energy peak at 300 keV is far below the Coulomb barrier where the cross section is too small for direct measurements ($\sim 10^{-17}$ b) [1]. Therefore, we must rely on extrapolations from higher energy measurements down to lower energies of interest. But low energy extrapolations for this reaction are challenging because the cross section within the Gamow window is characterized by broad, interfering resonances in ^{16}O. Despite efforts to constrain the properties of these resonances, the reaction rate is not known to the desired uncertainty of 10%. One of the remaining sources of uncertainty for R-matrix extrapolation is the α-particle Asymptotic Normalization Coefficient (ANC) for the ground state of ^{16}O.

The ANC method uses peripheral direct transfer reactions to study direct capture at astrophysical energies. This technique relies on the fact that direct capture at stellar energies occurs at large distances from the nucleus. The cross section thus depends mostly on the asymptotic tail of the wave function whose amplitude is given by the ANC [2]. By ensuring that the chosen transfer reaction is peripheral, the ANC value can be determined for the corresponding direct capture reaction. Additionally, when the transfer is done at sub-Coulomb energies, the DWBA calculations depend mostly on the Coulomb potential rather than the nuclear potentials of the entrance and exit channels [3]. This allows the reaction to be nearly model-independent. The experimental cross section is related to the ANCs (C) of the initial and final states of the system by [2]:

$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} = \frac{\left(C^{A}_{a,x}\right)^2}{b_A^2}\frac{\left(C^{B}_{b,x}\right)^2}{b_B^2}\left(\frac{d\sigma}{d\Omega}\right)_{DWBA} \quad (1)$$

This equation holds for a direct peripheral transfer reaction of A + b → B + a, where A = a + x and B = b + x, with x being the transferred particle.

Currently, α-ANCs of all bound excited states in ^{16}O have been measured [4, 5]. The ANCs of these sub-threshold states play a crucial role in the determination of the capture cross section. However, at higher energies, the direct capture to the ground state plays a more dominant role. Thus our goal is to measure the ANC of the ground state of ^{16}O to constrain the direct capture cross section. In order to extract this α-ANC, we have used the α-transfer reaction of $^{12}C(^{20}Ne,^{16}O)^{16}O$ populating the ground state of both ^{16}O products. The energy of the beam was chosen such that both the entrance and exit channels of this reaction are sub-Coulomb, which minimizes model dependence and uncertainties.

Three experiments have been completed using the MDM spectrometer and newly built TexPPAC detector in preparation for the extraction of ANCs of interest. The first experiment measured the elastic scattering of $^{12}C(^{16}O,^{16}O)^{12}C$ to define the charge state fractions of ^{16}O at the energy of interest for the sub-Coulomb $^{12}C(^{20}Ne,^{16}O)^{16}O$ α-transfer reaction. An ^{16}O 3^+ beam at 1.25 MeV/u was delivered to the scattering chamber and impinged on a thin ^{12}C target. Separate charge states of the elastically scattered beam ions were then sent through the MDM and into the TexPPAC detector, allowing us to construct a full charge state distribution for ^{16}O (Fig. 1). We concluded that ^{16}O 6^+ has the largest charge state fraction and would be the most favorable for detecting the ^{16}O(g.s.) product from the α-transfer reaction.

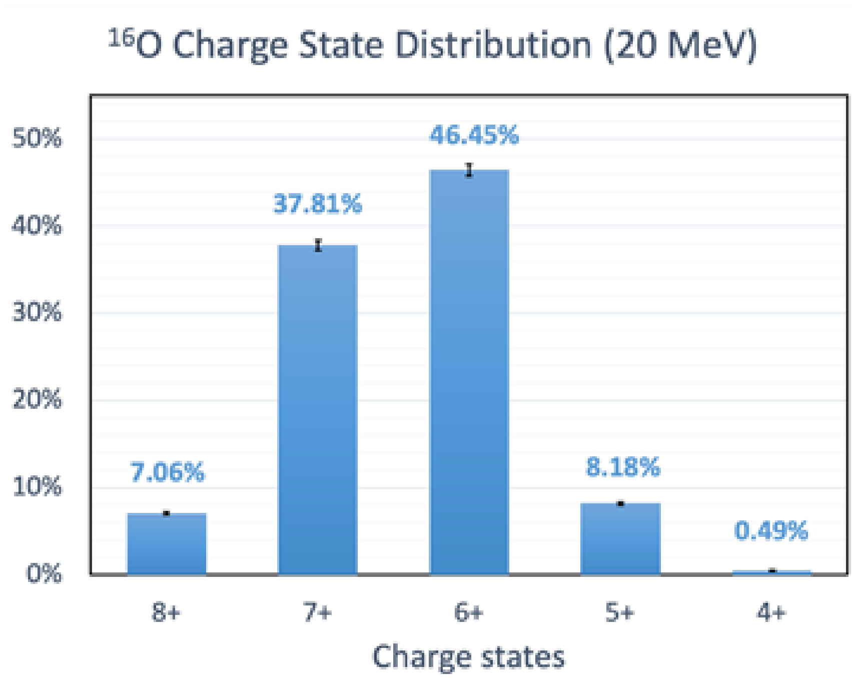

Fig. 1. Charge state fractions of ^{16}O at 20 MeV.

The main experiment to measure the α-ANC of ^{16}O using the $^{12}C(^{20}Ne,^{16}O)^{16}O$ reaction was performed in June 2021. To reduce the background from the beam, modifications were made to the TexPPAC detector. Optimal background reduction was found for a distance of 42 cm between PPAC detectors and a gas pressure of 4 Torr. At this setting, the ^{16}O from the α-transfer reaction has enough energy to reach the second PPAC detector, while the ^{20}Ne does not. A coincidence trigger between PPAC-1 and PPAC-2 was employed in order to filter out the beam background. A ^{20}Ne 3^+ beam at 1.0 MeV/u was delivered to the scattering chamber and impinged on a thin ^{12}C target. A silicon detector was placed inside the scattering chamber to collect signals from all charge states that were elastically scattered from the target. Meanwhile, TexPPAC collected signals from specific charge states sent through the MDM. Charge state measurements were taken for ^{20}Ne, as well as ^{12}C from elastic scattering to be used for normalization. The position along the X-plane of the detector along with TOF between PPACs was used for particle identification of ^{16}O (Fig. 2). With a theoretical cross section of 10 μb/sr, an assumption of 10 pnA of ^{20}Ne, target thickness of 0.02 mg/cm^2, and a solid angle of 8 msr, we expected to see about 10 events per hour for the ground state population.

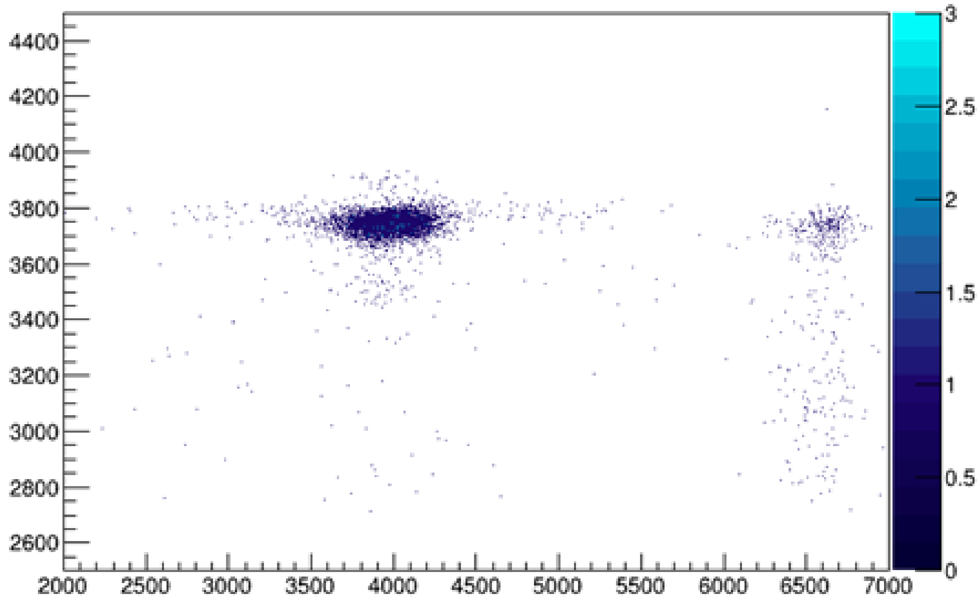

Fig. 2. Preliminary particle ID plot for the ^{12}C(^{20}Ne,^{16}O)^{16}O reaction. The X-axis is position on the focal plane in channels and the Y-axis is TOF in channels. The circle indicates ^{16}O events.

The final experiment was a supplemental measurement to find the ANC of the ground state of ^{20}Ne, which is currently unknown. The same α-transfer reaction was used, but with a higher ^{20}Ne beam energy of 1.525 MeV/u to populate the ^{16}O(6.05 MeV) excited state. Using the known ANC of ^{16}O(6.05 MeV) along with Eq. 1, the ANC of ^{20}Ne can be easily determined. The setup for this measurement was changed slightly from the previous experiment. TexPPAC was used to detect the ^{16}O(6.05 MeV) excited state while the Si was angled to detect the ^{16}O(g.s.) product from the same α-transfer reaction. We then used a coincidence trigger between TexPPAC and Si to reduce the background further. ^{12}C charge state fractions were experimentally determined at this energy and used for normalization of the beam. The analysis of data collected during these experiments is ongoing at this time.

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