# $\alpha$ asymptotic normalization coefficient of the sub-threshold $1/2^+$ state at 6.356 MeV in $^{17}O$

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The slow neutron capture process, or s process, occurs in a relatively low neutron density environment in asymptotic giant branch (AGB) stars. This process is essential for the nucleosynthesis of heavier elements. It is believed that the s process is responsible for nearly half of the heavy elements observed in the universe [1]. The main characteristic of this process is that neutron capture is slower than β decay. At low temperature ($<10^8$ K) for low-mass stars the $^{13}C(\alpha,n)^{16}O$ reaction plays the major role and is considered to be the main source of neutrons for the s-process in such stars [2]. Thus, this reaction rate is a necessary ingredient for constraining the models of AGB stars. Direct measurements are only available for center-of-mass (c.m.) energies above 279 keV. This is 100 keV above the energy for which α-capture is most efficient (Gamow energy). Below this energy the cross section has to be extrapolated. Extrapolation to lower energies causes a large uncertainly due to the presence of a sub-threshold $1/2^+$ resonance in $^{17}O$ at excitation energy of 6.356 MeV (3 keV below the $^{13}C+\alpha$ threshold energy). This sub-threshold resonance enhances the cross section at low energies, making an important contribution to the astrophysical S factor.

There have been several attempts to use various α-transfer reactions to constrain the contribution of the $1/2^+$ state to the low energy $^{13}C(\alpha,n)^{16}O$ cross section [3-7]. However, significant discrepancy still remains. In particular, previous measurement of the asymptotic normalization coefficient for the $1/2^+$ state using the $^{13}C(^6Li,d)^{17}O$ reaction at sub-Coulomb energy [4] produced the squared Coulomb-modified ANC of $0.89\pm0.23$ fm$^{-1}$. While α-transfer measurements at above barrier energies in Refs. [5] and [6] indicate much larger ANC values, $4.5\pm2.2$ and $4.0\pm1.1$ fm$^{-1}$ respectively. The most recent measurements using the Trojan Horse Method indicate even larger ANC of $7.7\pm0.3\pm1.5$ fm$^{-1}$ [7]. The main goal of this work is to remeasure the corresponding ANC using the sub-Coulomb α-transfer reaction and resolve the discrepancies between the ANC measured at sub-Coulomb energies and the ANC measured at above Coulomb barrier energies.

Measurements were performed at the John D. Fox Superconducting Accelerator Laboratory at Florida State University. The spectrum of deuterons from the $^6Li(^{13}C,d)^{17}O$ reaction at 8 MeV of $^{13}C$ beam at $144^0$ in c.m. is shown in Fig. 1. The $1/2^+$ state at 6.356 MeV is clearly observed. The DWBA calculations using code FRESCO were used to extract the ANC from the experimental angular distribution shown in Fig. 2. The squared Coulomb-modified ANC that we determined in this work for the $1/2^+$ state at 6.356 MeV in $^{17}O$ is $3.6\pm0.7$ fm$^{-1}$. The ANCs reported in Refs. [4-7] and the value obtained in this work are shown in Fig. 3. The cross section measured in Ref. [4] is about a factor of three smaller than the cross section measured in the present work. The main reason for this difference is the target deterioration effect that was not taken into account in [4]. The target thickening due to material buildup was observed in this experiment, causing the beam energy in the middle of the target to decrease. The effect was mitigated by frequent target change and also by monitoring of the target condition using

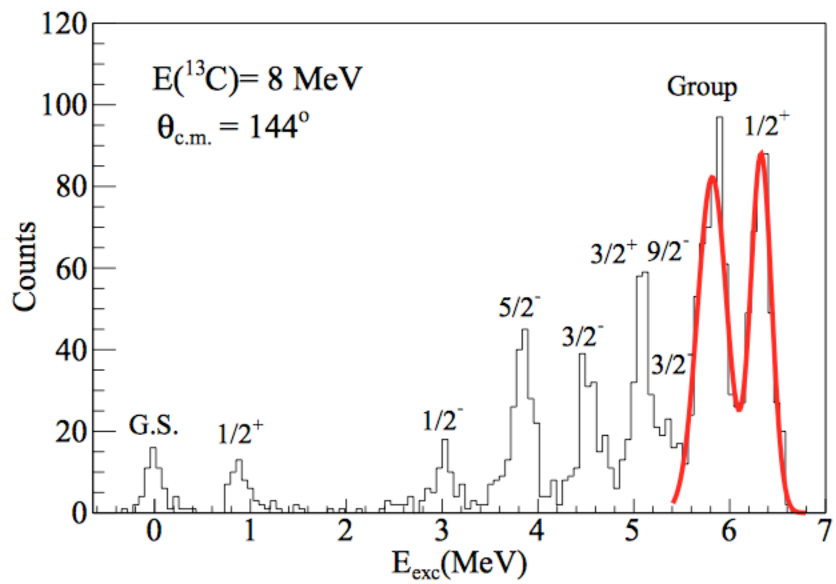


**FIG. 1.** Spectrum of deuterons from $^{6}Li(^{13}C,d)^{17}O$ reaction at 8 MeV (7.72 MeV effective energy after energy-loss corrections) of $^{13}C$ beam at $144^0$ in c.m.

elastic scattering of the Li beam. This was not done in the previous experiment [4]. Therefore, the beam energy in the middle of the target was decreasing during measurements that used the same target over extended periods of time in Ref. [4]. As a result, the measured cross section is

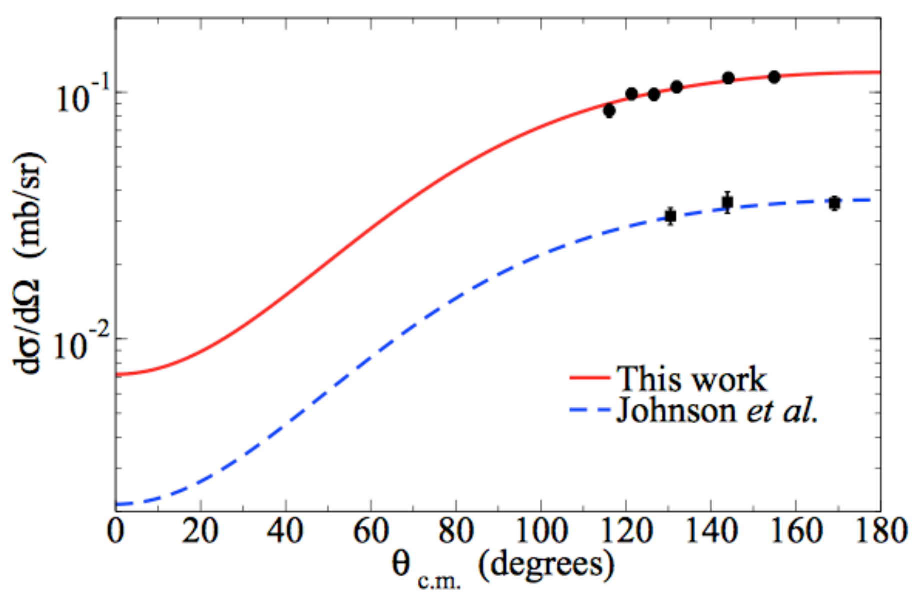


**FIG. 2.** Cross section and DWBA fit as a function of center-of-mass angle for the $^{6}Li(^{13}C,d)^{17}O$ reaction populating the $1/2^+$ sub-threshold state at 6.356 MeV in $^{17}O$. Solid curve is the present work and the dashed curve is that from Ref. [5] (dashed line).

significantly lower than it should have been. One of the characteristic features of sub-Coulomb transfer reactions (unlike the reactions performed at higher energies) is the strong dependence of the reaction cross section on the energy of the beam. The lower reaction cross section measured in Ref. [4] naturally led to the smaller ANC.

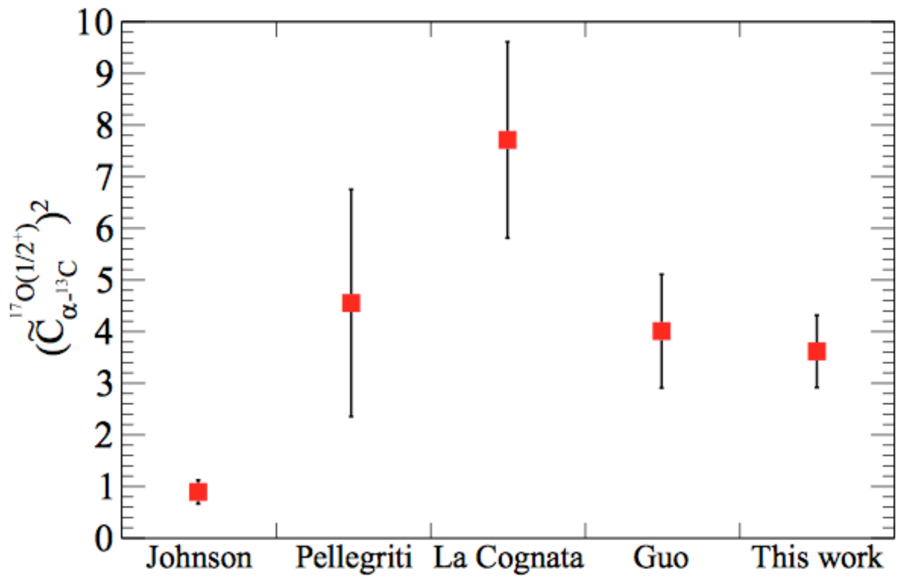


**FIG. 3.** Squared Coulomb-modified ANC value obtained in this work, for the $1/2^+$ at excitation energy of 6.356 MeV in $^{17}$O, compared with previous results from Johnson et al. [4], Pellegriti et al. [5], Cognata et al. [7], and Guo et al. [6].

In summary, we used the direct α-transfer reaction $^6$Li($^{13}$C,d)$^{17}$O at a sub-Coulomb energy to extract the α ANC for the $1/2^+$ state at 6.356 MeV in $^{17}$O. This parameter is the major source of uncertainty for the astrophysically important $^{13}$C(α,n)$^{16}$O reaction rate at temperatures relevant for the s process in AGB stars (<100 MK). The Coulomb-modified square ANC for the $1/2^+$ state is measured to be 3.6±0.7 fm$^{-1}$. This is the most precise value to date but in good agreement with the results of Refs. [5,6]. The main value of this work is that the discrepancy between the present results obtained by α-transfer reactions at higher energy and the sub-Coulomb energies is now removed. Both give similar values but the advantage of sub-Coulomb transfer is that this technique is much less model dependent. The discrepancy (although a much smaller one than before) still remains between the Trojan Horse method measurements [7] and the sub-Coulomb ANC results. It is important to investigate the source of this discrepancy further in order to improve the reliability of both indirect methods, which promise to be important tools for nuclear astrophysics. The more accurate ANC for the $1/2^+$ at 6.356 MeV state in $^{17}$O and the new low-energy α+$^{13}$C elastic scattering data [8] can now be used to impose tighter constraints than before on the $^{13}$C(α,n)$^{16}$O reaction rate (see also discussion in Ref. [9]). The results of this work are published in Ref. [10].

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