**α-cluster asymptotic normalization coefficients from sub-Coulomb ($^{6}$Li,d) reaction: Benchmark measurement**

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Nuclear reaction rates that involve α particles are often key nuclear physics inputs required for stellar models. There are many examples of reactions that involve α particles on both stable and radioactive nuclei that are critical for nuclear astrophysics. To name a few: the $^{12}$C(α,γ) reaction that determines the carbon to oxygen ratio in the Universe, the $^{13}$C(α,n) and $^{22}$Ne(α,n) neutron source reactions for s-process in AGB stars, the αp-chain reactions $^{18}$Ne(α,p) and $^{22}$Mg(α,p) that play an important role during x-ray bursts, etc. Yet, direct measurements of the α induced reaction cross sections at energies that are relevant for stellar environments have not been possible. The product of the reaction cross section and the Maxwell-Boltzmann energy distribution for α particles in a stellar environment defines the energy range at which the specific reaction is most efficient. This energy range, known as the Gamow window, is typically far below the Coulomb barrier, where the Coulomb repulsion dominates, and therefore the nuclear reaction cross section is very small and drops exponentially with energy. Since the cross section is often too small to be measured directly we are forced to rely on extrapolation of measurements done at higher energies down to the energies of interest. However, the reliability of these extrapolations is handicapped by the unknown nuclear structure of the systems involved. For example, direct measurements of the $^{12}$C(α,γ) reaction cross section have been performed only down to 900 keV in the center-of-mass frame (c.m.), while the Gamow window for the helium-burning stage is around 300 keV. The extrapolation is strongly affected by the sub-threshold states in $^{16}$O. Indirect methods can be used to constrain the properties of these resonances and therefore reduce the uncertainties related to low energy extrapolations.

One such method is the α-transfer reaction performed at sub-Coulomb energy. By measuring the α-transfer reaction cross section at energies low enough to be below the Coulomb barrier in both entrance and exit channels the dependence of the result on the optical model parameters is significantly reduced. Moreover, if the asymptotic normalization coefficients (ANCs) are extracted instead of the spectroscopic factors (SFs) then the dependence on the shapes of the α-cluster form factors and the number of nodes of the cluster wave function is also eliminated. Therefore, this technique yields an almost model independent result, as long as the peripheral direct reaction mechanism dominates.

The approach has already been applied to determine the α-ANCs for the astrophysically important states in $^{16}$O, $^{17}$O and $^{18}$O [1-3]. However, the benchmark measurement that allows to verify the technique using resonances with known partial α-width close to the α-decay threshold has not been performed so far and is the main goal of this work. The key to proving this technique is the choice of a specific case that can serve as its verification. The nearly ideal opportunity to test the sub-Coulomb α-transfer approach is provided by the $1^{-}$ state at 5.79 MeV in $^{20}$Ne. It is a purely α-cluster state with a partial α-width close to the single-particle (SP) limit. This state is above the $^{20}$Ne α-decay threshold by 1.06 MeV. Its natural width is known with good accuracy to be 28(3) eV [4] and it equals to partial α width.

We measured the α-ANC for the $1^-$ state at 5.79 MeV in $^{20}$Ne using the $^{16}$O($^{6}$Li,d) reaction performed at sub-Coulomb energy and related it to the partial α-width following the prescriptions of Ref. [5]. Measurements were performed at the John D. Fox Superconducting Linear Accelerator Laboratory at Florida State University. The differential cross section for the $^{6}$Li($^{16}$O,d)$^{20}$Ne($1^-$,5.79 MeV) reaction at 12.57 MeV energy of $^{16}$O beam is shown in Fig. 1. The theoretical analysis of the cross section is done using the finite-range DWBA approach via the

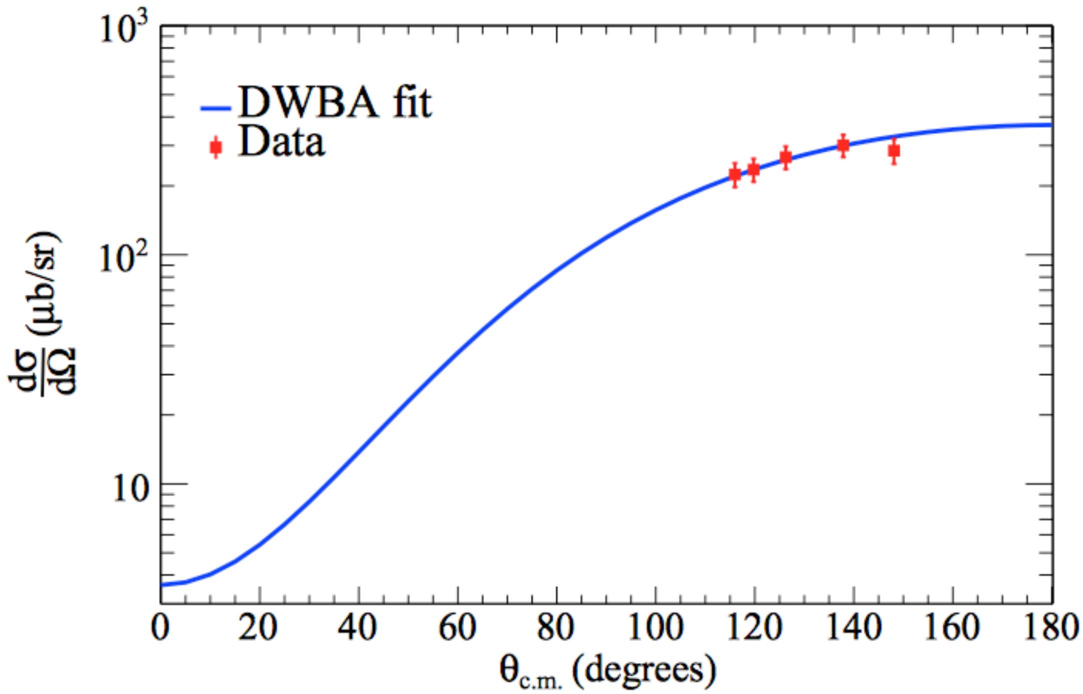


**FIG. 1.** Angular distribution of deuterons from the $^{6}$Li($^{16}$O,d) reaction populating the $1^-$(5.79 MeV) state in $^{20}$Ne and DWBA fit for E($^{16}$O)=12.57 MeV.

computer code FRESCO. Due to sub-Coulomb regime,

dependence of the final result on the optical model parameters is very weak (<13%). The FRESCO code is designed for calculating transfer cross section into the bound states and since the $1^-$ at 5.79 MeV is an unbound resonance an artificial binding energy was used in the calculations. The fit shown in Fig. 1 is obtained using a binding energy of 0.1 MeV. The value of the ANC and partial α width calculated from it depend on the choice of binding energy so that the partial α width for different binding energies was calculated and a nearly linear dependence on the binding energy was found as shown in Fig. 2. Linear extrapolation allows the partial α width for the correct binding energy of −1.06 MeV for this unbound state to be determined. The Whittaker function and penetrability factor are calculated using a channel radius of R = 5.1 fm (the result is almost independent of this parameter as well). The final result obtained for the

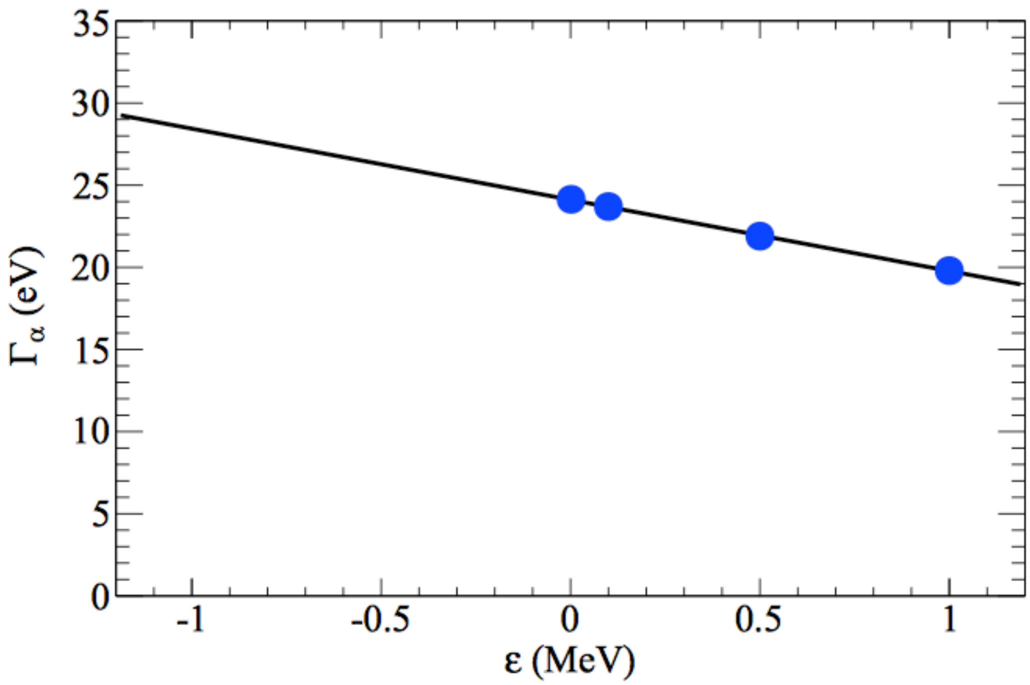


**FIG. 2.** Partial α width as a function of binding energy for the $1^-$ (5.79 MeV) state in $^{20}$Ne.

partial α width for the unbound $1^-$ state at excitation energy of 5.79 MeV in $^{20}$Ne is 28(6) eV. This is in perfect agreement with the known partial α width for this state [4].

We have verified that an α-transfer reaction performed at sub-Coulomb energies can produce an accurate and model-independent determination of the alpha asymptotic normalization coefficients of the near-threshold resonances and sub-threshold states. These model independent ANCs can be used to constrain key astrophysical reaction rates. The results of this work are published in Ref. [6].


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