α ANCs of the near α-threshold states in ^{16}O, ^{17}O and ^{20}Ne

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The ^{12}C(α,γ) and ^{13}C(α,n) are two very important reactions for nuclear astrophysics. The first one is considered the "Holy Grail" of nuclear astrophysics. During the helium burning process in a massive star the ^{12}C to ^{16}O ratio determines the subsequent nucleosynthesis of heavier elements. This ratio is set by the ^{12}C(α,γ) reaction rate. The relative carbon/oxygen abundance in the Universe also hinges on the rate for this reaction. The ^{13}C(α,n) reaction is an important source of neutrons for the s-process, slow neutron capture that is believed to be responsible for the production of half of all chemical elements in the Universe that are heavier than Iron. Direct measurements of these astrophysically important reaction rates cannot be done due to very small cross sections at energies of interest. This is because at low energies, relevant for stellar nucleosynthesis, the cross section of the reactions that involve charged particles is strongly suppressed due to the Coulomb barrier. Therefore, one has to rely on extrapolation made from the direct measurements at higher energies down to the energy of interest. However, near α-threshold resonances with unknown properties may affect these extrapolation for the ^{12}C(α,γ) and ^{13}C(α,n) reactions. The goal of this work was to measure the α-particle Asymptotic Normalization Coefficients (ANC) for the excited states in ^{16}O and ^{17}O. This is done by measuring the cross section for the (^{6}Li,d) α-transfer reaction at sub-Coulomb energy. This technique was first suggested in Ref. [1] and was further developed in [2,3]. The main advantage of the method is substantial and quantifiable reduction of the dependence of the final result on specifics of theoretical analysis. The only unknown value for the relevant resonances in ^{16}O and ^{17}O is the corresponding α-ANC. Once it is known, the contribution of the specific state to the reaction rate can be evaluated. In spite of the fact that the method of sub-Coulomb α-transfer reaction was used previously, no direct verification of the accuracy of this method was reported.

We performed the verification of the sub-Coulomb α-transfer technique by measuring the ANC of the 1^- state at 5.8 MeV in ^{20}Ne using the ^{16}O(^{6}Li,d) reaction. All experiments discussed in this report were carried out at the John D. Fox superconducting linear accelerator facility at Florida State University. The partial α-width of the 1^- state (same as the total width) is known from direct measurements (28±0.3 eV). It can also be calculated from the measured ANC using formulation suggested in [4]. This gives the value of 29±6 eV. The 6 eV uncertainty includes statistical and systematic experimental uncertainties and also uncertainty related to the theoretical analysis. The agreement with the known value is excellent.

The excited states in ^{16}O that influence the ^{12}C(α,γ) reaction rate the most are the 1^- at 7.12 MeV and 2^+ at 6.92 MeV. ANCs for these states were measured previously in [1], and the ANC values determined in this work are in good agreement with the previous measurements. However, the 0^+ state at 6.05 MeV can also contribute through the direct α-capture. The α ANC for this state have not been measured before. We measured the ^{12}C(^{6}Li,d) reaction cross section at several beam energies. The reaction was performed in inverse kinematics (^{12}C beam, E_{12C} = 5, 7 and 9 MeV). Recoil deuterons were detected at the forward angle (backward angle in c.m.) by a telescope detector. The telescope consisted of position sensitive propositional counter, backed by an array of silicon pin-diode detectors. Pure ^{6}Li target was used. Spectrum of deuterons is shown in Fig. 1. All three states relevant for the α-capture reaction rate are populated. Angular distributions for the 0^+ state measured at three beam energies (5, 7 and 9 MeV) are shown in Fig. 2. Curves are the corresponding DWBA fits. It is clear from the shape of angular distributions that reaction becomes sub-Coulomb at 5 MeV (the cross section is peaked at 180° c.m.). The ANC of the 0^+ state at 6.05 MeV was determined to be $2.25 \pm 0.82 \times 10^6$ fm^{-1}. The contribution of this state to the astrophysical S-factor determined from the measured ANC at the energies relevant for astrophysics is 2-3 keV b. All of it is due to a direct E2 transition (E1 and E0 are negligible). This is only about 2% of the total s-factor value for the ^{12}C(α,γ) at 300 keV [1]. Although small, this value is at the level of the desired uncertainly for the S-factor for this reaction. Our result eliminates the uncertainty that was associated with contribution of the 0^+ state to the ^{12}C(α,γ) reaction rate.

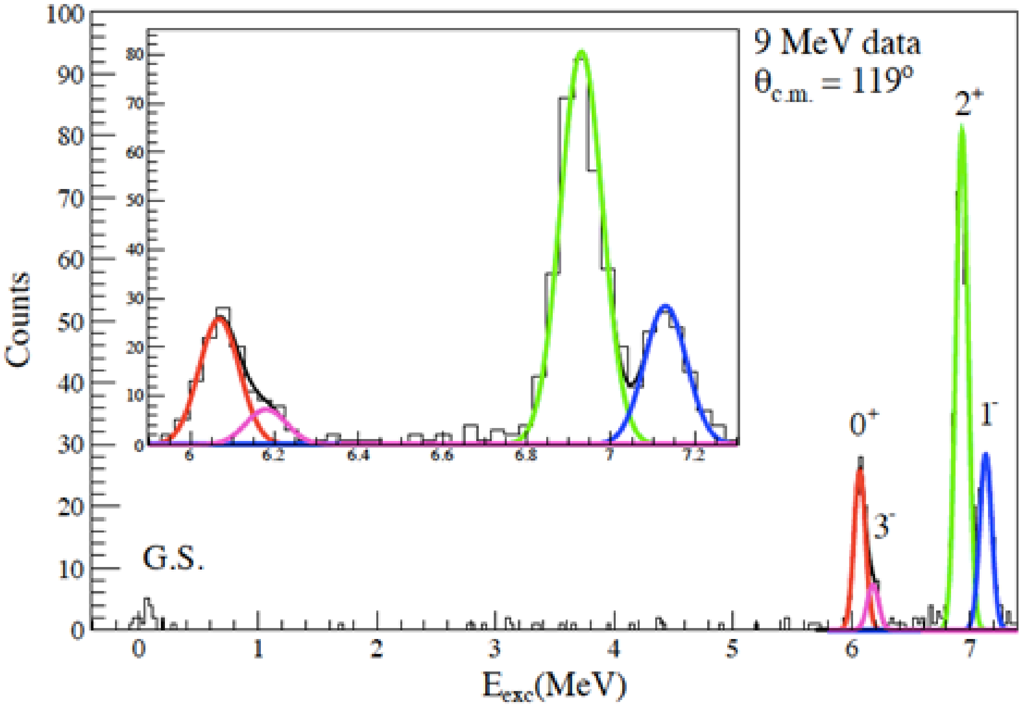

FIG. 1. Spectrum of deuterons from the ^{6}Li(^{12}C,d) reaction at E_{12C} = 9 MeV. The astrophysically relevant 1^-, 2^+ and 0^+ excited states in ^{16}O are populated.

The ANC for the $1/2^+$ state at 6.356 MeV in ^{17}O was determined using the ^{13}C(^{6}Li,d) reaction. Previously the SF_α and ANC for this state were measured [5,2,6,7,8], but results were not consistent. We remeasured the ANC for this state to constrain its contribution to the ^{13}C(α,n) reaction rate. The coulomb-modified ANC determined in this work is 3.4+/-0.5 fm^{-1}. It is the most precise measurement and it is consistent with [6,7] but not consistent with [5,2,8]. We used the same sub-Coulomb α-transfer reaction (^{6}Li,d) that was used in [2]. We believe that disagreement with [2] is caused by the fact that the target thickness was not controlled during the run in Ref. [2], and the effective beam energy in the middle of the target was changing due to target deterioration. This beam energy shift caused the lower (wrong) value of the ANC in [2]. The analysis in [5] appears to be wrong (as shown in [9]). The Trojan Horse Method

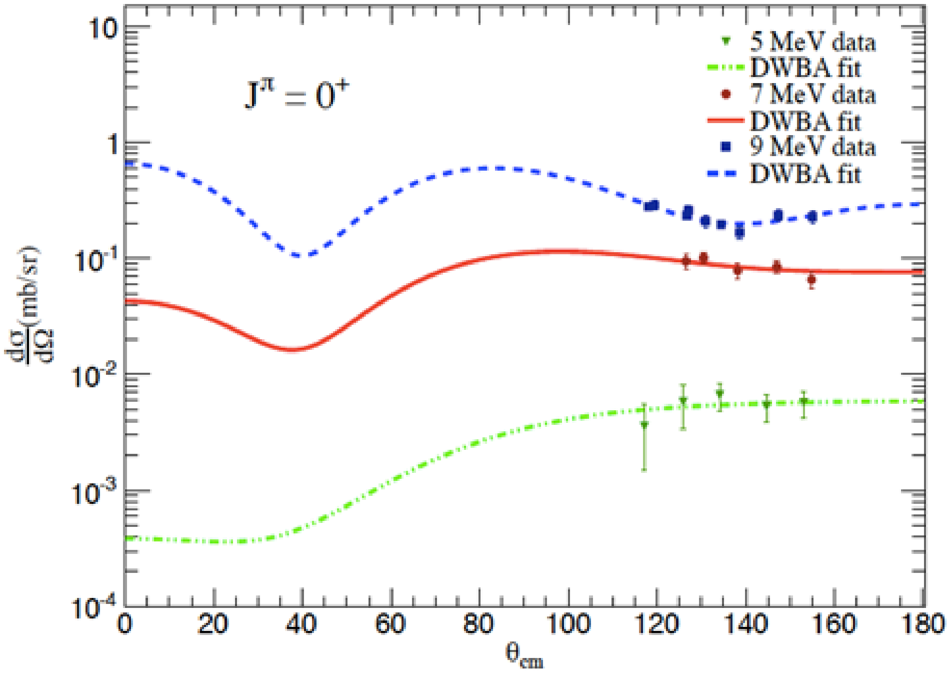

FIG. 2. Angular distribution of deuterons for the ^{6}Li(^{12}C,d) reaction measured at three beam energies (5, 7 and 9 MeV) and the corresponding DWBA fits.

(THM) was used to determine ANC in [8] and it has the largest value of all previous measurements, $6.7^{+0.9}_{-0.6}$ fm^{-1}. We do not have a good explanation what can cause the difference of the ANC values determined from the α-transfer reactions ([6,7] and this work) and the THM measurements [8].

In summary, the sub-Coulomb α-transfer reaction is a very useful tool to determine ANCs for the near α-threshold states that can then be used to constrain the astrophysical reaction rate. The method was verified using the 1^- state at 5.8 MeV in ^{20}Ne with the known partial α-width. The ANCs for the 0^+ state at 6.05 MeV in ^{16}O and $1/2^+$ state at 6.356 MeV in ^{17}O, that contribute to the astrophsically important ^{12}C(α,γ) and ^{13}C(α,n) reaction rates, were measured. The contribution of these states to the astrophysical S-factor were evaluated.

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