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Using the Asymptotic Normalization Coefficients

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Constraining the 6.05 MeV 0^+ and 6.13 MeV 3^- cascade transitions in the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction using the Asymptotic Normalization Coefficients

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Abstract

Background: The $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction plays a fundamental role in astrophysics and needs to be known with accuracy better than 10%. Cascade γ transitions through the excited states of ^{16}O are contributing to the uncertainty.

Purpose: To constrain the contribution of the 0^+ (6.05 MeV) and 3^- (6.13 MeV) cascade transitions.

Method: The α Asymptotic Normalization Coefficient for these states were measured using the α -transfer reaction $^{12}\text{C}(^6\text{Li}, d)^{16}\text{O}$ at sub-Coulomb energies.

Results: The 0^+ and 3^- cascade transitions contribution was found to be 1.96 ± 0.3 keV b and 0.12 ± 0.04 keV b for destructive interference of the direct and resonance capture and 4.36 ± 0.45 keV b and 1.44 ± 0.12 keV b for constructive interference respectively.

Conclusions: The combined contribution of the 0^+ and 3^- cascade transitions to the reaction at 300 keV does not exceed 4%. Significant uncertainties have been dramatically reduced.

The radiative capture of α -particles on ^{12}C plays a fundamental role in astrophysics. The $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction is activated during the helium burning stages of stellar evolution. This reaction becomes important when the triple- α reaction, dominant during the initial stage of helium burning, produces significant abundance of carbon. At temperatures that correspond to helium burning the α -capture is most efficient at energies near 300 keV (Gamow energy). The $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction cross section at this energy determines the relative abundance of $^{12}\text{C}/^{16}\text{O}$ in the stellar core, which is crucial for the later stellar burning stages, in particular, for the rates of the reaction $^{16}\text{O}(\alpha, \gamma)^{20}\text{Ne}$. This, in turn, has important implications for the sequence of later quiescent and explosive burning stages in stars, including nucleosynthesis and production of long-lived radioactive isotopes, such as ^{26}Al , ^{44}Ti and ^{60}Fe in core collapse supernova [1]. It also has direct influence on the composition of white dwarfs, and therefore plays an important role in the type Ia supernova ignition process (see Ref. [2] and references therein).

Significant progress in constraining the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction rate has been achieved over the last 40 years, however, the astrophysically required precision of better than 10% [3] is still out of reach. This is because direct measurement of radiative α -capture reaction on ^{12}C at 300 keV is unfeasible (cross section is $\sim 10^{-17}$ b) and extrapolations from higher energy measurements have to be used. However, extrapolations are difficult because there are no resonances near 7.5 MeV excitation energy in ^{16}O that can dominate the cross section (300 keV above the α -decay threshold) and the α -capture process is determined by the mixture of ground state and cascade transitions. It was assumed in the past that the ground state transition through the tails of sub-threshold states and above threshold resonances plays a dominant role and that cascade transitions are relatively unimportant. This assumption was called into question in [4] where the S-factor at 300 keV for the 0^+ state at 6.05 MeV cascade transition was determined to be 25^{+16}_{-15} keV b. This is comparable to the $E2$ transition to the ground state (53^{+13}_{-18} keV b) [5] and corresponds to 15% of the total S-factor. Very different conclusions were made in Refs. [6, 7], where the upper limit for the transition was set at <1 keV b. Both measurements were performed at higher energies (>2 MeV) using recoil separators and the results were extrapolated down to 300 keV. The discrepancy is caused mostly by different extrapolation approaches but it is also due to a 50% lower cross section for the 6.05 MeV transition measured in [6, 7] as compared to [4]. This discrepancy causes significant uncertainty for the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction rate. In Ref. [7] the contribution of

another cascade transition, the 3^- at 6.13 MeV, was determined to be negligibly small (0.3 keV b). The main goal of this letter is to constrain the 6.05 MeV 0^+ and 6.13 MeV 3^- cascade transitions using an independent technique.

It has been shown that reliable constraints on direct proton capture transitions can be obtained if one determines the proton Asymptotic Normalization Coefficient (ANC) of the corresponding state [8]. A large number of proton-capture reactions have been investigated this way and results were benchmarked against the direct measurements (see recent review paper and references therein [9]). Application of the ANC technique for α -capture reactions was pioneered in Ref. [10], where α ANCs for the 2^+ and 1^- states at 6.92 and 7.12 MeV in ^{16}O were measured using the sub-Coulomb α -transfer reactions $^{12}\text{C}(^6\text{Li},d)^{16}\text{O}$ and $^{12}\text{C}(^7\text{Li},t)^{16}\text{O}$. The advantage of using sub-Coulomb energies for α -transfer reactions is that the extracted ANCs are practically independent of the optical model potentials. Extracting the ANC instead of the spectroscopic factor eliminates uncertainties associated with the shape of the cluster form factor potential and the number of nodes of the cluster wave function. Therefore, results of these measurements are nearly model independent and do not require any additional normalization as long as the reaction mechanism is dominated by peripheral single-step α -capture. This experimental approach has previously been used to investigate the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ and $^{14}\text{C}(\alpha,\gamma)^{18}\text{O}$ reactions [11, 12]. More recently, a benchmark experiment was performed in Ref. [13] where the validity of the sub-Coulomb α -transfer approach was demonstrated by measuring the ANC of the 1^- state at 5.9 MeV in ^{20}Ne and comparing it to the well known width of this state.

The ANCs for the 2^+ at 6.92 MeV and 1^- at 7.12 MeV states in ^{16}O have been previously measured using sub-Coulomb energies in Ref. [10] and above barrier energies in Refs. [14, 15]. However, the ANCs of the 0^+ at 6.05 MeV and 3^- at 6.13 MeV states have not been measured. The 6.05-MeV 0^+ transition could not be studied in previous sub-Coulomb $^{12}\text{C}(^6\text{Li},d)^{16}\text{O}$ measurements [10] because de-excitation γ -rays were detected and the 6.05 MeV 0^+ state decays by monopole ($E0$) transition (mostly electron-positron pair creation). The experimental technique employed in the present work does not suffer from this limitation and the ANCs for all relevant sub-threshold states were measured simultaneously: 6.05 MeV 0^+ , 6.13 MeV 3^- , 6.92 MeV 2^+ and 7.12 MeV 1^- .

The experiment was carried out at the John D. Fox Superconducting Accelerator Laboratory, at Florida State University. The cross section for $^6\text{Li}(^{12}\text{C},d)^{16}\text{O}$ was measured at

three energies of ^{12}C beam (5, 7 and 9 MeV) using ^6Li enriched targets with thickness of $35\text{ }\mu\text{g}/\text{cm}^2$. The effective beam energies in the middle of the target were 4.7 MeV, 6.75 MeV and 8.7 MeV. More details are given in Ref. [13, 16]. For the identification of the reaction products two ΔE - E telescopes were mounted on remotely controlled rotating rings placed to the right and left of the beam axis. Each of the ΔE - E telescopes was constructed with a position sensitive proportional counter and four pin diode $2\times 2\text{ cm}^2$ silicon detectors, contained in a box filled with a P10 gas (10% methane and 90% Ar mixture). A Kapton foil of $7.5\text{ }\mu\text{m}$ thickness was used as the entrance window separating the P10 gas inside the detector from the chamber vacuum. This setup allows the measurement and identification of deuterons down to an energy of 1 MeV when 150 Torr of P10 pressure is used and also to observe the backscattered ^6Li ions when the pressure in the proportional counters is reduced to 50 Torr. The intensity of the incoming beam was measured using a Faraday cup placed at the end of the chamber.

The two-dimensional ΔE vs E scatter plot is shown in Fig. 1 where it can be seen that deuterons are clearly identified. A strong proton peak around 1 MeV is seen in Fig. 1. This peak corresponds to $^{12}\text{C}+p$ elastic scattering due to the hydrogen contained in the target and has a much higher intensity than the events of interest. The ΔE tail from these protons leaks into the deuteron cut and prevents deuteron identification below 1 MeV. For the 9 MeV and 7 MeV data this proton background does not overlap with the deuterons of interest. However, for the 5 MeV data the deuterons from the 2^+ and 1^- states overlap with the proton background. Therefore, only the 0^+ and 3^- states were studied in the lowest energy 5-MeV dataset.

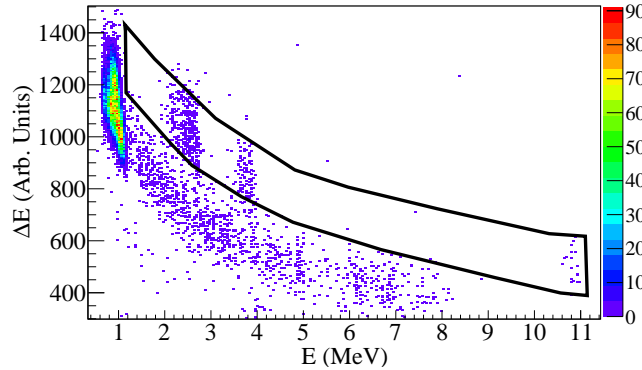


FIG. 1. (Color online) ΔE vs E scatter plot with the cut on the deuterons using the 9-MeV data for a pin detector at 30° in the laboratory frame.

The spectrum of deuterons from $^{12}\text{C}(^6\text{Li},d)^{16}\text{O}$ reaction at sub-Coulomb energy is shown in Fig. 2. As can be seen in Fig. 2, the energy resolution of the experiment is good enough to resolve the 2^+ and 1^- states that are 200 keV apart, but insufficient for clean separation between the 0^+ and 3^- states that are only 80 keV apart. The 3^- state manifests itself as a shoulder toward the higher excitation energy visible in the peak that is dominated by the 0^+ state. We used two overlapping Gaussians fit to determine strengths of the 0^+ and 3^- states. This fit has only two free parameters (amplitudes of the two Gaussians) since the excitation energies of the states are well known and the experimental resolution is set by the widths of the resolved states (2^+ and 1^-). A reliable fit could only be achieved for the 9- and 7-MeV dataset since the 5-MeV dataset had limited statistics. For the 5-MeV data all the events in the 6 MeV peak were used to calculate the cross section of the 0^+ and 3^- states combined. Then, the values of the ANCs and cross section for each of the states were calculated based on the ANCs ratios of the 0^+ and 3^- states obtained with the 9- and 7-MeV data.

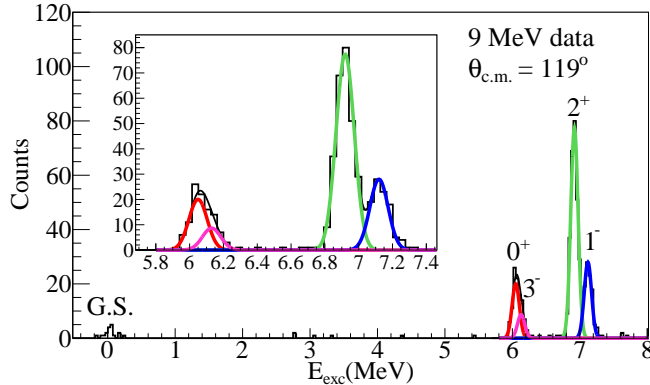


FIG. 2. (Color online) Spectrum of deuterons from the $^{12}\text{C}(^6\text{Li},d)^{16}\text{O}$ reaction. The ^{12}C effective beam energy is 8.7 MeV (energy in the middle of the ^6Li target) and the deuteron scattering angle is 119° in the center of mass.

Angular distributions for deuterons from the $^6\text{Li}(^{12}\text{C},d)^{16}\text{O}$ reaction, performed at the ^{12}C beam energies of 9, 7 and 5 MeV, populating 0^+ , 3^- , 2^+ and 1^- states at 6.05 MeV, 6.13 MeV, 6.92 MeV and 7.12 MeV respectively are shown in Fig. 3 together with the corresponding DWBA calculations. For beam energy of 5 MeV, all the data points (corrected to the 0^+ cross section) are shown in Fig. 3 (a) and only the calculated DWBA cross section is shown in Fig. 3 (b) for the 3^- state. The computer code FRESKO (version FRES 2.9) [17] was

used to perform finite range DWBA calculations with the full complex remnant term. The potential for ${}^6\text{Li}+{}^{12}\text{C}$ is obtained from Ref. [18], where energy dependent parameters are obtained for energy range from 4.5 to 156 MeV (${}^6\text{Li}$ beam energy). It was observed that changing the value of V_0 from 174 to 167 MeV produces better fit to the shape of the 0^+ angular distribution. The $d+{}^{16}\text{O}$ optical potential parameters were obtained from [19]. The potential parameters for $\alpha+d$ form factor were taken from Ref. [20]. By normalizing the DWBA calculations to the experimental data and using the equations provided in Refs. [10, 21] together with the known value for ${}^6\text{Li}$ α -ANC ($(C_{\alpha d}^{6\text{Li}})^2 = 5.3 \pm 0.5 \text{ fm}^{-1}$) [22], the ANC values for the 0^+ (6.05 MeV), 3^- (6.13 MeV), 2^+ (6.92 MeV) and 1^- (7.12 MeV) states were determined. The obtained squared ANCs are shown in Table I and compared to previous measurements for the 2^+ (6.92 MeV) and 1^- (7.12 MeV) states.

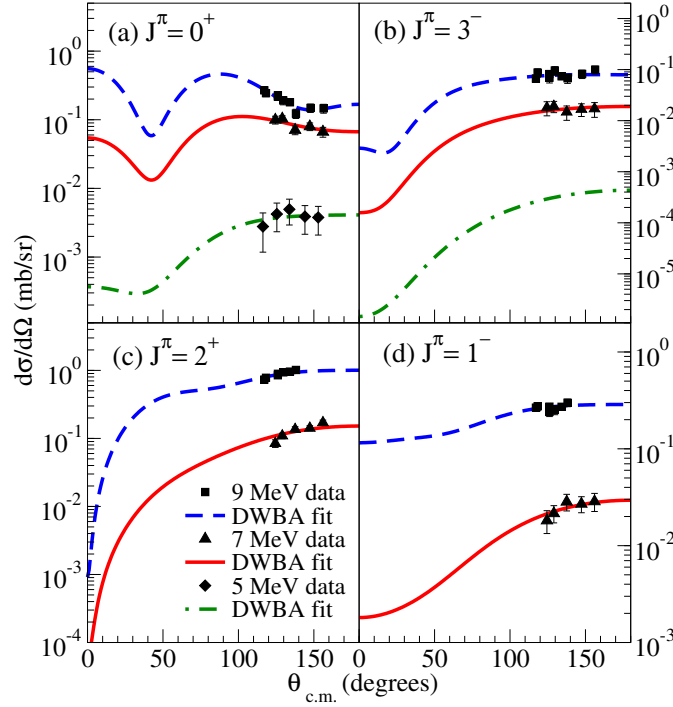


FIG. 3. (Color online) Experimental data and DWBA cross section as a function of center-of-mass angle for the 0^+ at 6.05 MeV (a), 3^- at 6.13 MeV (b), 2^+ at 6.92 MeV (c) and 1^- at 7.12 MeV (d) in ${}^{16}\text{O}$ using the ${}^{12}\text{C}$ beam energies of 5 MeV (dashed-dotted line), 7 MeV (solid line) and 9 MeV (dashed line).

The total uncertainty of the extracted ANCs is a combination of statistical uncertainties, normalization uncertainties and uncertainties in the parameters used for the DWBA

TABLE I. Squared ANCs for the 0^+ (6.05 MeV), 3^- (6.13 MeV), 2^+ (6.92 MeV) and 1^- (7.12 MeV) sub-threshold states in ^{16}O , compared to previous measurements.

$\left(C_{\alpha-^{12}\text{C}}^{^{16}\text{O}(0^+)}\right)^2$ (10^6 fm^{-1})	$\left(C_{\alpha-^{12}\text{C}}^{^{16}\text{O}(3^-)}\right)^2$ (10^4 fm^{-1})	$\left(C_{\alpha-^{12}\text{C}}^{^{16}\text{O}(2^+)}\right)^2$ (10^{10} fm^{-1})	$\left(C_{\alpha-^{12}\text{C}}^{^{16}\text{O}(1^-)}\right)^2$ (10^{28} fm^{-1})	Ref.
-	-	2.07 ± 0.80	4.00 ± 1.38	[14]
-	-	1.29 ± 0.23	4.33 ± 0.84	[10]
-	-	$1.96^{+1.41}_{-1.27}$	3.48 ± 2.0	[15]
2.43 ± 0.30	1.93 ± 0.25	1.48 ± 0.16	4.39 ± 0.59	This work

calculations such as the optical potential parameters and the number of nodes (see Refs. [13, 16]). Due to the fact that the reaction is performed at near and sub-Coulomb energies the uncertainty related to the optical potential parameters is small with one exception. It was found that for the highest energy dataset (9 MeV) the angular distribution for the 6.05 MeV 0^+ state is somewhat sensitive to the optical model parameters because the exit channel ($d+^{16}\text{O}$) is above the Coulomb barrier. The ANCs for each state and the corresponding uncertainties were determined for each beam energy datasets and then combined into a single value with the corresponding statistical weights. For example, for the 0^+ 6.05 MeV state the square of the ANCs are $\left(C_{\alpha-^{12}\text{C}}^{^{16}\text{O}(0^+)}\right)^2 = (2.04 \pm 0.41) \times 10^6 \text{ fm}^{-1}$, $\left(C_{\alpha-^{12}\text{C}}^{^{16}\text{O}(0^+)}\right)^2 = (2.52 \pm 0.50) \times 10^6 \text{ fm}^{-1}$ and $\left(C_{\alpha-^{12}\text{C}}^{^{16}\text{O}(0^+)}\right)^2 = (2.73 \pm 0.63) \times 10^6 \text{ fm}^{-1}$ for beam energies of 9, 7 and 5 MeV respectively. This gives the average value and combined uncertainty of $\left(C_{\alpha-^{12}\text{C}}^{^{16}\text{O}(0^+)}\right)^2 = (2.43 \pm 0.30) \times 10^6 \text{ fm}^{-1}$. The uncertainty for 9-MeV dataset is dominated by uncertainty of the optical potential parameters and uncertainty for the 5-MeV dataset is dominated by the statistical uncertainty.

The ANCs for the 2^+ (6.92 MeV) and 1^- (7.12 MeV) sub-threshold states have been measured in [10, 14, 15]. There is excellent agreement between all measurements with sub-Coulomb α -transfer ([10] and this work) providing the most precise values. The contribution of the 2^+ (6.92 MeV) and 1^- (7.12 MeV) sub-threshold states to the astrophysical S-factor have been evaluated in [10] using ANCs that are nearly identical to the results of the present work and therefore there is no need to repeat the R-matrix analysis already performed in [10]. The ANC of the 0^+ and 3^- states have been measured for the first time. The S-factor for direct α -capture to the 0^+ and 3^- states was calculated using the R-matrix formalism

described in [23] and implemented in the code AZURE [24]. The $E2$ transition dominates the direct α -capture to the 0^+ and 3^- states ($E1$ and $M1$ transitions were evaluated and were found to be negligible for both cascade transitions). The S-factor for the direct $E2$ transitions to the 0^+ and 3^- states are shown in Fig. 4 (solid curve). They are completely determined by the measured ANCs with uncertainties related to the choice of channel radius being very small compared to the experimental uncertainties of the ANCs. The corresponding S-factors at 300 keV are 3.2 ± 0.4 keV b and 0.6 ± 0.1 keV b for direct capture to the 0^+ and 3^- states respectively.

The $E2$ radiative capture to the first excited state of ^{16}O (0^+ at 6.05 MeV) state is contributed by the interfering direct capture and the capture through the sub-threshold resonance 2^+ at 6.92 MeV. Similarly, $E2$ radiative capture to the second excited state of ^{16}O (3^- at 6.13 MeV) is contributed by the interfering direct capture and the capture through the sub-threshold resonance 1^- at 7.12 MeV. The amplitude of the capture through the sub-threshold resonance contains the product of the α partial width amplitude in the entrance channel and the radiative width amplitude for the decay of the sub-threshold resonance to the first excited state 0^+ . The relative sign between these two amplitudes determines if interference is destructive or constructive and it cannot be determined from the experimental data presented in this letter. Therefore, we consider both possibilities here. It is important to note that since ANCs for all sub-threshold states in ^{16}O are fixed now, there is a good chance that interference sign can be determined by complete R-matrix analysis of the direct α -capture measurements performed at higher energies. However, this analysis is beyond the scope of this letter.

While direct capture amplitude dominates the 0^+ cascade transition at 300 keV, interference between the direct capture and the capture through the sub-threshold resonance 2^+ at 6.92 MeV is non-negligible and modifies the “pure” direct capture S-factor by 37% at this energy. Therefore, the corresponding S-factor at 300 keV is either 1.96 ± 0.3 keV b or 4.36 ± 0.45 keV b for the destructive or constructive interference case respectively. The situation is more dramatic for the 3^- cascade transition. The direct capture and resonance capture through the sub-threshold 1^- state at 7.12 MeV have about equal amplitudes at 300 keV and destructive interference makes the corresponding transition very small, 0.12 ± 0.04 keV b. The constructive interference enhances the S-factor by a factor of 3, making it 1.44 ± 0.12 keV b. Fig. 4 (a) and (b) shows the S-factors for the 0^+ and 3^- cascade transitions without

interference (direct capture only) and constructive and destructive interference with the 2^+ at 6.92 MeV and the 1^- at 7.12 MeV respectively.

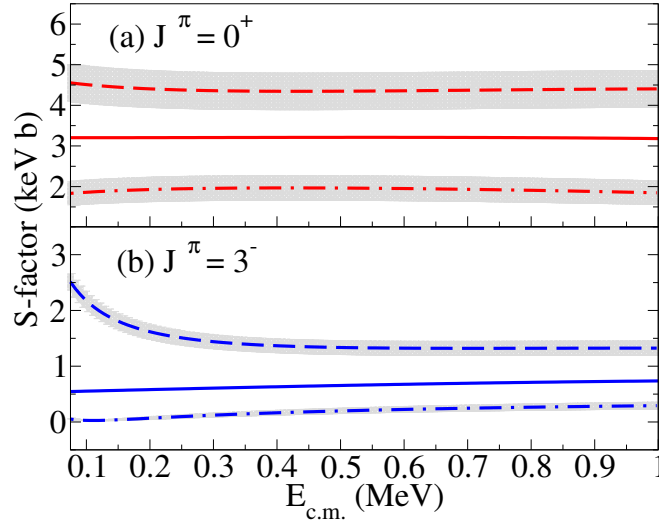


FIG. 4. (Color online) S-factor of the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction for the direct $E2$ transition to the sub-threshold 0^+ at 6.05 MeV (a) and for the 3^- at 6.13 MeV (b) without interference (solid line) and assuming constructive (dashed line) or destructive (dash-dotted line) interference with the 2^+ at 6.92 MeV and the 1^- state at 7.12 MeV in ^{16}O , respectively. The shaded bands correspond to one standard deviation uncertainties.

This result is in obvious disagreement with [4] where it was found that the 0^+ cascade transition contributes 25 keV b to the total S-factor. That experiment assumed $E1$ as a dominant component for the transition. Angular distribution of γ -rays was measured in Ref. [6] and it was shown that in fact $E2$ dominates. We find that contribution from the 0^+ cascade transition is at least a factor of 5 smaller. However, we also disagree with the results of [7], where the 0^+ cascade transition was found to contribute only 0.3 keV b. The origin of this disagreement is easy to point out. It turned out that the cross section for the 0^+ cascade transition at 300 keV is dominated by a single parameter - the ANC for the 0^+ state at 6.05 MeV. This is largely due to the α -cluster nature of this state. Based on the measured ANC (and assuming a channel radius of 5.2 fm), this state has an $\alpha+^{12}\text{C}(\text{g.s.})$ spectroscopic factor of around 40%. This is not surprising, since this state has long been identified as a bandhead of an α -cluster inversion doublet quasi-rotational band [25]. The α reduced width amplitude calculated from the measured ANC (using equations provided in Ref. [21]) is $\gamma_{6.05} = 0.48 \pm 0.08 \text{ MeV}^{1/2}$. The reduced width amplitude used in Refs.

[6, 7] for this state was $\gamma_{6.05} = 0.01 \pm_{0.01}^{0.05} \text{ MeV}^{1/2}$. This accounts for one order of magnitude difference in the S-factor. Such small value was based on the $^{12}\text{C}+\alpha$ elastic scattering data of [26]. However, an extensive R-matrix analysis of all available ^{16}O compound nucleus reactions has been carried out recently in Ref. [27]. The elastic scattering data from [26] was included into the fit and the small α reduced width amplitude for the 6.05 MeV state was not confirmed. On the contrary, the ANCs for the 0^+ and 3^- suggested in [27] ($3.2 \times 10^6 \text{ fm}^{-1}$ and $2.3 \times 10^4 \text{ fm}^{-1}$, no uncertainties are given) are in surprisingly good agreement with the direct measurements reported here.

In summary, we have investigated the important astrophysical reaction $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ through the α -transfer reaction $^{12}\text{C}(^6\text{Li}, d)^{16}\text{O}$ at sub-Coulomb energies. The ANCs for the sub-threshold states 0^+ (6.05 MeV), 3^- (6.13 MeV), 2^+ (6.92 MeV) and 1^- (7.12 MeV) in ^{16}O have been determined. The extracted ANCs for the 2^+ and 1^- states are in very good agreement with previous measurements [10, 14, 15]. The ANCs of the 0^+ (6.05 MeV) and 3^- (6.13 MeV) states were directly measured for the first time. The uncertainties related to the contribution of the 0^+ (6.05 MeV) and 3^- (6.13 MeV) cascade transitions to the total S-factor at energies near 300 keV are now dramatically reduced. The cascade transitions to the 0^+ and 3^- states were found to be determined by the interference of the E2 direct capture amplitude with the amplitude for the sub-threshold resonance capture through the 2^+ state at 6.92 MeV and 1^- state at 7.12 MeV respectively. The ANCs of the corresponding states, all of which were measured in this work, determine the direct capture and sub-threshold resonance capture amplitudes. While interference sign is still the source of uncertainty that can be eliminated by performing complete R-matrix fit of higher energy experimental data for the corresponding transitions, the maximum contribution of the 0^+ and 3^- cascade transitions can be determined by assuming positive interference in both cases. The combined contribution of these cascade transitions does not exceed 4% of the total $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ S-factor.

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