Constraining the cascade transitions in the astrophysically important $^{12}C(\alpha,\gamma)^{16}O$ reaction

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The radiative capture of α-particles on ^{12}C plays a fundamental role in astrophysics. The $^{12}C(\alpha,\gamma)^{16}O$ reaction cross section at 300 keV determines the relative abundance of $^{12}C/^{16}O$ in the stellar core as a result of helium burning. Not only this ratio determines the relative carbon-oxygen abundance in the Universe, but it 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 $^{12}C(\alpha,\gamma)^{16}O$ 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. 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 (transitions by capture to the sub-alpha-threshold excited states in ^{16}O with subsequent decay to the ground state) 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 keV b (this is 15% of the total S-factor). Contradicting conclusion was made in Refs. [5, 6], where the upper limit for the cascade transitions was set at <1 keV b. The main goal of this work was to constrain the 6.05 MeV 0^+ and 6.13 MeV 3^- cascade transitions using an independent technique.

We measured the Asymptotic Normalization Coefficients (ANCs) of all sub-alpha-threshold states in ^{16}O using the $^{12}C(^6Li,d)$ alpha-transfer reaction at sub-Coulomb energy. Measurements were performed at the John D. Fox Superconducting Accelerator Laboratory at Florida State University. The advantage of using the 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. The technique was benchmarked using the $^{16}O(^6Li,d)$ reaction and the results of this test are described in a separate report [7] and published in Ref. [8].

All four sub-alpha-threshold excited states in ^{16}O have been populated (see Fig. 1) and the ANCs for these states have been measured. Table I contains the squared ANCs for these states determined in this work in comparison with previous results for the 2^+ at 6.92 MeV and 1^- at 7.12 MeV. The ANCs for the 0^+ at 6.05 MeV and the 3^- at 6.13 MeV have been measured for the first time.

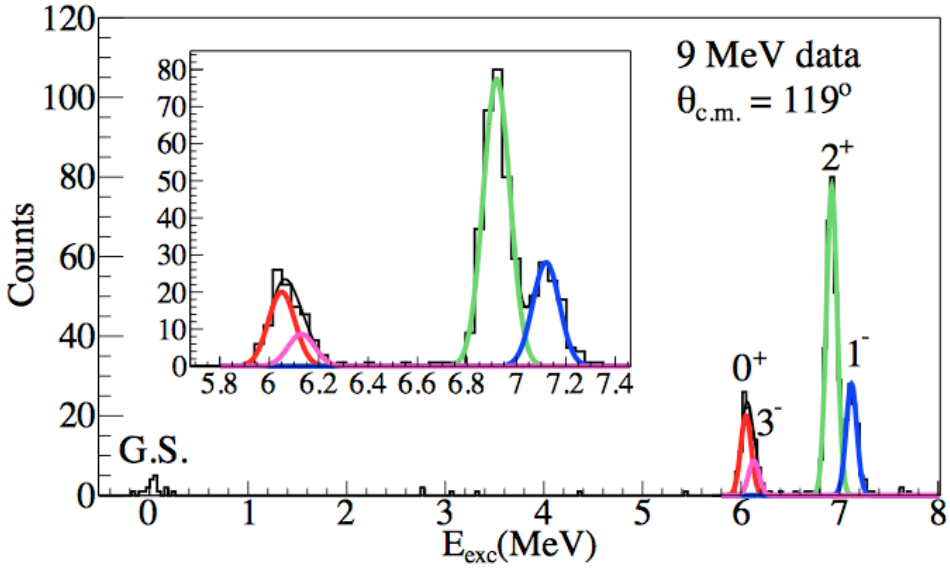

FIG. 1. Spectrum of deuterons from the $^{12}C(^{6}Li,d)^{16}O$ reaction. The ^{12}C effective beam energy is 8.7 MeV (energy in the middle of the ^{6}Li target) and the deuteron scattering angle is 119◦ in the center of mass.

Table I. Squared ANCs (in fm^{-1}) 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.

0^+ at 6.05 MeV	3^- at 6.13 MeV	2^+ at 6.92 MeV	1^- at 7.12 MeV	Ref.
		$2.07(80)\times10^{10}$	$4.0(14)\times10^{28}$	[9]
		$1.29(23)\times10^{10}$	$4.33(84)\times10^{28}$	[10]
		$2.0(13)10^{10}$	$3.5(20)\times10^{28}$	[11]
$2.43(30)\times10^{6}$	$1.93(25)\times10^{4}$	$1.48(16)\times10^{10}$	$4.39(59)\times10^{28}$	This work

Using the measured alpha ANCs the cross section for direct capture can be calculated unambiguously using the approach outlined in [12] for all cascade transitions. The strongest one is the E2 transition through the 0^+ state at 6.05 MeV with the corresponding S-factor 3.2(4) keV b. However, in addition to the direct capture component, capture through the high energy tail of the 2^+ state at 6.92 MeV into the 0^+ at 6.05 MeV is also possible. Since ANC for the 2^+ is also known the corresponding resonance amplitude can be calculated. The interference sign between

these two amplitudes (direct capture into 0^+ and capture through the tail of the 2^+ state) is not known and cannot be determined in present work. Taking into account interference, the total S-factor at 300 keV for the 0^+ cascade transition can be either 4.36(45) keV b for constructive or 1.96(30) keV b for destructive interference. Similar situation is observed for the 3^- cascade transition, for which the direct E2 capture interferes with capture through the tail of 1^- state at 7.12 MeV. The total S-factor for the 3^- cascade transition is 1.44(12) keV b for the constructive and 0.12(04) keV b for the destructive interference.

The main conclusion of this work is that while interference sign is still the source of uncertainty, the maximum contribution of the 0^+ and 3^- cascade transitions can be determined by assuming positive interference in both cases and the combined contribution of these cascade transitions does not exceed 4% of the total $^{12}C(\alpha,\gamma)^{16}O$ S-factor. Significant uncertainty for the $^{12}C(\alpha,\gamma)^{16}O$ reaction S-factor have been dramatically reduced. The results of this work are published in Ref. [13].

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