Determination of the Subthreshold State Contribution in $^{13}C(\alpha, n)^{16}O$, the Main Neutron-Source Reaction for the *s* Process

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The reaction rate of the stellar reaction $^{13}C(\alpha, n)^{16}O$, which is currently considered to be the main neutron source for the slow (*s*) process at low energies, has been rederived using the direct α-transfer reaction $^{13}C(^6Li, d)^{17}O$ leading to the subthreshold state at 6.356 MeV in ^{17}O. The contribution of the subthreshold state is found to be much smaller than the currently accepted predictions for the main neutron source of the *s* process, indicating less of a role of this reaction as the neutron source for the *s*-process scenario in low-mass stars at the asymptotic giant branch.

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Roughly half of all heavy elements in the universe are considered to have been produced through a process called the slow (*s*) process [1,2], which basically includes neutron-induced capture reactions and beta decays in relatively quiescent sites in the universe. Recent astronomical observations have reported a new class of very metal-poor stars that have almost pure *s*-process elements [3]. These require better understanding of the *s* process, including the neutron source that drives the process. The neutron source for this process is not well identified yet, and is one of the crucial issues in nuclear astrophysics. In low-mass stars at the asymptotic giant branch (AGB), the $^{13}C(\alpha, n)^{16}O$ reaction is considered to be the main source of neutron production for the *s* process [2] at low temperatures.

The major astrophysical site for the *s* process is now considered to be deep layers of low-mass stars at AGB in the late phase of the evolution [4,5]. According to the models [4,5], a ^{13}C pocket will be produced by a thermal pulse in the He shell and the successive dredge-up, where ^{13}C will be synthesized by the CNO cycle, $^{12}C(p, \gamma)^{13}N(\beta^+)^{13}C$. Then, ^{13}C burns by the (α, n) reaction in the He shell for a long time duration, providing the neutrons for the *s* process. One of the most critical problems here for nuclear physics is the reaction rate of the neutron producing reactions. The *s* process models [4–7] critically depend on the neutron flux from the $^{13}C(\alpha, n)$ reaction. They all use quite large reaction rates at low energies, following some predictions for the $^{13}C(\alpha, n)$ reaction by experiments [8] and theories [9–11], as discussed below.

However, the astrophysical *S* factor of the $^{13}C(\alpha, n)$ reaction was determined down to only 270 keV by measuring the neutrons from the reaction [8], and there is no data below 270 keV, where this reaction burns predominantly. Here, the *S* factor is defined as follows:

$$\sigma(E) = \frac{S(E)}{E}\exp(-2\pi\eta), \tag{1}$$

where η is the Coulomb parameter. Since the cross section becomes extremely small very rapidly as the incident energy decreases, the direct measurement at lower energies seems very difficult. The experimental data points at the lowest energies marginally suggest a possible rapid increase of the *S* factor toward zero energy. This would imply a large contribution [9] of the subthreshold state at 6.356 MeV, 3 keV below the α threshold in ^{17}O [12]. The recent data compilation, NACRE [10], is also adopting a very large *S* factor, although there are no other experiments. Since the experimental uncertainties are very large, it is also consistent with no enhancement [8].

The *S* factor at lower energies can be better investigated through an indirect method, a direct alpha transfer reaction in the present case. One can deduce the α-spectroscopic factor S_α from the direct α-transfer reaction and the finite-range distorted wave Born approximation (DWBA) analysis, and hence one may easily obtain the α-reduced width from it. Since the total width of the subthreshold state at 6.356 MeV is known to be 124 ± 12 keV from the $^{16}O(n, n)$ resonance study [12], the most critical parameter that determines the reaction rate of the stellar reaction $^{13}C(\alpha, n)$ is the α width.

The subthreshold contribution can be expressed using S_α of the state, as explained in the following paragraph. The *s*-process models mentioned above use about $S_\alpha = 0.3$–0.7, which implies that the state should have a

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well-developed α-cluster structure. Therefore, it is of critical importance to determine experimentally the property of the state for the problem here.

The α-reduced width γ_α^2 is related to the α-spectroscopic factor S_α as follows:

$$\gamma_\alpha^2 = 3\hbar^2/(2\mu R^2) S_\alpha. \tag{2}$$

The α width for the state can be obtained as

$$\Gamma_\alpha = 2 k_\alpha R P_l \gamma_\alpha^2, \tag{3}$$

where $R = r_0(A_1^{1/3} + A_2^{1/3})$, and P_l is the penetrability. Then, the cross section of the $^{13}C(\alpha, n)^{16}O$ reaction through the tail of the subthreshold resonance can be calculated using the Breit-Wigner single-level formula [13]:

$$\sigma(E) = \pi \lambda\!\!\!^{-2} \omega \frac{\Gamma_\alpha(E)\Gamma_n(E+Q)}{(E - E_R)^2 + [\Gamma_{tot}(E)/2]^2}, \tag{4}$$

where ω is $(2J_r + 1)/(2J_1 + 1)(2J_2 + 1)$ with J_r being the resonance spin, J_1 the projectile spin, and J_2 the target spin, and Q is the Q value of the reaction. Therefore, one should be able to determine, using Eq. (1), the astrophysical S factor due to this subthreshold resonance from measurement of the spectroscopic factor of the direct α-transfer reaction $^{13}C(^6Li, d)^{17}O$ leading to the state at 6.356 MeV.

We report here the first experimental determination of the astrophysical S factor of the $^{13}C(\alpha, n)^{16}O$ stellar reaction at low energies (< 270 keV), using the direct α-transfer reaction $^{13}C(^6Li, d)^{17}O$.

An experiment was performed using a 60-MeV ^{6}Li beam from the SF cyclotron of the Center for Nuclear Study, University of Tokyo. Isotopically enriched ^{13}C self-supporting targets (enriched to about 99.9%) with thicknesses of 140, 300, and 520 μg/cm^2 and a Mylar foil of 3-μm thickness were bombarded. The reaction products were momentum analyzed by a high-resolution magnetic spectrograph [14], and detected by a position-sensitive gas proportional counter [15] together with a plastic scintillator on the focal plane. The time-of-flight (TOF) was measured using the scintillator signal and the RF signal of the accelerator. Particle identification was made unambiguously using ΔE, E, and TOF. The overall energy resolution was about 170 keV with an aperture of 5 msr for the spectrograph.

Figure 1 shows a typical deuteron spectrum from the $^{13}C(^6Li, d)^{17}O$ reaction obtained at 30°. The peak for the 6.356 MeV state in ^{17}O was separated at large scattering angles $\theta \geq 25°$. The contribution from the carbon contamination in the target was subtracted at small angles by measuring the cross sections of $^{12}C(^6Li, d)^{16}O$ (6.917 MeV) with the same setup using the Mylar foil mentioned above. The amount of subtraction was determined with the yield ratio to the transition to the ground state in ^{16}O which was clearly separated at all angles. The

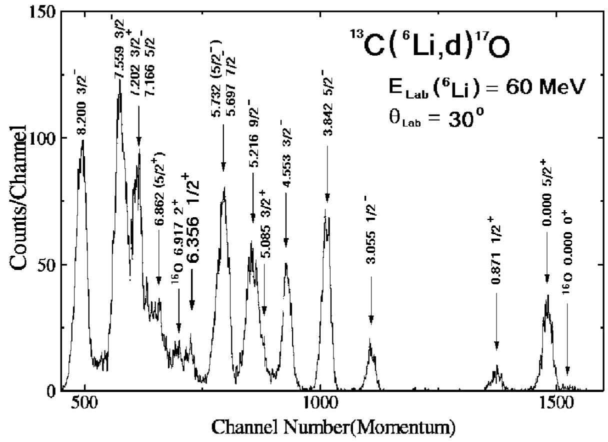

FIG. 1. Momentum spectrum of deuterons from the $^{13}C(^6Li, d)^{17}O$ reaction, measured at $\Theta_{lab} = 30°$ with a 60-MeV ^{6}Li beam.

differential cross sections for elastic scattering of $^{13}C + {}^6Li$ were also measured to determine the amount of contamination as well as to determine the optical potential parameters for the incident channel.

Figure 2 displays the $^{13}C(^6Li, d)$ angular distributions measured for the 6.356-MeV state together with the ones for other states including the 0.87-MeV $1/2^+$ state and the 3.055-MeV $1/2^-$ state in ^{17}O. The uncertainties in the experimental data are mainly due to the subtraction of the contamination contribution for the 6.356-MeV state. The two transitions to the $1/2^+$ states have similar shapes because both have the same transferred angular momentum of $L = 1$. The curves are the results of the exact finite-range DWBA calculations carried out by a computer code, TWOFNR [16], where the optical potential sets were obtained from the fitting of the elastic scattering data for the incident channel, and the ones for the exit channel were taken from Refs. [17,18]. They are summarized in Table I, where a typical set is listed for the incident channel. The bound state parameters were set to be $r_0 =$ 1.25 fm and $a = 0.65$ fm, and the depth was searched to reproduce the separation energy as is often adopted.

The experimental shapes of the angular distributions in Fig. 2 were reasonably well reproduced by the DWBA calculations. Here the optical potential sets SET1 and SET2 were chosen since the DWBA calculation gives an overall fit to the transitions. However, the behavior at very forward angles is sensitive to the choice of optical potential parameters, as can be seen by the solid and dashed lines. The DWBA curve for the 6.356-MeV $1/2^+$ state is different from that for the 0.87-MeV $1/2^+$ state at very forward angles, which is considered to be due to the Q-value dependence of the calculations, although the experimental data show less energy dependence. Here the same deuteron potential was used for the two calculations. The bumps at around 20°–30° are relatively stable against the potential parameters. Thus, we fitted the data in this angular range.

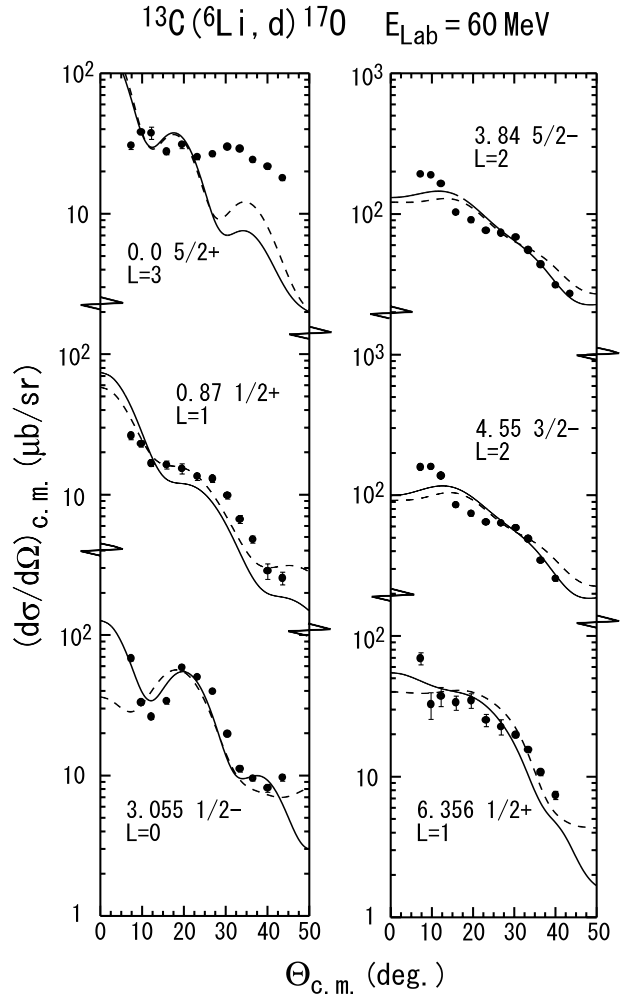

FIG. 2. Angular distributions of the $^{13}C(^6Li, d)^{17}O$ reaction leading to the states denoted. The solid lines are the DWBA calculations with the potential sets SET1 + SET2, and the dashed lines with SET1 + SET3.

It is known that the absolute cross sections of α-transfer reactions are not fully explained yet within the DWBA framework, mainly because of the difficulty of exact treatment of the cluster structure for the DWBA calculations [19]. Therefore, a normalization factor has been obtained so that the DWBA cross sections of the transition to the 3.055-MeV $1/2^-$ state, which is known to be a good α cluster state, has $S_\alpha = 0.25$. This was derived by a microscopic cluster-model calculation [20] that explains reasonably well the cluster structures in the light mass region. The normalized α-spectroscopic factor for the 6.356-MeV state is $S_\alpha = 0.011$. This S_α value changes about 5% or less due to having a different combination of the optical potential sets, which can be seen partly by the dashed line in Fig. 2. From the present experimental result, it can be concluded that the 6.356-MeV state is not a state that has a large S_α amplitude. Note that even if the measured S_α is as large as 1.0 for the 3.055 MeV state, the normalized S_α for the 6.356 MeV state can be 0.044 at most. Thus, we can conclude that S_α for the 6.356 MeV state is much smaller than that predicted before.

The reduced width for the 6.356-MeV state was obtained, using Eq. (2), to be $\gamma_\alpha^2 = 7.4$ keV, where $r_0 = 1.4$ fm was used. Then, Γ_α was derived using Eq. (3). By taking the experimental value of $\Gamma_{\rm tot} = 124$ keV, the S factor of the $^{13}C(\alpha, n)^{16}O$ reaction was calculated by Eqs. (1) and (4). Figure 3 displays the energy dependence of the S factor, which is the sum of the nonresonant contribution and the tail contributions of the subthreshold state as well as the resonant states at higher energies. Here the nonresonant term was obtained from Ref. [10]. The present S factor is much smaller than the one in [9,10], which is shown by curve A, and that suggested in [8] by curve B. The higher energy part was obtained by fitting the data of the direct measurement [8] that includes the resonances above the α threshold.

The reaction rate of the $^{13}C(\alpha, n)^{16}O$ reaction was calculated using the S factor derived above, and has been parametrized by fitting the rate with using the following formula:

$$N_A\langle\sigma v\rangle = \exp(a_1 + a_2 T_9^{-1} + a_3 T_9^{-1/3} + a_4 T_9^{1/3} + a_5 T_9 + a_6 T_9^{5/3} + a_7 \log T_9) \quad (5)$$

Here N_A is the Avogadro's number. The coefficients a_i are listed in Table II. Here the reaction rate can be valid at $T_9 = 0.01$–4.0. The uncertainty is estimated to be 26% at $0.01 \leq T_9 < 0.3$ and 20% at $0.3 \leq T_9 \leq 4.0$, which is discussed next in detail.

TABLE I. Optical potential parameters for the analysis of the $^{13}C(^6Li, d)^{17}O$ reaction. The parameters for the incident channel of $^{13}C + ^6Li$ were obtained by fitting the elastic scattering cross section data obtained in the present experiment. The exit channel parameter SET2 was obtained from Ref. [17], and the SET3 from Ref. [18]. Here the optical potential uses the Woods-Saxon form factor $f(x)$. The surface absorption term and the spin-orbit term are defined as $4W_D df(x)/dx$ and $(\hbar/m_\pi c)^2 V_{so} 1/r df(x)/drls$, respectively. Here the radius R is defined by $r_x A_{\rm target}^{1/3}$.

Set	Channel	V (MeV)	r_r (fm)	a_r (fm)	W_V (MeV)	W_D (MeV)	r_i (fm)	a_i (fm)	V_{so} (MeV)	r_{so} (fm)	a_{so} (fm)	r_C (fm)
SET1	$^{13}C + ^6Li$	135.1	1.428	0.750	11.0		2.161	0.680				1.3
SET2	$^{17}O + d$	68.2	1.250	0.693		12.2	1.25	0.750	6.0	1.25	0.693	1.3
SET3	$^{17}O + d$	83.1	1.050	0.782		8.8	1.29	0.776	4.4	1.05	0.782	1.3

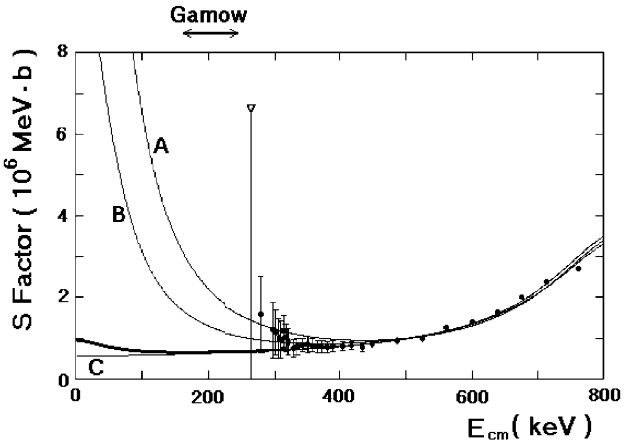

FIG. 3. Astrophysical S factors of the $^{13}C(\alpha, n)^{16}O$ stellar reaction together with the experimental data taken from Ref. [8]. The thick solid curve is the result derived here, including the subthreshold resonance contribution. Curves A, B, and C are the results with $S_\alpha = 0.7$, 0.3, and 0.0, respectively. See text for details.

The contribution of the subthreshold state to the present reaction rate is much smaller than that suggested before, roughly 1.6% at low temperatures. The present reaction rate, thus, is smaller than the NACRE recommendation [10] roughly by a factor of 4 at $T_9 = 0.1$, indicating that the subthreshold state contribution is very minor even at low temperatures. Since the possible maximum S_α factor is 0.044 as discussed before, the maximum uncertainty due to the subthreshold contribution is about 17% at $T_9 < 0.3$. The total uncertainty at low temperatures includes mainly two components, one from this subthreshold contribution and the other from the uncertainty of the direct measurement and the extrapolation procedure, which totally amount to about 20% [8,10] below $T_9 = 0.3$. Altogether, these will give the uncertainties provided in the last paragraph. Therefore, the reaction rate in Eq. (5) represents the experimental data at high energies measured and the subthreshold contribution of the 6.356 MeV state derived here as well. Note that the old rate [21] is not applicable at any temperature region because it was obtained before the direct measurement [8] and it did not include any of the subthreshold contribution at low temperatures. The s-process models that used the reaction rate of large subthreshold enhancement need to be checked carefully since the neutron flux changes considerably. They might need more ^{13}C to have the same neutron densities by thermal pulses, or need to have a longer time period between the thermal pulses, for example.

In summary, the reaction rate of the possible main neutron-source stellar reaction, $^{13}C(\alpha, n)^{16}O$, was investigated by the direct α transfer reaction, and it has been found that there would be no such large enhancement of neutron productions due to the subthreshold state at 6.356 MeV at low temperatures for the s process. It would be of great interest to determine the effect of the new reaction rate in the s process analysis.

TABLE II. Reaction rate parameters obtained for the $^{13}C(\alpha, n)^{16}O$ stellar reaction. The parameters have been optimized at $T_9 = 0.01$–4.0.

Parameter	Value
a_1	-3.690392×10^1
a_2	7.784191×10^{-2}
a_3	-4.815691×10^1
a_4	1.093879×10^2
a_5	-2.195909×10^1
a_6	3.161556×10^0
a_7	-2.592545×10^1

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