Resonant Rate for $^{15}O(\alpha,\gamma)^{19}Ne$

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We have measured angular distributions for the $^{15}N(^6Li,d)^{19}F$ and $^{16}O(^6Li,d)^{20}Ne$ reactions at a bombarding energy of 22 MeV. Distorted-wave Born-approximation and Hauser-Feshbach calculations were used to analyze the data. Ratios of α-transfer cross sections in ^{19}F and ^{20}Ne, plus isospin invariance, provide ratios of α widths in ^{19}Ne and ^{20}Ne. Using ^{20}Ne (1^-, 5.788 MeV) as a standard allows the determination of the α-particle width for the state at 4.033 MeV in ^{19}Ne, and hence the resonant rate for the $^{15}O(\alpha,\gamma)^{19}Ne$ reaction, contributed from the 504 keV, $\frac{3^+}{2}$ resonance, at temperatures of astrophysical interest.

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One of the two links between the hot CNO (HCNO) cycles and the rapid proton capture process (rp process) is through the $^{15}O(\alpha,\gamma)^{19}Ne$ reaction [1]. At temperatures $T \geq 3.5 \times 10^8$ K ($T_9 \geq 0.35$), the $^{15}O(\alpha,\gamma)^{19}Ne$ $(p,\gamma)^{20}Na(\beta^+\nu)^{20}Ne$ reaction sequence causes a breakout. Once the ^{20}Ne has been formed, no sequence of reactions can recycle the seed nuclei back to CNO cycles, and proton-rich nuclei above mass 20 are the dominant product of explosive hydrogen burning. Furthermore, the rate of energy production is not limited by the slow β decay of ^{15}O, and the energy generated by the resulting sequence of rp process and β decays can exceed the energy generation rate of the HCNO cycle by a factor of 100 [2]. Although many theoretical and experimental efforts have been made [2–5], the rate for the $^{15}O(\alpha,\gamma)^{19}Ne$ reaction remains unclear because of the unknown resonant reaction rate from the potentially most important state at $E_{c.m.} = 504$ keV ($E_x = 4.033$ MeV, $J^\pi = \frac{3^+}{2}$). This state is located in the Gamow peak for most of the temperatures of astrophysical interest ($T_9 = 0.1$ to 2) and has low-angular-momentum transfer ($L = 1$) in α capture. Direct measurement of the cross section is difficult because the penetration factor is reduced dramatically by the Coulomb barrier at this energy.

The resonant reaction rate can be expressed as

$$N_A\langle\sigma v\rangle = 1.5396 \times 10^5 \frac{1}{A^{3/2}T_9^{3/2}} \times (\omega\gamma)_r \exp\left(-\frac{11.605E_r}{T_9}\right) \text{cm}^3\,\text{s}^{-1}\,\text{mole}^{-1}$$

for an isolated narrow resonant state, where A is the reduced mass number of the resonant system and E_r is the resonant energy in MeV. In the above formula, $(\omega\gamma)_r$ is called resonant strength and is in eV. The expression for $(\omega\gamma)_r$ is

$$(\omega\gamma)_r = \frac{2J+1}{(2I_1+1)(2I_2+1)} \frac{\Gamma_\alpha\Gamma_\gamma}{\Gamma_{\text{tot}}}$$

for the (α,γ) reaction, where J is the total angular momentum of a resonance and I_1, I_2 are the spins of the fragment nuclei. The quantities Γ_γ, Γ_α, and Γ_{tot} are the γ-ray, the α, and the total widths. Thus the resonant cross section can be calculated by using the resonant energy, spins, the total width, the γ-ray width, and the α width of a state. The resonant energy and the spin of the 504 keV resonance have been measured accurately [6], and the γ-ray width can be estimated from the width of its mirror state in ^{19}F (located at $E_x = 3.908$ MeV). Actually, at an energy of 504 keV, the total width is dominated by the γ-ray width, and the ratio between the α width and the total width is expected to be about 10^{-4}, which makes the measurement of the α width very difficult. Because the γ-ray width is much larger than the α width, the total width is approximately equal to the γ-ray width. Then the resonant strength depends on only the α width. The states at 3.908 MeV in ^{19}F and 4.033 MeV in ^{19}Ne are mirrors; therefore they should have the same α-particle spectroscopic factor. The α width of the ^{19}Ne state can thus be determined from the α spectroscopic factor measured in α transfer leading to the ^{19}F state. We see below that we can, by using information in both ^{19}F and ^{20}Ne, actually bypass the spectroscopic factor and determine the ^{19}Ne α width directly.

Langanke *et al.* [3] and Magnus *et al.* [5] adopted an α width of 7.2 μeV in their calculation of the rate for the 504 keV resonance. This value of the α width was based on an estimate of its reduced width $\theta_\alpha^2 = 0.06$, from a preliminary analysis of the present $^{15}N(^6Li,d)$ reaction. A more careful analysis of the experimental data is desirable to obtain a more accurate α width of the 504 keV resonance for a more reliable rate for the $^{15}O(\alpha,\gamma)^{19}Ne$ reaction (the reaction rate is sensitive to the α width because of $\omega\gamma \sim \Gamma_\alpha$). The α width of a state can be obtained from $\Gamma_\alpha = S_\alpha\Gamma_{\text{sp}}$, where Γ_{sp} is the α single-particle width and S_α is the α stripping spectroscopic factor of the state. The single-particle width of the 504 keV resonance can be calculated using the code ABACUS [7], approximating the α nucleus potential by a real Woods-Saxon well. Details of this calculation are given later in the present Letter.

To obtain an experimental spectroscopic factor, we have measured the $^{15}N(^6Li,d)^{19}F$ and $^{16}O(^6Li,d)^{20}Ne$

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reactions at a bombarding energy of 22 MeV. Distorted-wave Born-approximation (DWBA) and Hauser-Feshbach (HF) calculations were performed in order to obtain the alpha spectroscopic factors for all low-lying states. The contribution from the 504 keV resonance to the rate of the $^{15}O(\alpha,\gamma)^{19}Ne$ reaction is calculated using the new value of its α width.

The experiment was performed with 22 MeV $^6Li^{+++}$ ions from the University of Pennsylvania tandem accelerator. Outgoing deuterons were momentum analyzed in a multiangle spectrograph and detected on 25 μm NTA nuclear emulsion plates. The ^{15}N target gas was isotopically enriched in ^{15}N (99.5%). The ^{16}O experiment used natural oxygen (99.8% ^{16}O). The gas cell contained no entrance window. Outgoing deuterons exited through a 295 $\mu g/cm^2$ Mylar window and the emergent Li beam through a Ni foil [8]. Deuteron spectra were recorded in 7.5° angular intervals, beginning at 7.5° and ending at 80.0° for ^{15}N and 135° for ^{16}O. Spectra at 7.5° are presented in Fig. 1 for the regions of interest. The absolute scale of the cross sections is probably accurate to a few percent, relative cross sections to better than ±3%.

The $^{16}O(^6Li,d)$ angular distributions for the 4.967 MeV, 2^- and 5.788 MeV, 1^- states in ^{20}Ne were measured, for the purpose of normalizing theoretical cross sections. Figure 2 displays the angular distributions for these two states. The 1^- state is strongly excited and has a known α-particle width [6]. It thus serves as an excellent calibrator of the DWBA calculation, as discussed later. The unnatural parity 2^- state is forbidden in simple α transfer, and thus can be used, with HF calculations, to assess the magnitude of the compound-nucleus contribution to the cross section.

At a bombarding energy of 22 MeV, analyses of other $(^6Li,d)$ experiments in the mass region of $A = 10-20$ have demonstrated that a direct reaction mechanism dominates. We have assumed the states are populated through a pure one-step direct reaction mechanism in the DWBA calculation. In order to test the stability of the calculations, we have tried several different optical potentials. The *PL* optical potentials of Ref. [9] produced smooth behavior of the maximum differential cross sections when we varied the radius parameter ($r_{0\alpha}$) and principal quantum number (q) of the transferred α, for both the $^{15}N(^6Li,d)$ and $^{16}O(^6Li,d)$ reactions. Given the ^{20}Ne 1^- state, whose α width is known ($\Gamma_\alpha = 28 \pm 3$ eV) and whose α transfer cross section is presented herein, the α width of the ^{19}Ne, $\frac{3}{2}^+$ state can be determined in an almost parameter-free way from its mirror α-transfer cross section, also presented herein. For $^{16}O(^6Li,d)^{20}Ne$ (1^-), we have $\sigma_{exp}(20) = NS_\alpha(20)\sigma_{DW}(20)$, while for $^{15}N(^6Li,d)^{19}F$ $(\frac{3}{2}^+)$, the result is $\sigma_{exp}(19) = \frac{2}{3}NS_\alpha(19)\sigma_{DW}(19)$, where S_α is the α spectroscopic factor, N is a constant related to the structure of the incident particle, and σ_{DW} is the cross section calculated using the code DWUCK4 [10]. Furthermore, in $^{19,20}Ne$, $S_\alpha(19) = \Gamma_\alpha(19)/\Gamma_{sp}(19)$ and $S_\alpha(20) = \Gamma_\alpha(20)/\Gamma_{sp}(20)$, with the single-particle α widths calculated at the appropriate energies. Thus

$$\Gamma_\alpha(19) = \frac{3}{2}\Gamma_\alpha(20) \times \left[\frac{\Gamma_{sp}(19)}{\Gamma_{sp}(20)}\right]\left(\frac{\sigma\,\mathrm{exp}(19)}{\sigma\,\mathrm{exp}(20)}\right)\left[\frac{\sigma_{DW}(20)}{\sigma_{DW}(19)}\right].$$

Now, the quantities Γ_{sp} and σ_{DW} can depend sensitively on, for example, the radius of the α-particle potential

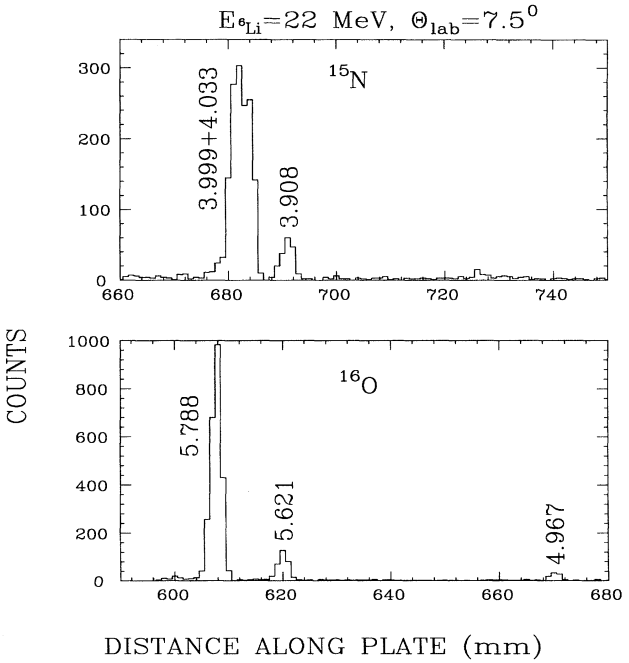

FIG. 1. Spectrum of the $^{15}N(^6Li,d)^{19}F$ (upper) and $^{16}O(^6Li,d)^{20}Ne$ (lower) reactions at bombarding energy of 22 MeV and a laboratory angle of 7.5°. Peaks are labeled with their excitation energies in MeV [6].

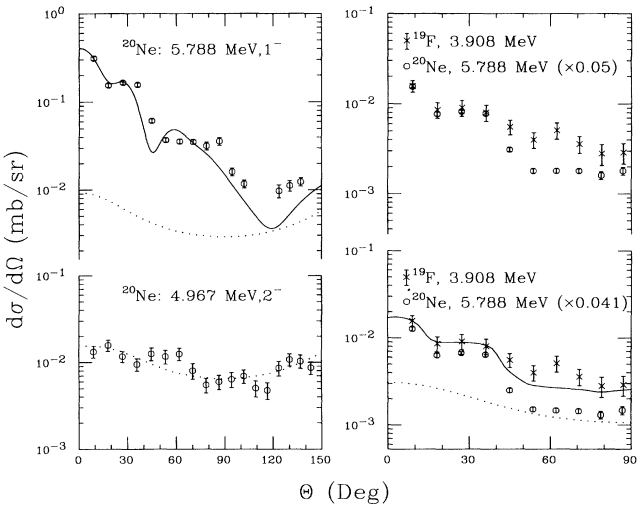

FIG. 2. Angular distributions of the $(^6Li,d)$ reactions, leading to the states indicated, compared with DWBA, HF, and empirical curves (see text).

well, or the principal quantum number. However, the dimensionless ratios in square brackets are nearly independent of changes in the parameters—provided the same value is used for $A = 19$ and 20. Similarly, the ratios $\Gamma_{sp}(A)/\sigma_{DW}(A)$ are very insensitive to q and $r_{0\alpha}$, provided the same values are used in ABACUS and DWUCK. For example, a 10% change in the radius parameter causes a change of only 8.5% in the extracted ^{19}Ne α width.

In this Letter, we present the results for $r_{0\alpha} = 1.40$ fm. This value gives absolute α spectroscopic factors near unity (0.90 ± 0.13) and near the expected 0.20 for ^{20}Ne (6^+, 8.78 MeV) [11,12]. Further details of this procedure will be presented in a forthcoming article. We have used both $q = 7$ and 9 for the total number of quanta of excitation. The latter is appropriate for $(sd)^3(fp)$ transfer, the former for $(1p)(sd)^3$. The 1^- state in ^{20}Ne is commonly thought to have $q = 9$, and, in fact, to have a nearly pure SU(3) configuration $(\lambda\mu) = (90)$. We have also computed, with the code ABACUS [7], the α single-particle widths for ^{19}Ne ($\frac{3}{2}^+$) and ^{20}Ne (1^-) with the above values of $r_{0\alpha}$ and q. As mentioned above, the value $q = 9$ is almost certainly the one to use for ^{20}Ne (1^-).

Of course, the experimental cross section for ^{15}N(^{6}Li, d)^{19}F (3.908 MeV) to be compared with σ_{DW} is merely the direct component, and the observed cross section is small enough that a check for other reaction mechanisms should be done. The experimental angular distribution (Fig. 2) of the first 2^- state in ^{20}Ne at an excitation energy of 4.967 MeV, populated in the ^{16}O(^{6}Li, d) reaction, is observed to be approximately symmetric about 90°, thus indicating that this 2^- state is probably populated via a compound reaction mechanism. The compound reaction cross section for the 2^- state is about 10^{-2} mb/sr, which is comparable to those at large angles for weak states in ^{19}F. Therefore, for (^{6}Li, d) reactions, a compound reaction mechanism is probably present. The code STATIS [13] calculates compound reaction cross sections by adopting the Hauser-Feshbach method. Because of the selection rule forbidding one-step direct reaction, we analyzed the date for this 2^- state by assuming a pure compound reaction mechanism. Shown in Fig. 2 is the theoretical HF angular distribution in comparison with the experimental data. A normalization factor of 0.60 ± 0.04 was obtained from the least-square fit ($\chi^2 = 1.4$). The HF mechanism makes a negligible contribution to the 1^- state. The HF cross sections for ^{15}N(^{6}Li, d) have also been calculated in the same way.

In the right-hand half of Fig. 2, we plot at the top the measured angular distributions for the 3.908 MeV state of ^{19}F and the 5.788 MeV state of ^{20}Ne (renormalized by a factor of 0.05). In the bottom right of Fig. 2 we have fitted to the expression $\sigma_{exp}(19) = \alpha\sigma_{exp}(20) + \beta\sigma_{HF}(19)$. Values extracted for α and β are 0.040 ± 0.004 and 0.65 ± 0.06 with $\chi^2 = 1.5$ from the least-square fit. The value of β is reassuringly close to the value extracted for ^{20}Ne (2^-), so we can use $\beta = 0.60$ in further fitting. Thus we obtained $\alpha = 0.041 \pm 0.004$. It is this α value that should be used for the ratio $\sigma_{exp}(19)/\sigma_{exp}(20)$ in the equation for $\Gamma_\alpha(19)$.

Values of Γ_α for the ^{19}Ne resonance are extracted. Uncertainties for each of those values contain contributions of about 10% from the measured direct component of the cross section, an estimated 4% from the *ratios* of σ_{DW}, and 11% from the experimental value of Γ_α for ^{20}Ne (1^-). The Γ_α are 8.8 ± 1.4 μeV for $q = 9$ and 11.0 ± 1.7 μeV for $q = 7$. The average is 9.9 ± 1.5 μeV. The dominant configuration of ^{19}F (3.91 MeV) [and its mirror ^{19}Ne (4.033 MeV)] is five-particle two-hole (5p-2h) relative to a closed ^{16}O core, i.e., $(sd)^5(1p)^{-2}$. As such, it can be reached via $q = 7$ α transfer from the 2p-3h $[(sd)^2(1p)^{-3}]$ configuration impurity in ^{15}N (g.s.). Alternately, the dominant $(sd)^5(1p)^{-2}$ configuration could mix slightly with $(1p)^{-1}[(sd)^3fp]$ and hence acquire $q = 9$ α strength from the dominant p^{-1} component of ^{15}N (g.s.). The true α width probably lies between the values extracted for pure $q = 7$ and 9 transfer.

The resonant rate for the ^{15}O(α, γ) reaction from the 504 keV resonance has been calculated using the above α widths obtained for $r_{0\alpha} = 1.40$ fm. Results are plotted in Fig. 3 (solid curves). A different reaction rate could be obtained by using different values of $r_{0\alpha}$. For example, the rate could be 30% larger for $r_{0\alpha} = 1.94$ fm and 10% lower for $r_{0\alpha} = 1.25$ fm. For the purpose of comparison, we have also plotted the rate of Langanke *et al.* [3] and Magnus *et al.* [5] in Fig. 3 (dashed curve). Our rate is 1.22 to 1.53 times that in Refs. [3,5]. Adopting the resonant reaction rate of Magnus *et al.* [5] for ^{15}O(α, γ)^{19}Ne from the other states, the total rate will increase by about 22% to 53% at $T_9 \leq 0.6$. Because of the 15% uncertainty, the lower boundary of the rate for $q = 7$ is very close to that adopted earlier

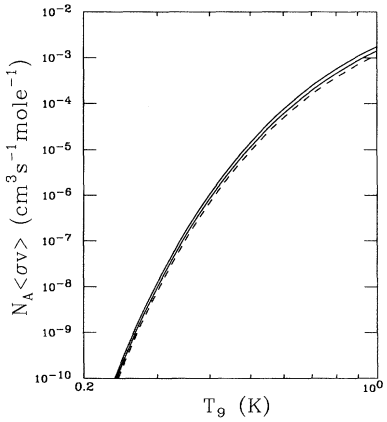

FIG. 3. Resonant rates of the ^{15}O(α, γ)^{19}Ne reaction from the 504 keV, $\frac{3}{2}^+$ resonance using $r_{0\alpha} = 1.40$ fm. The upper solid curve is for $q = 9$ and the lower one is for $q = 7$. The uncertainties are 15% in both cases. The dashed curve is the rate used in Refs. [3,5] for the same resonance.

[3,5]. However, we believe that the rate is somewhat larger than that used before, since the wave function of the 4.033 MeV, $\frac{3^+}{2}$ state consists of both $q = 7$ and 9 components.

A very recent experimental study by Page *et al.* showed that the upper limit of the resonant rate for $^{19}\mathrm{Ne}(p,\gamma)^{20}\mathrm{Na}$ from the 447 keV resonance [14] is only about 25% of that Brown *et al.* predicted [15], but still about 3 times that of Smith *et al.* [16]. Therefore, the reaction rate for $^{19}\mathrm{Ne}(p,\gamma)^{20}\mathrm{Na}$ is much larger than that for $^{15}\mathrm{O}(\alpha,\gamma)^{19}\mathrm{Ne}$. Assuming hydrogen and helium mass fractions of $X_{\mathrm{H}} = 0.77$ and $X_{\mathrm{He}} = 0.20$, the ratio of the reaction rate for $^{19}\mathrm{Ne}(p,\gamma)^{20}\mathrm{Na}$ to that for $^{15}\mathrm{O}(\alpha,\gamma)^{19}\mathrm{Ne}$, used in Refs. [3,5], varies from $10^{6.4}$ at $T_9 = 0.4$ to 10^2 at $T_9 = 2.0$, indicating that once material is converted into $^{19}\mathrm{Ne}$, it will be rapidly passed along to higher masses. Our new rate for $^{15}\mathrm{O}(\alpha,\gamma)^{19}\mathrm{Ne}$ thus will enhance the rate of the breakout of the HCNO cycle by a factor of about 1.4 to 1.8. This enhanced rate will also lower the temperature-density boundary line at which $^{15}\mathrm{O}(\alpha,\gamma)^{19}\mathrm{Ne}$ competes equally with $^{15}\mathrm{O}$ β decay. However, detailed calculation of the reaction network should be done before drawing any further conclusion on any significant change of the breakout of HCNO cycle in astrophysical sites.

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[1] A. E. Champagne and M. Wiescher, Annu. Rev. Nucl. Part. Sci. **42**, 39 (1992).
[2] R. K. Wallace and S. E. Woosley, Astrophys. J. Suppl. **45**, 39 (1981).
[3] K. Langanke, M. Wiescher, W. A. Fowler, and J. Görres, Astrophys. J. **301**, 629 (1986).
[4] P. V. Magnus, M. S. Smith, P. D. Parker, R. E. Azuma, C. Campbell, J. D. King, and J. Vise, Nucl. Phys. **A470**, 206 (1987).
[5] P. V. Magnus, M. S. Smith, A. J. Howard, P. D. Parker, and A. E. Champagne, Nucl. Phys. **A506**, 332 (1990).
[6] F. Ajzenberg-Selove, Nucl. Phys. **A475**, 1 (1987).
[7] S. Zawadski, computer code ABACUS (unpublished).
[8] R. R. Betts, H. T Fortune, and R. Middleton, Phys. Rev. C **8**, 660 (1973).
[9] H. T. Fortune, M. N. I. Al-Jadir, R. R. Betts, J. N. Bishop, and R. Middleton, Phys. Rev. C **19**, 756 (1979).
[10] P. D. Kunz, computer code DWUCK4 (unpublished).
[11] H. T. Fortune, R. R. Betts, J. D. Garrett, and R. Middleton, Phys. Lett. **44B**, 65 (1973).
[12] H. T. Fortune and D. Koltenuk, Phys. Rev. C **51**, 1859 (1995).
[13] R. Stokstad, computer code STATIS (unpublished).
[14] R. D. Page *et al.,* Phys. Rev. Lett. **73**, 3066 (1994).
[15] B. A. Brown, A. E. Champagne, H. T. Fortune, and R. Sherr, Phys. Rev. C **48**, 1456 (1993).
[16] M. S. Smith, P. V. Magnus, K. I. Hahn, A. J. Howard, P. D. Parker, A. E. Champagne, and Z. Q. Mao, Nucl. Phys. **A536**, 333 (1992).