^{22}Ne(d,p)^{23}Ne reaction and neutron balance in the s process

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One possible source of neutrons for the astrophysical s process is the ^{22}Ne(α,n)^{25}Mg reaction. However, the number of neutrons available to synthesize heavy elements may be limited by the rate of the ^{22}Ne(n,γ)^{23}Ne reaction. To aid in the interpretation of recent (n,γ) measurements, we have used the ^{22}Ne(d,p)^{23}Ne reaction to investigate the single-particle structure of states located near the ^{22}Ne+n threshold. No states that correspond to astrophysically significant resonances were found, and so the (n,γ) rate is effectively determined by direct capture.

Neutron-capture nucleosynthesis via the s process is believed to occur during core He burning in massive stars[1,2] and/or in the He-burning shells of asymptotic-giant-branch (AGB) stars.[3,4] In the core-burning and low-mass AGB's ($M \leq 2M_{\odot}$) scenarios, the ^{13}C(α,n)^{16}O reaction is thought to be the major source of neutrons, but in intermediate-mass AGB's ($M=2-10M_{\odot}$), the ^{22}Ne(α,n)^{25}Mg reaction, operating at $kT=20-30$ keV, has been postulated as the primary neutron source (see Ref. 3 and references therein). A major unresolved question is the extent to which the ^{22}Ne(n,γ)^{23}Ne reaction serves to limit the amounts of neutrons and ^{22}Ne available to catalyze the synthesis of heavy elements.

Whereas early calculations[5] which included the effect of neutron capture by ^{22}Ne used an estimate of σ_γ ($kT=30$ keV)=0.05 mb for the Maxwellian-averaged capture cross section (evaluated at the canonical s-process energy), a subsequent measurement[6] indicated a value in the range 0.2 mb$\leq \sigma_\gamma \leq$1.6 mb. Such a large ^{22}Ne+n cross section would cause a substantial reduction in the s-process yield of heavy elements.[7–9] However, a recent remeasurement[10] of this capture cross section indicates a reduced magnitude (by a factor ≈ 6) in the range 0.04 mb$\leq \sigma_\gamma \leq$0.27 mb and thus implies a reduced influence on the s-process yield. Using a neutron beam with an approximately Maxwellian energy profile, Beer *et al.*[11] have made a direct measurement of the average capture cross section at $kT \approx 25$ keV, yielding an extrapolated value of σ_γ (30 keV)=0.060$\pm$0.005 mb. The magnitude of this cross section is near what would be expected for formation via a pure direct-capture (DC) process. The latter two results[10,11] are consistent with one another and with the previous theoretical estimate[5] for energies near $kT=30$ keV.

The (n,γ) cross section presented in Ref. 10 was obtained by subtracting a substantial background from the raw data, and there may have been some systematic effects associated with that procedure. In contrast, the technique employed in Ref. 11 (activation followed by measurement of residual nuclei) is comparatively free of systematic bias. However, in view of the importance of this cross section to models of the s process, an independent confirmation of these results is warranted. In the present work, we have used the ^{22}Ne(d,p)^{23}Ne neutron-transfer reaction to investigate the properties of states located near the ^{22}Ne+n threshold. Here neutron-capture resonances would manifest themselves as single-particle states, and their neutron spectroscopic factors C^2S are linearly related to the neutron width of the resonance, as discussed below. Note that the magnitude of the cross section in Ref. 11 implies that there should be no astrophysically significant resonances located in the vicinity of 25 keV above the neutron-capture threshold [$Q_{(n,\gamma)}$ =5.200(2) keV (Ref. 12)].

The ^{22}Ne(d,p)^{23}Ne reaction was induced using a 24.1-MeV deuteron beam provided by the Princeton AVF cyclotron. The target was prepared[13] by ion implantation into a 40-μg/cm^2 carbon foil. This produced a stable target with a ^{22}Ne areal density of $\sim$6 μg/cm^2. Outgoing protons were detected in the focal plane of a QDDD spectrometer at angles $10° \leq \theta_{lab} \leq 20°$ in 2.5° steps and at θ_{lab}=25°, 30°, and 35°. A spectrum collected at θ_{lab}=15° is shown in Fig. 1. Excitation energies were determined from a calibration based upon the energies of well-known states (tabulated in Ref. 14) populated in the ^{18}O(d,p)^{19}O reaction. The resulting ^{23}Ne energies are in good agreement with prior results.[12,15] The angular-distribution data were analyzed using the distorted-wave Born approximation (DWBA) code DWUCK4 (Ref. 16) with optical-model parameters appropriate for this mass and energy region.[17,18] An absolute cross-section scale was established by normalizing the relative spectroscopic factors measured for several low-lying bound states to tabulated[12] values. The overall uncertainty in the absolute

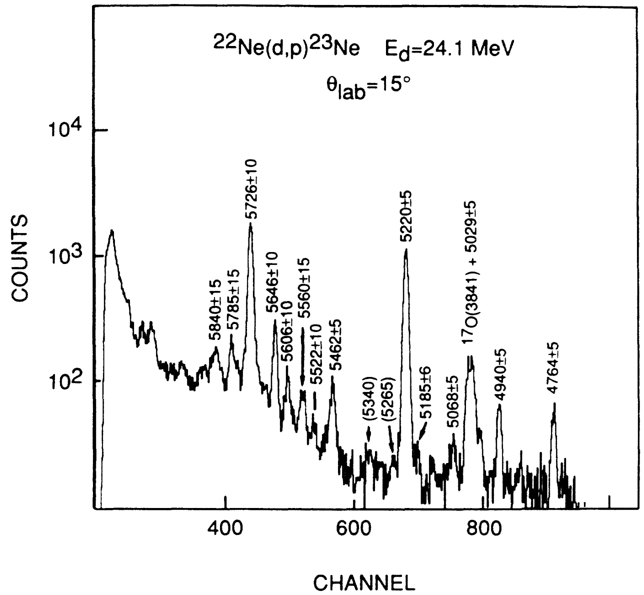

FIG. 1. Spectrum from the ^{22}Ne$(d,p)^{23}$Ne reaction. The excitation energies (in keV) are from the present work. The states labeled with parentheses are at the limit of detectability, but are observed at more than one angle and shift kinematically as would be expected for ^{23}Ne. The neutron-capture threshold is located at $E_x = 5200$ keV.

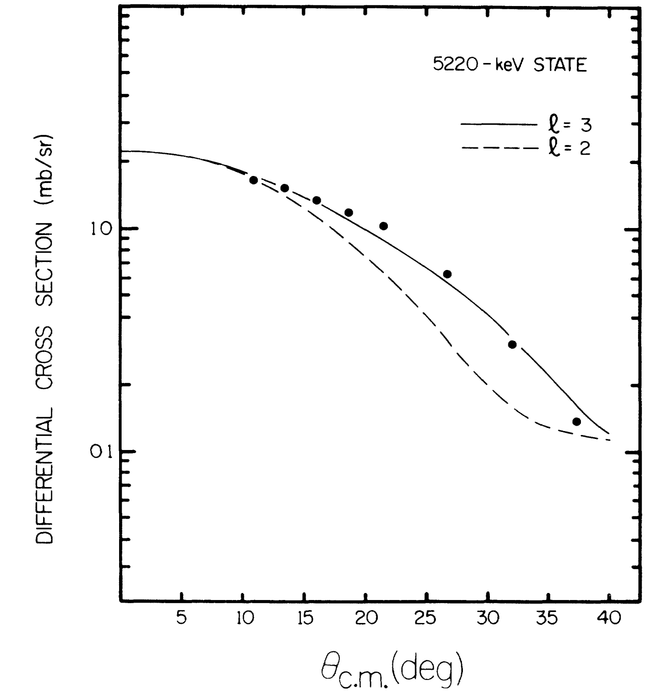

FIG. 2. Angular distribution and associated DWBA fits for $l_n = 2$ and 3 for the 5220-keV state. The intercomparisons establish $l_n = 3$ for this case.

cross sections obtained by this procedure is $\pm 30\%$.

In this mass and energy region, the (d,p) reaction predominantly populates states formed by angular momentum transfers $l_n \leq 3$ (in a first-order direct reaction) and is therefore less selective than the (n,γ) reaction which, because of barrier-penetrability considerations, is dominated by any $l_n = 0$ and 1 resonances at low energy. Thus in regions of high level density, it can be difficult to make a direct comparison between (d,p) and (n,γ) data.[19,20] However, in the present case, the level density is low enough so that a direct correspondence can be made with existing (n,γ) data: The lowest tabulated[21] (n,γ) resonance is a p-wave resonance at $E_{\text{c.m.}} = 262$ keV, which corresponds to the state observed at $E_x = 5462$ keV. Its (d,p) angular distribution clearly indicates $l_n = 1$ transfer. Only one state below this level is strongly populated: that at an excitation energy $E_x = 5220$ keV. Its angular distribution (Fig. 2) is characteristic of $l_n = 3$ angular momentum transfer. The $l_n = 2$ DWBA calculation, also shown in Fig. 2, clearly does not fit the data. Therefore, this state corresponds to an f-wave resonance at $E_{\text{c.m.}} = 20 \pm 6$ keV. However, the strong centrifugal barrier implies that this resonance is quite weak, as is demonstrated below. No other states in this energy region show discernible single-particle structure in their angular distributions.

The Maxwellian-averaged capture cross section for a narrow resonance can be written as

$$\sigma_\gamma(kT) = \frac{4\pi^{3/2}}{k^2(E_{\text{c.m.}})} \frac{(2J_r+1)}{2} \frac{\Gamma_n \Gamma_\gamma}{\Gamma} \frac{E_{\text{c.m.}}}{(kT^2)} e^{-E_{\text{c.m.}}/kT} ,$$

where $k(E_{\text{c.m.}})$ is the neutron wave number evaluated at the resonance energy $E_{\text{c.m.}}$, J_r is the spin of the resonance, and Γ_n, Γ_γ, and Γ are, respectively, the neutron and gamma-ray partial widths and the total width of the resonance. The neutron width can be calculated from the usual prescription[22]

$$\Gamma_n = 2\gamma_{\text{sp}}^2 C^2 S P_l(E_{\text{c.m.}}) ,$$

where γ_{sp}^2 is a single-particle reduced width, C^2S is the neutron spectroscopic factor, and $P_l(E_{\text{c.m.}})$ is the neutron penetrability. The spectroscopic factor can be obtained from the relationship[16] between the measured (d,p) cross section σ_{exp} and the DWBA prediction σ_{DW}:

$$\sigma_{\text{exp}} = 1.53 C^2 S \sigma_{\text{DW}} .$$

For the 20-keV resonance, γ_{sp}^2 was calculated by finding the wave function for a neutron scattered from a realistic, diffuse nuclear potential, and $C^2S = 0.04$ was obtained from the angular-distribution data (assuming $J^\pi = \frac{5}{2}^-$). The resulting neutron width is $\Gamma_n = 6 \times 10^{-4}$ eV. The uncertainty in the resonance energy results in an uncertainty in the neutron width of about a factor of 2.

The magnitude of the measured thermal cross section $\sigma_{\text{th}} = 45.5 \pm 6.0$ mb (Ref. 21) is consistent with pure direct capture (DC). Thus the DC component of the capture cross section at $kT = 30$ keV can be obtained from a $1/v$ extrapolation[23] of σ_{th} with the result that σ_γ (30 keV)$_{\text{DC}} = 4.2 \times 10^{-2}$ mb. The total cross section is the sum of DC and resonant parts, but the resonance contribution appears to be negligible: Assuming that $\Gamma_\gamma \gg \Gamma_n$, the capture cross section for the 20-keV resonace is 5×10^{-4} mb, a factor of 84 smaller than the DC cross section. Similarly, the tail of the next known resonance (at 262 keV) contributes 7×10^{-4} mb to the total capture cross section. Note that this resonance is slightly stronger at $kT=30$ keV than the 20-keV resonance even though it is located well above threshold. This situation is a rather dramatic consequence of penetration through the centrifugal barrier, which inhibits formation of the low-energy f-wave resonance (20 keV) as compared to the higher-energy p-wave resonance (262 keV). It is possible that intermediate states, corresponding to astrophysically significant s- or p-wave resonance, could escape our detection if weakly populated in the (d,p) reaction (in this case, if $C^2S\leq3\times10^{-3}$). However, no statistically significant evidence for any such state exists in the (n,γ) data of Winters and Macklin.[10]

The lack of any threshold states which are characterized by low angular momentum transfer *and* measurable single-particle strength implies that the dominant contribution to the $^{22}Ne(n,\gamma)^{23}Ne$ reaction is *most probably* DC at stellar energies. Therefore, the low-energy cross section should display a $1/v$ velocity dependence. This conclusion is consistent with the allowed range for σ_γ (30 keV) in Ref. 10 and is in qualitative agreement with the measurement of σ_γ (25 keV) by Beer *et al.*[11] In consequence, it does not appear that the $^{22}Ne(n,\gamma)^{23}Ne$ reaction will cause a significant reduction in the number of neutrons available for the s process.

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