THE ASTROPHYSICAL JOURNAL, 495:905–910, 1998 March 10
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IMPLICATIONS OF A SUBTHRESHOLD RESONANCE FOR STELLAR BERYLLIUM DEPLETION

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Received 1997 August 19; accepted 1997 October 20

ABSTRACT

Abundance measurements of the light elements lithium, beryllium, and boron are playing an increasingly important role in the study of stellar physics. Because these elements are easily destroyed in stars at temperatures $(2-4)\times10^6$ K, the abundances in the surface convective zone are diagnostics of the star's internal workings. Standard stellar models cannot explain depletion patterns observed in low-mass stars, and so do not account for all the relevant physical processes. These processes have important implications for stellar evolution and primordial lithium production in big bang nucleosynthesis. Because beryllium is destroyed at slightly higher temperatures than lithium, observations of both light elements can differentiate between the various proposed depletion mechanisms. Unfortunately, the reaction rate for the main destruction channel ^{9}Be(p, α)^{6}Li is uncertain. A level in the compound nucleus ^{10}B is only 25.7 keV below the reaction's energetic threshold. The angular momentum and parity of this level are not well known; current estimates indicate that the resonance entrance channel is either s- or d-wave. We show that an s-wave resonance can easily increase the reaction rate by an order of magnitude at temperatures $T\approx4\times10^6$ K. Observations of $M<M_\odot$ stars can constrain the strength of the resonance, as can experimental measurements at laboratory energies lower than 30 keV.

Subject headings: nuclear reactions, nucleosynthesis, abundances — stars: abundances — stars: pre–main-sequence

1. INTRODUCTION

In recent years the abundances of the light elements lithium, beryllium, and boron have been increasingly used as diagnostics of stellar physics. The fragility of these elements to proton capture makes their abundances exquisite probes of a star's internal machinery. Abundance measurements of both beryllium and lithium can differentiate between proposed depletion mechanisms. This presupposes that the destruction rate is accurately known. Unfortunately, the reaction cross section for one of the beryllium destruction channels ^{9}Be(p, α)^{6}Li is uncertain. Just 25.7 keV below the energetic threshold for the reaction, there is a level in the compound nucleus ^{10}B. Uncertainties in the angular momentum and parity of the compound nucleus level prohibit an accurate theoretical calculation of the reaction rate, and laboratory measurements of the cross section to date are inconclusive. Current astrophysical rates (e.g., Caughlan & Fowler 1988, hereafter CF88) do not account for the cross section's uncertainty. In this paper, we describe astrophysical topics for which accurate reaction rates are needed, estimate how large a correction to the reaction rate might be, and discuss how astrophysical observations may be used to inform the nuclear physics as to the possible magnitude of the reaction cross section.

In § 2 we outline the motivation for investigating the contribution of compound nucleus formation (^{10}B) to the destruction rate for beryllium. Section 2.1 reviews lithium and beryllium depletion observations in F stars (the "F gap") and illustrates how abundance ratios of beryllium to lithium can constrain the various mechanisms for destroying these elements. We discuss in § 2.2 the depletion patterns in subsolar-mass stars. We list different scenarios for destroying beryllium and lithium in these stars and the consequences of each scenario.

After describing the importance of correctly calculating the destruction rate for beryllium, we then outline (§ 3) the uncertainties in the ^{9}Be(p, α)^{6}Li cross section. Section 3.1 describes experimental studies of the cross section and the quantum numbers characterizing the ^{10}B compound nucleus. We then recalculate the astrophysical S-factor and estimate the thermally averaged cross section in § 3.2. In § 4 we discuss the prospects for using astrophysical observations to constrain the reaction S-factor.

2. MOTIVATION: THE IMPORTANCE OF BERYLLIUM ABUNDANCES

The light-element isotopes ^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, and ^{11}B both trace Galactic chemical evolution and probe the interior workings of stars. The high stability of helium nuclei dominates the nuclear physics of these elements; indeed, all three are easily destroyed by proton capture at stellar temperatures $T=(2\text{–}6)\times10^6$ K. Only ^{7}Li is produced in appreciable quantities by standard big bang nucleosynthesis (BBN). Inhomogeneous BBN models (Boyd & Kajino 1989; Kajino & Boyd 1990) can produce beryllium, but this would imply a "plateau" in beryllium abundances for very low metallicity stars. There is no firm observational evidence for such a plateau; instead, $[^9\mathrm{Be}]\equiv12+\log(N_{^9\mathrm{Be}}/N_{\mathrm{H}})$ appears to be linearly correlated with [Fe/H] for abundances of $[^9\mathrm{Be}]\gtrsim-1$ (Boesgaard & King 1993; Gilmore et al. 1992; Rebolo, García López, & Pérez de Taoro 1995; Ryan et al. 1992). All three elements are also produced by spallation reactions, in which high-energy H and He nuclei bombard CNO elements. Formation by the reverse reaction, bombardment of H and He nuclei by CNO elements accelerated in supernovae, may also be important in star-forming regions (Cassé, Lehoucq, & Vangioni-Flam 1995). Because spallation is the only mechanism for producing ^{9}Be (there is no low-energy formation channel), measurements of beryllium trace the cosmic-ray history of the Galaxy (for a review see Reeves 1994).

Observations of surface beryllium abundances in stars

can reveal the cause of discrepancies between observed surface abundance patterns and standard stellar models. A challenge to any stellar theory is to explain the lithium and beryllium F gap, the solar abundances, and the increased depletion with decreasing effective temperature for F-, G-, and K-type stars. Beryllium observations, when used in conjunction with lithium observations, provide a powerful diagnostic of the stellar physics, as we discuss in §§ 2.1 and 2.2.

Of these three elements, lithium is most easily observed, because of the Li I optical transition at $\lambda = 6708$ Å. In contrast, the abundance of beryllium is inferred from measurement of the Be II doublet in the near-UV ($\lambda = 3130$ and 3131 Å). Although Be I has a transition at $\lambda 2349$, observable with the *Hubble Space Telescope* (*HST*), the line strength depends only weakly on the abundance (García López 1996). Only recently have UV observations attained sufficiently high signal-to-noise ratios to allow spectral analysis of this doublet for low-mass stars (the spectra of solar-mass stars are typically crowded about this wavelength). Very low mass stars ($M \lesssim 0.3\ M_{\odot}$) are quite UV dim, so they offer little prospect for beryllium observations in the near future. This is unfortunate, as beryllium observations in these very low mass stars can easily constrain the uncertain reaction rate (see § 4).

2.1. *The Lithium and Beryllium F Gap*

Severe lithium depletion in Hyades F stars was first observed by Boesgaard & Tripicco (1986). This gap is remarkable: the lithium abundance falls by a factor of 100 over a narrow ($\sim$600 K) range of effective temperatures about $T_{\rm eff} \sim 6600$ K. Standard stellar models do not predict this feature, and so do not account for all the relevant physics. Several mechanisms have been proposed to explain the removal of light elements from the surfaces of these stars. Among those which do not rely on nuclear burning are mass loss (Swenson & Faulkner 1992) and microscopic diffusion (Richer & Michaud 1993).

Mass loss can nominally explain the Hyades F gap, although it requires a finely tuned mass-loss rate; stars in the gap must have higher mass-loss rates than stars of slightly hotter and cooler $T_{\rm eff}$. Because the lithium preservation region is more shallow than the beryllium preservation region, mass loss would essentially remove all of the surface lithium before diluting the beryllium-rich layers. If the beryllium destruction rate were greatly enhanced, then a star could exist that was slightly depleted in beryllium and yet had some lithium remaining.

In contrast, microscopic diffusion predicts a beryllium gap in the Hyades (Richer & Michaud 1993). At an age of 700 Myr, the Be gap will be centered about 70 K cooler than the lithium gap. Because other species, most notably ^{4}He, will also sink relative to hydrogen, increasing the diffusivity has strong consequences for inferred stellar properties. Metal abundances in both lithium- and beryllium-depleted F stars (Boesgaard & Lavery 1986) do not show any obvious trend, which disfavors pure diffusion models. One strong prediction of the diffusion models, which also include radiative levitation, is the presence of a lithium "bump," a range of effective temperatures (6900 K $< T_{\rm eff} <$ 7100 K) for which stars are overabundant. A corresponding Be bump will also exist for 6700 K $< T_{\rm eff} <$ 6900 K (Richer & Michaud 1993).

Another class of mechanisms slowly mix lithium, beryllium, and boron to depths where reactions can occur. The abundance ratio of these three elements is then sensitive to their proton-capture rates, which set the depth at which destruction of each species occurs. This mixing can be caused by, for example, internal waves (Montalbán & Schatzman 1996), meridional circulation (Zahn 1992; Chaboyer, Demarque, & Pinsonneault 1995a, 1995b; Charbonnel, Vauclair, & Zahn 1992), and rotation-induced turbulence (Zahn 1992; Charbonnel et al. 1994). Horizontal turbulence inhibits chemical advection so that angular momentum transport is much more efficient than chemical species transport; the movement of species is then a diffusive process (Chaboyer & Zahn 1992). The F gap is explained if angular momentum loss via a stellar wind drives the circulation. Stars on the hot side of the lithium gap do not spin down during their main-sequence lifetime, but stars on the cool side do (Kraft 1967).

While the morphology of the lithium gap alone can differentiate between depletion models (e.g., Balachandran 1995), each proposed mechanism also affects the abundances of beryllium and boron. Deliyannis & Pinsonneault (1997) discuss how observations of both lithium and beryllium can be used to explore the nature of the nonstandard physics responsible for the lithium F gap. In particular, 110 Her, which is depleted in lithium by a factor of 100–200 and in beryllium by a factor of about 10 (Boesgaard & Lavery 1986) is possibly an F-type star caught "in the act" of depleting both elements. Recent boron measurements, using the *HST*, find no boron deficiencies in Li- and Be-depleted F stars (Boesgaard et al. 1998). Since boron burns at even higher temperatures (i.e., at greater depths) than beryllium and lithium, these observations argue in favor of some type of mixing as the means of destroying lithium and beryllium.

2.2. *Depletion for $M \lesssim M_{\odot}$*

For effective temperatures below $\sim$6000 K, the surface convective zone deepens, and the abundance of lithium (and possibly beryllium) not unexpectedly decreases with declining $T_{\rm eff}$. Observations show that lithium is depleted in the Sun by a factor $\sim$100 relative to meteoric values ([Li] $= 3.31 \pm 0.04$; Anders & Grevesse 1989). Recent measurements (King et al. 1997) suggest that beryllium is also depleted, relative to the meteoric abundance ([^{9}Be] $= 1.42 \pm 0.04$; Anders & Grevesse 1989), by a factor of 1.4–3.0 in the sun. This depletion is mirrored in the solar-like stars α Cen A and α Cen B (King et al. 1997; Primas et al. 1997).

Comparisons between Pleiades (age $\sim$100 Myr), Hyades (age $\sim$600 Myr), and M67 stars (age $\sim$5 Gyr) (see Fig. 1 in Ryan & Deliyannis 1995) indicate that G and K dwarfs deplete lithium on the main sequence. Stars with effective temperatures $T_{\rm eff} \lesssim 6000$ K show an increasing depletion of lithium with decreasing $T_{\rm eff}$. Although standard models with convective overshoot can match the Pleiades abundance pattern, they are unable to duplicate the Hyades depletion. As with F-gap stars, a variety of different mechanisms exist to explain this abundance pattern.

Although mass loss is somewhat consistent with the formation of a lithium F gap, it cannot explain the decrease in lithium abundance with declining $T_{\rm eff}$ for Hyades G dwarfs (Swenson & Faulkner 1992). Diffusion appears necessary for agreement between the standard solar models and helioseismic constraints on the depth of the convective zone (Bahcall, Pinsonneault, & Wasserburg 1995) and the sound

speed (Bahcall et al. 1997). Chaboyer, Demarque, & Pinsonneault (1995a, 1995b) considered both rotational mixing and microscopic diffusion (for $M < 1.3\ M_\odot$). They found that although microscopic diffusion alone was insufficient to match simultaneously observations of different clusters, a model incorporating both rotation and diffusion was. Observations of lithium abundances in halo stars also do not agree with pure diffusion models (Chaboyer & Demarque 1994). If depletion is due to meridional circulation, then lithium should be better preserved in tidally locked binaries (Zahn 1994); there is some evidence for this (Ryan & Deliyannis 1995).

The different scenarios for destroying lithium have cosmological consequences. Models that use internal mixing to destroy lithium and beryllium imply that lithium is not as well preserved in old cluster members as previously thought (Chaboyer & Demarque 1994). Differences in the lithium abundances of identical M92 subgiants might imply differential depletion due to rotation-induced mixing (Deliyannis, Boesgaard, & King 1995), and either a higher primordial lithium abundance or some form of chemical enrichment. An enhanced primordial lithium abundance is a challenge to standard BBN (see, e.g., Fig. 13 of Walker et al. 1991). Diffusion of ^{4}He from the surface lowers $T_{\rm eff}$ (Richer & Michaud 1993) so reduces the ages of halo dwarfs by 2–3 Gyr (Chaboyer et al. 1992; Chaboyer & Demarque 1994). Diffusion of heavy elements mitigates this effect, but an age reduction of ~ 1 Gyr appears unavoidable (Castellani et al. 1997).

Stars of mass $M \lesssim M_\odot$ deplete lithium and beryllium while contracting to their main-sequence radius. Stars less massive than $\sim 0.5\ M_\odot$ (the exact mass depends on the isotope) destroy that element before developing a radiative core (e.g., Ushomirsky et al. 1998); otherwise, destruction of a given light element occurs at the base of the outer convective zone. As the convective zone moves outward (in mass coordinates), the temperature at the base of the convective zone passes through a maximum, which is typically hot enough for lithium, and to a lesser extent beryllium, to burn. As a result, zero-age main-sequence (ZAMS), subsolar-mass stars display abundances that reveal the history of their convective zone's base. These stars offer the best astrophysical environment for examining the nuclear physics (see § 4).

3. THE ^{9}Be(p, α)^{6}Li CROSS SECTION

An important part of the microphysics in any stellar model is the destruction rates of the light elements. The lithium rates have recently been adjusted (Raimann 1993) slightly. For the case of beryllium, there is a potentially strong correction to the CF88 rates. Just 25.7 keV below the energetic threshold (see Table 1) of the reaction ^{9}Be(p, α)^{6}Li lies an excited level ($E_{\rm exc} = 6.56$ MeV) of ^{10}B (Ajzenberg-Selove 1988). This state primarily decays by α-emission and so forms a resonant channel for the ^{9}Be(p, α)^{6}Li reaction. As we discuss in § 3.1, the S-factor used by CF88 is based on the resonant level having an angular momentum and parity $J^\pi = 2^+$. Current knowledge (see Ajzenberg-Selove 1988) is that the angular momentum and parity of the ^{10}B state is either $J^\pi = 2^-$ or $J^\pi = 4^-$, with 4^- thought the better guess. The angular momentum and parity of ^{9}Be is $(3/2)^-$. Hence, if the resonant state has $J^\pi = 2^-$, the reaction can proceed with $\ell = 0$; if instead $J^\pi = 4^-$, the lowest entrance channel available is $\ell = 2$. Because the strength of the resonance strongly depends on the angular momentum, the reaction rate can vary by several orders of magnitude for these alternatives. We estimate the cross section in § 3.2.

3.1. *Experimental Measurements*

The reaction $^9\mathrm{Be} + p$ was of interest historically for fusion power generation because of its large cross section at low energies. Sierk & Tombrello (1973) studied the reactions ^{9}Be(p, d)2 ^{4}He and ^{9}Be(p, α)^{6}Li at center-of-mass (CM) energies of 30–630 keV. They concluded that the 310 keV resonance (see Table 1) had negative parity because of s-wave proton formation. Because of low-energy asymmetries in the d and α angular distributions, they then assigned a positive parity to the $E_{\rm exc} = 6.56$ MeV level. In their fit to the reaction cross section, they used $J^\pi = 2^+$, so that the entrance channel was p-wave. Mindful of the astrophysical importance of this reaction, they estimated the S-factor for both ^{9}Be(p, α)^{6}Li and ^{9}Be(p, d)2 ^{4}He to be $S(0) = 35^{+45}_{-15}$ MeV barns. The contribution of the resonance to the total S-factor was between 20% and 40%. Uncertainties in the compound nucleus formation allow the possibility that the S-factor could actually increase at lower energies.

Measurements of the angular momentum and parity of the levels in ^{10}B have also been performed via ^{11}B(^{3}He, α)^{10}B(α_0)^{6}Li, ^{6}Li(α, α)^{6}Li, ^{9}Be(^{3}He, d)^{10}B, and ^{9}Be(d, n)^{10}B reactions. Young, Lindgren, & Reichart (1971) used correlations in ^{11}B(^{3}He, α)^{10}B(α_0)^{6}Li to determine that $J(E_{\rm exc} = 6.56\ \mathrm{MeV}) \geq 3$. Interference between this level and the one at $E_{\rm exc} = 7.00$ MeV, which was presumed to have $J^\pi = 3^+$ [note that the currently accepted value is $(1, 2)^+$; Table 1] led them to infer that $J^\pi(E_{\rm exc} = 6.56\ \mathrm{MeV}) = 3^-$ or 4^-. Measurements from ^{6}Li(α, α)^{6}Li scattering (Balakrishnan, Mehta, & Divatia 1971) suggested that J^π equaled either 4^- or 2^-, with 2^- preferred. Park, Niiler, & Lindgren (1971), using the reaction ^{9}Be(d, n)^{10}B at laboratory energies in excess of 7 MeV, assigned $J^\pi = 3^-$ to the 6.13 MeV level and a negative parity to the 6.56 MeV level. Bland &

TABLE 1

LEVELS IN ^{10}B NEAR THE ^{9}Be(p, α)^{6}Li REACTION THRESHOLD ($E = 6.5857$ MeV)

Level Energy (MeV)	Resonance Energy (keV)	Angular Momentum, Parity[a]	Level Width (keV)	Decay Channel
6.127	−459	3^-	2.36 ± 0.03	α
6.560	−25.7	$(4)^-$	25.1 ± 1.1	α
6.873	287	1^-	120 ± 5	γ, p, d, α
7.002	416	$(1, 2)^+$	100 ± 10	p, d, α

NOTE.—The resonance energy is measured with respect to the energetic threshold for ^{9}Be(p, α)^{6}Li.

REFERENCES.—Ajzenberg-Selove 1988.

[a] Parentheses indicate that the values are uncertain.

Fortune (1980) found that a *positive* parity for the 6.13 and 6.56 MeV levels gave a better fit to angular distributions in ^{9}Be(^{3}He, d)^{10}B. However, the spectroscopic strengths were then much larger than expected. An assignment of $J^\pi = 3^-$ to the 6.13 MeV level agreed well with predicted strengths because the angular distribution of the 6.56 MeV level was very similar to that of the 6.13 MeV level. Bland & Fortune (1980) concluded that both levels have negative parity. This choice also gave the greatest consistency between the (d, n) and (^{3}He, d) reactions. Their conclusion was tempered by the poor angular distribution fit of their distorted-wave Born approximation, which they were unable to explain. Recent shell-model calculations (Warburton & Brown 1992) favor $J^\pi = 4^-$.

It is clear that the parameters of the ^{10}B level $E_{\rm exc} = 6.56$ MeV are still uncertain. We note that the S-factor used by CF88 is the same as that measured by Sierk & Tombrello (1973), which assumed a *positive* parity [and hence a P-wave entrance channel for ^{9}Be(p, α)^{6}Li] for the ^{10}B level. Given the importance of beryllium abundance observations to astrophysics, accurate measurements of the cross section at low energies are greatly needed. For the purposes of this paper, we treat both possibilities ($J^\pi = 4^-$ or 2^-) as equally possible, and recalculate the S-factor and reaction rate for each case.

3.2. *An Estimate of the Resonant Cross Section and Reaction Rate*

For a reaction that proceeds via a subthreshold compound nucleus, the cross section is given by the Breit-Wigner single level formula

$$\sigma(p,\,\alpha) = \left(\frac{\pi}{k^2}\right)\left[\frac{2J_{\rm B}+1}{(2J_p+1)(2J_{\rm Be}+1)}\right]\left[\frac{\Gamma_p\Gamma_\alpha}{(E-E_r)^2+(\Gamma/2)^2}\right], \tag{1}$$

where the first term is the geometrical cross section (k is the wavevector), and the second is the statistical factor. The total width of the state, at an energy E_r relative to the energetic threshold, is Γ, which for ^{9}Be(p, α)^{6}Li is just the width of the α-channel (Ajzenberg-Selove 1988), and $\Gamma = \Gamma_\alpha = 25.1$ keV. The cross section is therefore completely determined once the proton width Γ_p is known.

We parameterize the entrance channel Γ_p by the dimensionless reduced width θ_ℓ^2,

$$\Gamma_p(\ell;\,E) = \frac{3\hbar v}{R}\,P_\ell^2\,\theta_\ell^2\,, \tag{2}$$

where R is the strong-force interaction radius (we use $R = 3.88$ fm), v is the relative velocity in the CM frame, and P_ℓ is the penetration factor for proton angular momentum ℓ. In terms of the Coulomb wave functions F_ℓ and G_ℓ, the penetration factor is $P_\ell = [F_\ell(E;\,R)^2 + G_\ell(E;\,R)^2]^{-1}$. We use the low-energy approximation for F_ℓ and G_ℓ (Abramowitz & Stegun 1965),

$$F_\ell \approx \frac{(2\ell+1)!C_\ell(\eta)}{(2\eta)^{\ell+1}}\,(2\eta\varrho)^{1/2}I_{2\ell+1}[2(2\eta\varrho)^{1/2}]\,, \tag{3a}$$

$$G_\ell \approx \frac{2(2\eta)^\ell}{(2\ell+1)!C_\ell(\eta)}\,(2\eta\varrho)^{1/2}K_{2\ell+1}[2(2\eta\varrho)^{1/2}]\,, \tag{3b}$$

where

$$2\pi\eta \equiv \left(\frac{E_G}{E}\right)^{1/2} \equiv \left[\left(\frac{2\pi Z_{\rm Be}Z_{\rm H}e^2}{\hbar}\right)^2\left(\frac{\mu}{2}\right)\right]^{1/2}E^{-1/2} \tag{4}$$

parameterizes tunneling through the Coulomb barrier (E_G is the Gamow energy, $Z_{\rm Be}$ and $Z_{\rm H}$ are respectively the charge numbers of the ^{9}Be and H nuclei, and $\mu = 0.9m_u$ is the reduced mass of the p + ^{9}Be system), $\varrho = (2\mu R^2E/\hbar^2)^{1/2}$ accounts for the centrifugal barrier, $I_{2\ell+1}$ and $K_{2\ell+1}$ are the modified Bessel functions of order $2\ell+1$, and

$$C_\ell(\eta) = 2^\ell\,\exp\left(-\frac{\pi\eta}{2}\right)\frac{|(\ell+i\eta)!\,|}{(2\ell+1)!}\,. \tag{5}$$

Numerically, $2\pi\eta = 118E^{1/2}$ and $\varrho = 0.0255E^{1/2}$, when E is measured in keV. At typical astrophysical energies, $E \sim 10$ keV, the penetration factor reduces to the standard WKB form (e.g., Clayton 1983) and is dominated by the term $\exp\,[-(E_G/E)^{1/2}]$.

We qualitatively estimate θ_0^2 by approximating the nuclear potential as a square well (see, e.g., Blatt & Weisskopf 1979). If we construct a wave packet out of states of average level spacing D, then the period of oscillation is $D/2\pi\hbar$. Multiplying this by the transmission probability $4k/K$, where K and k are respectively the wavevectors inside and outside the potential well, and by the Coulomb barrier penetration probability P_0, we obtain an estimate of the lifetime of the state, which is just $\Gamma_p/\hbar$. Equating this estimate with the equation for Γ_p, equation (2), we then obtain an estimate for θ_0^2,

$$\theta_0^2 \approx \frac{2}{3\pi}\left(\frac{\mu}{2E_{\rm exc}}\right)^{1/2}\frac{RD}{\hbar}\,, \tag{6}$$

where $E_{\rm exc} = 6.56$ MeV is the energy of the resonant level. We consider two values of D. First, the closest level with $J^\pi = 2^-$ is 310 keV above $E_{\rm exc}$; using this in equation (6) implies that $\theta_0^2 = 0.011$. If instead we average the energy separations of the two nearest levels with $J^\pi = 2^-$, we obtain $D = 880$ keV, which implies that $\theta_0^2 = 0.024$.

Experimental measurements (Sierk & Tombrello 1973) extend only to CM energies greater than 30 keV, for which the s-wave resonant contribution is negligible for $\theta_0^2 \lesssim 0.5$. Lower energy measurements are therefore needed to determine the nature of the resonance.

Upon specifying θ_ℓ^2, we compute the resonant cross section. Because the reaction proceeds through the tail of the resonance ($E - E_r > \Gamma$), we write $\sigma = S(E)E^{-1}\,\exp\,[-(E_G/E)^{1/2}]$, where $S(E)$ depends only weakly on the energy. Averaging over a Maxwellian velocity distribution then amounts to evaluating about the peak of the integrand $E_0 \approx (k_{\rm B}TE_G^{1/2}/2)^{2/3}$. We show in Figure 1 the ratio of the thermally averaged resonant ($E_r = -25.7$ keV) cross section to that of CF88, for three different combinations of ℓ and θ^2: (1) $\ell = 0$, $\theta_0^2 = 0.01$ (*solid line*); (2) $\ell = 0$, $\theta_0^2 = 0.10$ (*dotted line*); and (3) $\ell = 2$, $\theta_2^2 = 0.5$ (*dashed line*).

As is evident from Figure 1, a d-wave resonance contributes little. An s-wave resonance, however, will actually dominate the ^{9}Be(p, α)^{6}Li cross section for $\theta_0^2 \gtrsim 0.01$. We compute the astrophysical S-factor for this case,

$$S(0) = 47.0\left(\frac{\theta_0^2}{0.01}\right)\ \text{MeV barns}\,. \tag{7}$$

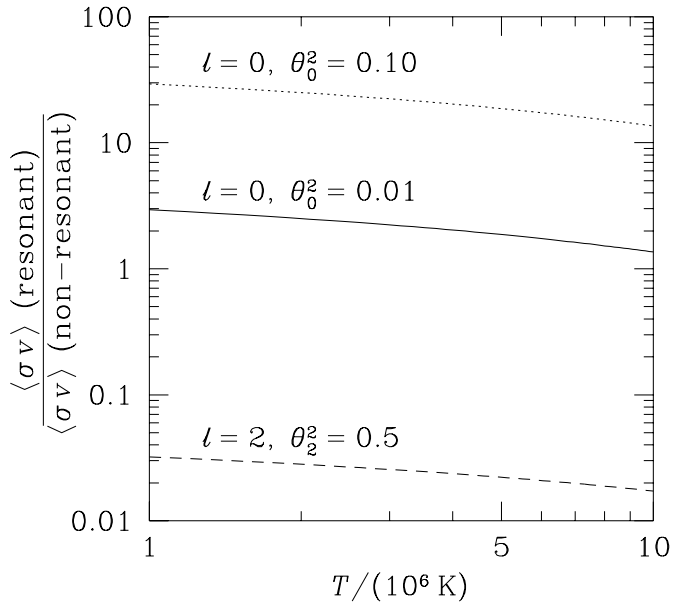


FIG. 1.—Comparison of the thermally averaged subthreshold resonant rate to the CF88 rate for the reaction ^{9}Be(p, α)^{6}Li. We show three cases: (1) angular momentum $\ell = 0$ and reduced width $\theta^2 = 0.01$ (*solid line*), (2) $\ell = 0, \theta^2 = 0.1$ (*dotted line*), and (3) $\ell = 2, \theta^2 = 0.5$ (*dashed line*).

This is larger than the combined S-factor estimated by Sierk & Tombrello (1973). A fit to the ^{9}Be(p, α)^{6}Li rate is

$$N_A\langle \sigma v \rangle|_{\ell=0} = 3.53 \times 10^{14}\left(\frac{\theta_0^2}{0.01}\right)\left(\frac{T}{10^6\ \mathrm{K}}\right)^{-1.367} \times \exp\left[-105.326\left(\frac{T}{10^6\ \mathrm{K}}\right)^{-1/3}\right] \mathrm{cm^3\ s^{-1}\ g^{-1}}\ . \quad (8)$$

In constructing this fit, we have neglected the nonresonant contribution to the total cross section; this is permissible for $\theta_0^2 \gtrsim 0.05$. The total destruction rate for ^{9}Be is then the rate for ^{9}Be(p, α)^{6}Li (eq. [8]) added to the rate for ^{9}Be(p, d)2 ^{4}He (CF88).

4. OBSERVATIONAL CONSTRAINTS ON THE CROSS SECTION

When observations of beryllium in pre–main-sequence stars of mass $M \lesssim 0.3\ M_\odot$ become possible, the reaction rate will be easily constrained. For example, a star of mass $0.2\ M_\odot$ will deplete ^{9}Be at a considerably (22%) younger age if the resonance is s-wave and $\theta_0^2 = 0.1$ (Ushomirsky et al. 1998). Observations of lithium abundances (Basri, Marcy, & Graham 1996; Bildsten et al. 1997; Ushomirsky et al. 1998), as well as fitting to the main-sequence turnoff, can independently constrain the ages and masses of cluster members.

Stars heavier than $\sim 0.3\ M_\odot$ form radiative cores before their center is hot enough to destroy beryllium. As the convective zone moves outward in mass, the base temperature passes through a maximum (e.g., D'Antona & Mazzitelli 1994; Forestini 1994). As first pointed out by Bodenheimer (1966), the base of the convective zone at maximum temperature is hot enough ($T \gtrsim 4 \times 10^6$ K) to burn beryllium for a short time during pre–main-sequence contraction. The ZAMS beryllium depletion is then determined by comparing the depletion timescale (Bildsten et al. 1997)

$$t_{\mathrm{depl}} \equiv \frac{1}{n_{\mathrm{H}}\langle \sigma v \rangle} \quad (9)$$

(n_{H} is the number density of hydrogen) to the time spent at maximum temperature by the convective zone (approximately the age of the star). Because higher mass stars develop radiative cores at colder central temperatures, the ZAMS abundance of beryllium increases with mass. A star of mass $0.5\ M_\odot$ at an age of 300 Myr will be 50% depleted (using CF88 rates), while an $0.8\ M_\odot$ star of the same age will only be 3% depleted (Forestini 1994). Standard models of main-sequence stars more massive than $0.7\ M_\odot$ do not show appreciable beryllium destruction while on the main sequence. Hence, a lack of beryllium in stars more massive than $\sim 0.6\ M_\odot$ is an indication either that the reaction rate is underestimated or that other mechanisms are at work. Because the various mixing mechanisms discussed in § 2 occur on the main sequence, younger clusters are promising targets for study. Recent observations of late-type dwarf stars in the Hyades (García López, Rebolo, & Pérez de Taoro 1995) are consistent with no depletion of beryllium for $T_{\mathrm{eff}} > 5250$ K. The age of the Hyades is 625 ± 50 Myr (Perryman et al. 1998), so a star of that effective temperature is on the main sequence and has a mass of about $0.9\ M_\odot$ (D'Antona & Mazzitelli 1994). The temperature at the base of the convective zone ($\approx 2.6 \times 10^6$ K) is far too cold to cause appreciable depletion of beryllium, even if the resonance were s-wave. At an age of 3 Myr, the base of the convective zone reaches its maximum temperature of 4×10^6 K (D'Antona & Mazzitelli 1994). If the depletion timescale is to be longer than the contraction timescale, $t_d \gg 2$ Myr, then we require that $\theta_0^2 \lesssim 0.1$. A less massive Hyades member that is beryllium-depleted will place a stronger lower bound on θ_0^2.

5. IMPLICATIONS

For different combinations of angular momentum and reduced width, we have estimated the ^{9}Be(p, α)^{6}Li S-factor (eq. [7]) and the thermally averaged reaction rate (eq. [8]). Neither experimental measurements of the S-factor (§ 3.1) nor observations of low-mass stars in the Hyades (§ 4) rule out an s-wave resonance; at best, the reduced width is only constrained to be $\theta_0^2 \lesssim 0.1$. This reduced width roughly doubles the standard (CF88) rate at typical stellar temperatures where beryllium is destroyed. Because the reaction rate at $T \approx 4 \times 10^6$ K is roughly proportional to T^{21}, a doubling of the rate corresponds to a reduction of 10% in the temperature at which beryllium destruction occurs. The depth of the beryllium preservation region is therefore reduced. As we sketched in § 2, the differences in beryllium and lithium depletion patterns can potentially discriminate between the many proposed depletion mechanisms.

While experimental measurements at laboratory energies $E_{\mathrm{lab}} < 30$ keV would ideally yield the S-factor, stellar observations of very low mass stars can possibly constrain the reduced width, if not the entrance channel angular momentum. There are few other areas of astrophysics where observations can inform nuclear physics. Although the best prospects, i.e., fully convective ($M < 0.3\ M_\odot$), pre–main-sequence stars, are too dim in the UV, observations of beryllium-deficient ZAMS stars heavier than roughly 0.7

$M_\odot$ would be persuasive evidence for an enhanced beryllium destruction rate.

Thanks to Lars Bildsten for suggesting this project and for many helpful discussions, to Richard Boyd for thoughtful comments on the manuscript, and to Michael Wiescher for providing a tabulated numerical calculation of the penetration factor and for helpful comments. E. F. B. was supported by a NASA GSRP Graduate Fellowship grant NGT-51662.

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Note added in proof.—Recently, Zahnow et al. (D. Zahnow, C. Rolfs, S. Schmidt, & H. P. Trautretter, Z. Phys. A, 359, 211 [1997]) measured $S(E)$ down to laboratory energies of 16 keV, which is significantly less than Sierk & Tombrello's (1973) measurement ($E_{\rm lab} < 28$ keV). Zahnow et al. (1997) found that $S(E)$ increases sharply with decreasing proton energy, and that $S(E_{\rm lab} = 15.93\ {\rm keV}) = 51 \pm 16$ MeV barns, which is greater than the previously measured S factor, $S(0) = 35^{+45}_{-15}$ MeV barns (Sierk & Tombrello 1973).