HELIUM-INDUCED REACTIONS IN ASTROPHYSICS

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1 Introduction

Helium-induced reactions play a crucial role in stellar nucleosynthesis. Carbon and oxygen are produced mainly during the helium-burning phase by the chain of reactions ^{8}Be$(\alpha, \gamma + e^+e^-)^{12}C(\alpha,\gamma)^{16}$O. The first step, often called "triple-α" capture, was proposed by Hoyle to bypass the mass stability gap at ^{8}Be. The second step gives rise to the largest uncertainty in most of the calculated stellar abundances. Later α-captures on ^{13}C are believed to be a major source of s-process neutrons. The status of each of these important reactions is reviewed in the following sections.

2 Triple-α Capture

This reaction consists of capturing an α-particle on the $\alpha - \alpha$ resonance that forms the ground state of ^{8}Be to give ^{12}C**($E_x = 7.6542$ MeV, $J^\pi = 0^+$), as shown in the level diagram of Figure 1. Because of its quantum numbers, there is only a small probability that this excited state will de-excite (rather than decay back into three α-particles), either by e^+e^- pair production, or by a γ-ray cascade through the first excited state, leaving ^{12}C in its 0^+ ground state.

The rate per unit volume for the de-excitation process at temperature T is given by the resonance form

$$r_{3\alpha} = \frac{N_\alpha^3}{2} 3^{3/2} \Big(\frac{2\pi\hbar^2}{M_\alpha kT}\Big)^3 \frac{\Gamma_{\rm rad}}{\hbar} \exp\Big(-\frac{Q}{kT}\Big), \tag{1}$$

with N_α the α-particle number density, M_α its mass, and $Q = (M_{^{12}\mathrm{C}^{**}} - 3M_\alpha)c^2$, in the approximation that $\Gamma_{\rm rad} = \Gamma_\gamma + \Gamma_{\rm pair} \ll \Gamma_\alpha \approx \Gamma$ (the total width). Current values of $\Gamma_{\rm rad} = (3.70 \pm 0.50)$ meV and $Q = 379.5 \pm 0.3$ keV determine the triple-α rate to within about 15%.

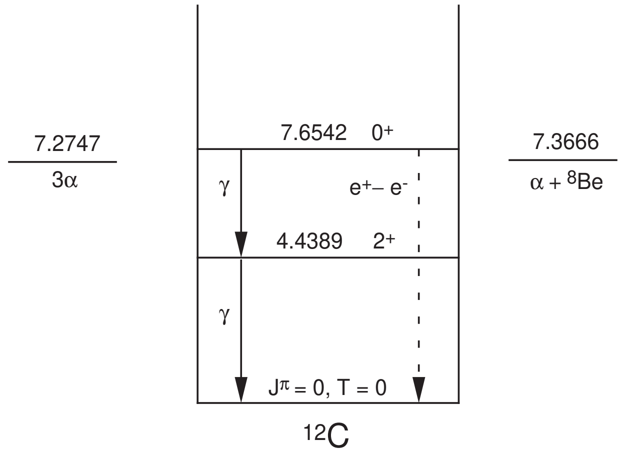

Figure 1: Levels and thresholds of ^{12}C involved in triple-α capture.

3 α+^{12}C Capture

The present experimental status of α+^{12}C capture S-factor extrapolations to $E_0 = 300$ keV is summarized for the individual multipoles in Table 1. The analysis method used to do the extrapolation is listed in parentheses beside (or under) the value. The 1996 values of Ouellet *et al.* reflect the currently "accepted" values of the extrapolated S-factor for α+^{12}C capture,

$$S_{\rm cap}(E_0) = S_{E1} + S_{E2}^{g.s.} + S_{E2}^{casc.} = 160 \pm 40 \text{ keV} - \text{b}, \tag{2}$$

which compares favorably with the value (170±50 keV-b) obtained by Weaver and Woosley from a sensitivity study of calculated abundances.

Reference	S_{E1} (keV-b)	$S_{E2}^{g.s}$ (keV-b)	$S_{E2}^{casc.}$ (keV-b)
Dyer and Barnes (1974)	140^{+140}_{-120} (3-lev. R) 80^{+50}_{-40} (hybr. R)		
Redder *et al.* (1987)	200^{+270}_{-110} (3-lev. R) 140^{+120}_{-80} (hybr. R)	96^{+24}_{-30} (SLBW + d.c.) 80±25 (hybr. R)	20±9 (direct capture)
Kremer *et al.* (1988)	10^{+130}_{-10} (3-lev. R)		
Trautvetter *et al.* (1996)	79±20 (MLBW)	14.5^{+96}_{-14} (MLBW + d.c.)	
Ouellet *et al.* (1996)	79±16 (3-level R, K)	36±6 (cluster model)	

Table 1: Extrapolated S-factors for ^{12}C(α,γ) capture from the measurements.

A new R-matrix analysis of the ^{16}O system underway at Los Alamos gives a different result for the $E1$ extrapolation, however. It includes differential cross sections for α+^{12}C elastic scattering [1] and integrated cross sections for ^{12}C$(\alpha,\gamma)^{16}$O $E1$ capture [2, 3, 4, 5]. The R-matrix parameters are obtained from a direct fit to the measurements (rather than to derived quantities such as S-factors and phase shifts), thereby avoiding unnecessary correlations in the input data.

Three levels were used to represent the $J^\pi = 1^-$ transitions, including the subthreshold state at $E = -45$ keV, in which the reduced photon width was fixed by the known total width of the γ-ray line, 55 meV. Fitting only the cross-section data, including the corrections [5] that Ouellet *et al.* recently reported to their 1992 data, gave an extrapolated value for S_{E1} of almost 60 keV-b. This fit is shown as the solid curve in Figure 2. However, when recent measurements [6, 7] of the α spectra from the β-decay of ^{16}N were taken into account, the extrapolated S-factor became lower, as represented by the (constrained) dashed curve in Figure 2.

The spectra were calculated from the expression

$$\frac{dN_\alpha}{dE} = f_\beta(E)P_\alpha(E)\Big|\sum_{\lambda=1}^{3} B_\lambda \sum_{\lambda'=1}^{3} A_{\lambda\lambda'}(E)\gamma_{\lambda'\alpha}\Big|^2, \tag{3}$$

involving Fermi's integrated β-decay function f_β, the α+^{12}C penetrability function P_α, dimensionless "β-feeding" amplitudes B_λ, and R-matrix parameters $A_{\lambda\lambda'}$ and $\gamma_{\lambda'\alpha}$. Fixing the value of B_1 to give the right number of integrated γ-counts in the TRIUMF spectrum constrains the reduced α-width in the subthreshold level ($\gamma_{1\alpha}$) to give the correct position and shape for the first maximum and interference minimum. The values of B_2 and B_3 were adjusted to give a good visual fit to all the data up to about 3 MeV, as shown in Figure 3. Making B_2 slightly complex allowed a good description of the region around the interference minimum without including an F-wave contribution.

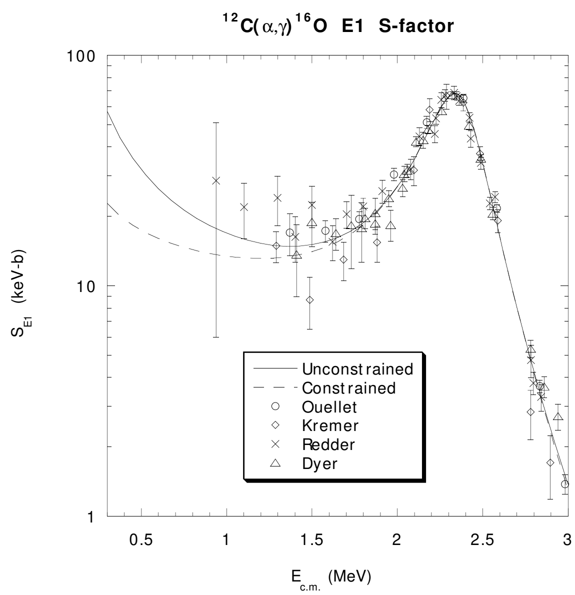

Figure 2: Calculated S-factor for the constrained and unconstrained fits compared with the measurements of refs. [2, 3, 4, 5].

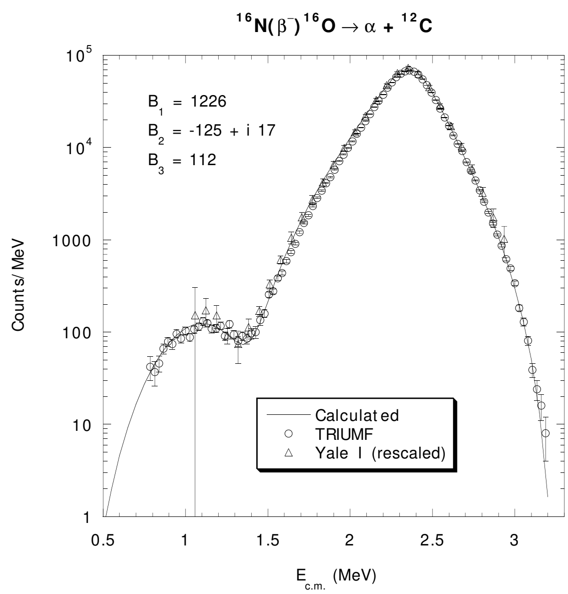

Figure 3: β-delayed α spectrum calculated from the parameters of the constrained fit, compared with the data of refs. [6, 7].

4 Neutrons from $\alpha +^{13} C$

Our R-matrix analysis of reactions in the ^{17}O system was originally started to provide cross sections for neutron scattering from ^{16}O at energies up to about 6 MeV, although it also included data for α+^{13}C elastic scattering. Therefore, in order to obtain an extrapolation of the ^{13}C$(\alpha, n)^{16}$O cross section to low energies, we added two recent (α, n) measurements [8, 9] to the existing data set (which included the measurements of Bair and Haas [10] as (n, α) data) and continued the analysis.

The results for the (α, n) cross section in S-factor form are compared with the measurements in Figure 4. One sees that significant renormalizations were required by the fit, especially for the data of Kellogg [9], measured at Caltech. These renormalizations bring the data into good agreement with the calculation and with each other. The magnitude of the calculated cross section agrees with the *original* normalization of Bair and Haas (not rescaled by 0.8), and with that of the neutron total cross section measurements. A good representation of all the previous data in the analysis was maintained.

In agreement with the Stuttgart group, we find that the extrapolated S-factor for this reaction rises to large values at low energies. However, in our case, the effect comes from known resonances in ^{17}O: a $J^\pi = 1/2^-$ level 419 keV below the threshold and a $1/2^+$ level 0.8 keV above the threshold. The $\alpha-^{13}$C reduced width amplitudes in these levels attain essentially their single-particle limiting values, but are still consistent with all the n+^{16}O and α+^{13}C data near the threshold. Error propagation from the parameters of the fit indicates that the extrapolated cross sections may be determined to within a few percent.

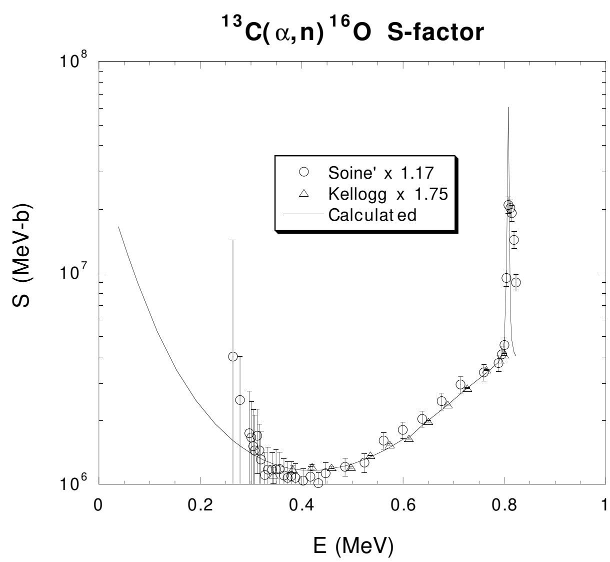

Figure 4: Calculated S-factor for ^{13}C$(\alpha, n)^{16}$O compared with the measurements of refs. [8, 9].

5 Conclusion

Whereas the rate for "triple-α" capture is probably known adequately well for astrophysical puposes (to within about 15%), serious questions remain about the extrapolated S-factor for $\alpha+^{12}$C capture. Despite the satisfying agreement of the currently accepted values with the adjusted value obtained from the sensitivity study, the Los Alamos R-matrix analysis of the ^{16}O system continues to indicate lower values of $S_{E1}(E_0)$. Especially puzzling is the fact that the β-delayed α-spectrum measurements appear to constrain the extrapolated S-factor to an even lower value, 23 keV-b, than do the cross-section data alone, in contrast to the results of the TRIUMF study (and others related to it). It is likely that the final resolution of this puzzle will require the very difficult measurement of $\sigma_{\alpha\gamma}$ with better precision in the region below 1.5 MeV.

In the case of the ^{13}C(α,n) reaction, present measurements of the cross section seem to be good enough to reveal large effects of near-threshold levels. We find (as did the Stuttgart group) that the extrapolated S-factor becomes much larger than the Caughlan-Fowler values at low energies, and that such a result is consistent with all the other measured data in the system, coming from known $J = 1/2$ levels in ^{17}O on either side of the threshold.

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