# Helium Burning Reactions in Stars

Helium burning[1] in stars occurs through the reactions: $3\alpha \rightarrow {}^{12}C$, ${}^{12}C(\alpha,\gamma){}^{16}O$ with reaction rates $r_{3\alpha}$ and $r_{\alpha C}$ respectively. Because of the very strong temperature dependence of these rates, the structure of a star is insensitive to uncertainties in them. However, the relative amounts of ${}^{12}C$ and ${}^{16}O$ remaining at the end of helium burning and hence the future behavior of the star depend sensitively on the relative rates of the two reactions. Thus, for example, if the $3\alpha$ process is found to be less rapid than previously thought, the amount of ${}^{12}C$ produced will be decreased and the amount of ${}^{16}O$ increased--carried to an extreme one might have no ${}^{12}C$ at the center of the star and the next reaction igniting would presumably be oxygen-burning rather than carbon burning.

In spite of concerted efforts these reaction rates are still uncertain.[2,3] Their dependence on the nuclear parameters is given by

$$r_{3\alpha} \sim \Gamma_{rad}\ e^{-\chi/kT} \qquad \chi = (M_C - 3M_\alpha)c^2 + E_x$$

$$r_{\alpha C} \sim \theta_\alpha^2$$

where $M_\alpha$ and $M_C$ are the atomic masses of ${}^4He$ and ${}^{12}C$, where $\Gamma_{rad}$ and $E_x$ are the radiative width and excitation energy of the second excited state of ${}^{12}C$ near 7.6 MeV and $\theta_\alpha^2$ is the reduced $\alpha$-width of the 7.12 MeV $1^-$ state in ${}^{16}O$. The determination of these three parameters then specifies the relevant reaction rates. Experiments to determine $\theta_\alpha^2$ from a detailed study of the line shape for $1^-$ states in ${}^{16}O$ via the ${}^{15}N({}^3He,d){}^{16}O$ reaction are in a preliminary stage (R.G.H. Robertson and Sam M. Austin). Experiments to determine more reliably $\Gamma_{rad}$ and $E_x$ are reported in more detail below.

## a) Measurements of $\Gamma_{rad}/\Gamma$ for the 7.66 MeV state of ${}^{12}C$

R. Markham, S. M. Austin and M.A.M. Shahabuddin

The value of $\Gamma_{rad}$ for the 7.66 MeV state is obtained from a combination of measurements of the pair-emission width $\Gamma_\pi$, $\Gamma_\pi/\Gamma$ and $\Gamma_{rad}/\Gamma$ according to

$$\Gamma_{rad} = \frac{\Gamma_{rad}}{\Gamma}\ \frac{\Gamma}{\Gamma_\pi}\ \Gamma_\pi .$$

It was thought that $\Gamma_{rad}/\Gamma$ was well known[4] ($\Gamma_{rad}/\Gamma = (2.9 \pm 0.3) \times 10^{-4}$) until the recent measurement of Chamberlin, *et al.*[2] yielding a value of $(4.2 \pm 0.2) \times 10^{-4}$, nearly 45% higher. Since this uncertainty is now the dominant uncertainty in determining $r_{3\alpha}$, we have undertaken the present experiment in an attempt to resolve this discrepancy.

The 7.66 MeV state is populated via the ${}^{12}C(\alpha,\alpha'){}^{12}C^*$ reaction at 40 MeV beam energy. Simultaneous detection of a stable recoiling ${}^{12}C$ ion and the inelastically scattered alpha particle signifies that the state decayed by radiative transition as opposed to particle emission and breakup. Thus, the number of coincident events divided by the total number of inelastic events gives the branching ratio $\Gamma_{rad}/\Gamma$.

The recoiling ${}^{12}C$ nuclei were detected in a gas-solid-state telescope having two dimensional position sensitivity and described elsewhere in this report. This device allowed identification of the ${}^{12}C$ recoils by their characteristic $\Delta E$-E and E-TOF (time of flight). The coincidence events were further characterized by their localized spatial distribution on the detector. The inelastic alphas were detected in a surface barrier detector at a lab scattering angle of 54 degrees. A stepped absorber was placed ahead of this detector to compensate for the large variation of energy with angle of the alphas.

The experimental procedure was to first align the beam and detectors by steering the beam vertically and moving the recoil detector horizontally ($\theta$ direction) while viewing the horizontal and vertical position spectra of coincident recoils from population of the $E_x = 4.4$ MeV state. With the system so aligned, a test of the detection efficiency was performed. For population of the bound 4.44 MeV state, every alpha must have a coincident recoil. A detection efficiency >98% has been observed with the missing <2% being attributed to a background of alpha particles not associated with population of the 4.44 MeV state of ${}^{12}C$. The detector's solid angle is sufficiently large so the detection efficiency for the 7.66 MeV state will also be ≃100%.

Following these tests the recoil detector was moved by the proper amount to put the coincident recoils from the 7.66 MeV state on the detector. Data was then stored event by event on magnetic tape for later analysis. Because only four analog to digital converters were available, each event could only be characterized by four parameters. These were chosen to be the alpha energy, the time difference between $\alpha$ and ${}^{12}C$ detectors, the final carbon energy and the $\theta$-position of the recoil.

In order to retain the $\Delta E$ information, the time difference, ${}^{12}C$ energy and $\theta$-position signals were gated by the output of a single channel analyzer on the $\Delta E$ signal in coincidence with the output of a single channel analyzer on the $\alpha$ energy signal. Non-coincident events were stored as the alpha energy with zeros for the other parameters. In this manner the coincidence and singles events experienced the same system dead time.

Analysis of the data is not yet complete but it is apparent that a reliable measurement of $\Gamma_{rad}/\Gamma$ will result. Since taking the data, two improvements to the system have become possible. First, ultra-thin windows for the telescope have been constructed. These windows (areal density of ~$150\mu$ gm/cm$^2$) greatly reduce the energy loss of the $^{12}C$ ions in the window thereby fixing much improved energy and time resolution in the stopping detector (or allowing operation of the telescope at angles where the $^{12}C$ energies are lower but the cross section is higher). Second an analog pulse divider has become available which will improve greatly the $\theta$-position resolution. To date the position signal stored in the computer has been the true position times the energy loss ($\Delta E$) and has been limited in accuracy by the 10% FWHM resolution of the $\Delta E$ signal.

Further measurements are planned using these improvements.

### b) Precise values of $E_x$ for the 7.66 MeV State of $^{12}C$

J. A. Nolen and S. M. Austin

Prior to 1971 the reaction rate in common use was based on the measurement of Cook, et al.,[5] which yields $E_x$=7.644±0.004 MeV. Although the most precise of available measurements it was in disagreement with the mean of a number of less precise measurements. Measurements of Austin, Trentelman and Kashy[6] found $E_x$=7.6562±0.0021 MeV, showing that the previous reaction rate was in error by about a factor of three. This result has been confirmed by Stocker, Rollefson and Brown[7], by McCaslin, Mann and Kavanagh,[8] and by Barnes and Nichols,[9] all of their results having uncertainties of about ±2 keV. Taking the weighted average of all these numbers and using Eq. 1, one finds $\chi$=380.0±1.2 keV, corresponding to an uncertainty in $r_{3\alpha}(T=10^8 \cdot K)$ which is about 15%.

We have undertaken experiments to reduce this uncertainty to about half its present value. The developments have made this possible. The first is the fact that the uncertainty in $3M_\alpha$ was recently reduced from 0.75 keV to 0.04 keV.[10] The second is the evolution and verification of techniques which permit the measurement of excitation energies with an accuracy or 1 keV or less. The present experiment involves photographic emulsions and the precision self-calibration method described in reference 11. Current tentative results using the same calibration lines as reference 6 indicate that result is essentially correct with the uncertainty reduced to ±1 keV. To insure completely independent results additional exposures are planned using different calibration lines. These lines include the 7.9 MeV excited state of $^{14}N$ and various lines near this excitation energy in $^{24}Mg$.

---

REFERENCES

1. D. D. Clayton, Principles of Stellar Evolution and Nucleosynthesis (McGraw-Hill, 1968).
2. D. Chamberlin, D. Bodansky, W. W. Jacobs and D. L. Obert, Phys. Rev. C9, 69(1974) and references therein.
3. S. E. Koonin, T. A. Tombrello and G. Fox, Nucl. Phys. A220, 221(1974).
4. F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. A114, 1(1968).
5. C. W. Cooke, W. A. Fowler, C. C. Lauritsen, and T. Lauritsen, Phys. Rev. 107, 508(1951).
6. S. M. Austin, G. F. Trentleman, and E. Kashy Astrophys. J. 163, L79(1971).
7. H. Stocker, A. A. Rollefson, and C. P. Browne, Phys. Rev. C4, 1028(1971).
8. S. J. McCaslin, F. M. Mann, and R. W. Kavanagh, Phys. Rev. C7, 489(1973).
9. C. A. Barnes and D. B. Nichols, Nucl. Phys. A217, 125(1973).
10. L. G. Smith and A. H. Wapstra, Phys. Rev., to be published.
11. J. A. Nolen, G. Hamilton, E. Kashy, and I. D. Proctor, Nucl. Instr. Meth. 115, 189(1974).

# The Production of $^7$Li in the $\alpha$+$\alpha$-Reaction

C. H. King, H. H. Rossner, W. S. Chien, and S. M. Austin

For the most part, the isotopes of lithium, Beryllium, and boron are not end products of normal nucleosynthetic processes in stellar interiors. As a result, it has been necessary to seek other mechanisms, occurring in non-thermal environments, to explain the observed abundances of these isotopes.[1,2,3] Spallation by galactic cosmic rays has been reasonably successful in explaining the abundances of the elements beryllium and boron, but appears to be inadequate to account for the large $^7$Li/$^6$Li abundance ratio.[1,2,3] It has recently been suggested that sufficient production of $^7$Li may occur in supernova explosions to account for this discrepancy.[4,5]

These calculations of $^7$Li production in cosmic-ray and supernova processes require knowledge of the cross sections for formation of $^7$Li in the $\alpha$+$\alpha$ reaction. These cross sections have never been measured directly, and consequently the calculations have been based on estimates derived from measurements of the $^7$Li(p,$\alpha$)$^4$He reaction. Therefore, we have undertaken to measure the $\alpha$+$\alpha$ cross sections within the energy range available at the Cyclotron Laboratory.

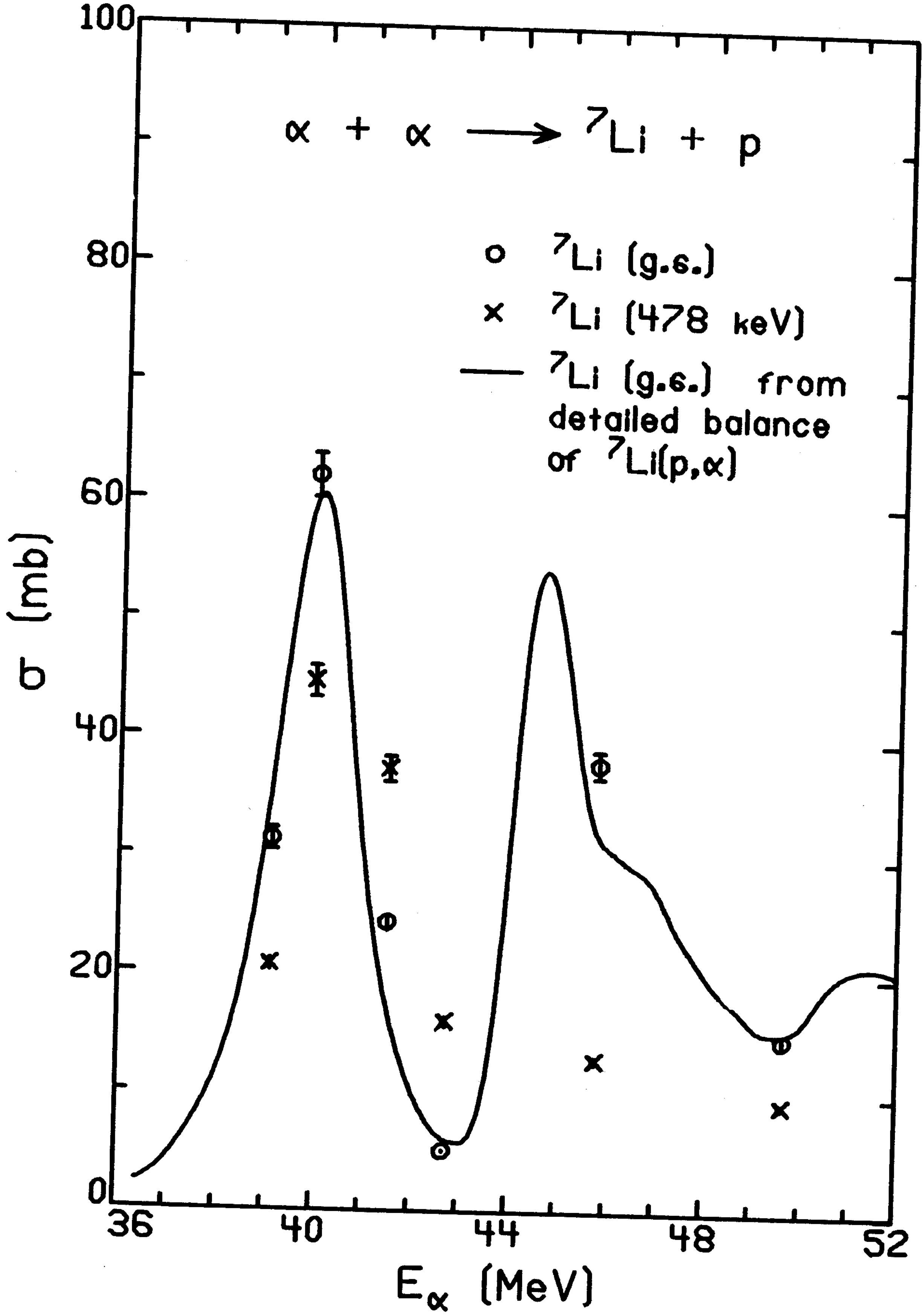
The isotope $^7$Li can be formed through two possible outgoing channels in the $\alpha$+$\alpha$ reaction: p + $^7$Li and n + $^7$Be with the $^7$Be subsequently decaying to $^7$Li by electron capture. The cross sections for the p + $^7$Li channel were determined by measuring the angular distribution of the outgoing protons in a scattering chamber. This has been done at six different incident energies between 39 and 50 MeV using alpha-particle beams from the MSU Cyclotron. The target consisted of a 5-inch diameter gas cell with 1 mil kapton windows, containing approximately 1 atm of helium. The outgoing protons were detected with silicon surface barrier detectors at angles from 10° to 90° with front and back slits positioned so as to eliminate particles resulting from reactions in the windows. The total cross sections were determined by fitting the angular distributions with Legendré polynomials up to L=6. The results for the transitions to the two particle-stable states of $^7$Li (ground and 0.478 MeV) are shown in the figure. The energies of the points take into account energy loss in the front window of the gas cell. Also shown is the cross section for the reaction leading to the $^7$Li ground state as determined from the inverse reaction[6] $^7$Li(p,$\alpha$)$^4$He by using the principle of detailed balance. The agreement between the two results is remarkable considering the difficulty in obtaining proper absolute normalizations for cross sections of reactions measured on Li foils.

The cross section for the reaction $\alpha+\alpha\rightarrow n+{}^7$Be was measured by detecting the recoiling $^7$Be nuclei. Since the $^7$Be nuclei are confined kinematically to a forward angle cone (half angle less than 11° at our energies) they could all be stopped in an absorber, consisting of 5 mil thick Al foil, placed behind the target. The target itself was a 1-inch diameter gas cell with 1/2 mil kapton windows and containing approximately 1 atm of helium. The number of $^7$Be nuclei captured in the foil was determined after the irradiation by detecting in a Ge(Li) detector the 478 keV $\gamma$-rays resulting from the 10.3% branch of the $^7$Be decay to the first excited state of $^7$Li. We have so far performed this irradiation at three different energies; the data are still being analyzed and the cross sections have not yet been determined. In addition, an irradiation was performed using hydrogen gas in the target to determine the number of background $^7$Be nuclei coming from reactions in the gas cell windows and the Al absorber. These contributions were found to be negligible.

---

REFERENCES

1. M. Meneguzzi, J. Audouze, and H. Reeves, Astron. and Astrophys. 15(1971)337.
2. H. E. Mitler, Astrophys. and Space Science 17(1972)186.
3. H. Reeves, J. Audouze, W. A. Fowler, and D. N. Schramm, Ap. J. 179(1973)909.
4. J. Audouze and J. W. Truran, Ap. J. 182 (1973)839.
5. J. Audouze and B. M. Tinsley, preprint (OAP-342, CalTech).
6. G. S. Mani, R. Freeman, F. Picard, A. Sadeghi, and D. Redon, Nucl. Phys. 60(1964)588.


α + α → $^7$Li + p
○ $^7$Li (g.s.)
× $^7$Li (478 keV)
$^7$Li (g.s.) from detailed balance of $^7$Li(p,α)
100
80
60
40
20
0
σ (mb)
36
40
44
48
52
$E_α$ (MeV)