^{7}Li and ^{7}Be Production in the α+α Reaction

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

A satisfactory explanation of the ^{7}Li abundance in the universe remains an outstanding problem in nuclear astrophysics. As is the case with most other light nuclides, the relatively small binding energy of ^{7}Li makes it readily susceptible to break up from nuclear reactions inside most stars. Thus, sources of ^{7}Li production must be sought either in unusual stellar processes or in extrastellar mechanisms.

A mechanism which has been particularly successful in accounting for the abundance of some other light nuclides is spallation of nuclei in the interstellar medium by cosmic rays. Because of the relatively high abundance of ^{4}He in both cosmic rays and the interstellar medium, the α+α reaction is particularly important for ^{7}Li production in cosmic-ray spallation. We have been measuring the cross sections for this reaction in order to determine the contribution of such spallation to the universal ^{7}Li abundance. Four α+α reaction channels are involved in ^{7}Li production: direct production via ^{4}He(α,p) to the two particle-stable states of ^{7}Li, and, since ^{7}Be decays to ^{7}Li, ^{4}He(α,n) to the two particle-stable states of ^{7}Be. We determined the cross sections for the first two channels by measuring the angular distributions of the outgoing protons. The ^{4}He(α,n) cross sections were obtained by collecting the recoil ^{7}Be ions in aluminum foil and then counting the 478-keV γ rays resulting from the 10.4% branch to the ^{7}Li first excited state in the electron-capture decay of ^{7}Be. These cross sections were measured below E_α=50 MeV using the MSU Cyclotron (data shown in Fig. 1). We have also measured cross sections above 50 MeV at a few energies in collaboration with a group at the University of Maryland.[1]

Two relatively extensive calculations of nuclide production in cosmic-ray spallation have been performed.[2,3] These calculations differ in their assumptions about the energy dependence and time dependence of the cosmic-ray flux and about the time dependnece of the composition of the interstellar medium. Nevertheless, they give qualitatively similar results. Thus, since the calculations involved in the model of Ref. 2 are more easily performed, we have used this model to determine the ^{7}Li production from cosmic-ray spallation. With our cross sections for the α + α production of ^{7}Li, we find the ^{7}Li to H abundance ratio coming from cos ray spallation is 1.3×10^{-10}. This should be compared to the observed value of 10^{-9} (see Ref. 5). Also, the ^{7}Li to ^{6}Li isotopic ratio resulting from cosmic-ray spallation is 1.4, as opposed to the observed value of 12.5. This indicates that most of the ^{7}Li in the universe was created via some other mechanism than cosmic-ray spallation. This is discussed more fully elsewhere in this Annual Report.

1. C.H. King, H.H. Rossner, S.M. Austin, W.S. Chien, G.J. Mathews, V.E. Viola, Jr., and R.G. Clark, Phys. Rev. Lett. 35, 988(1975).
2. H.E. Mitler, Astrophys. Space Sci. 17, 186(1972).
3. M. Meneguzzi, J. Audouze, and H. Reeves, Astron. and Astrophys. 15, 337(1971).
4. A.G.W. Cameron, Space Sci. Rev. 15, 121(1973).
5. A.M. Boesgaard, Publ. Ast. Soc. Pac. 88, 353(1976).

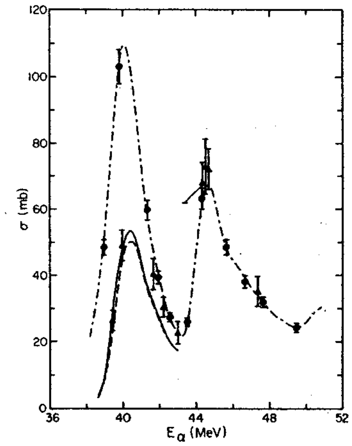

FIG. 1.--Comparison between integral cross sections for ^{7}Be production (sum of ^{4}He(α,n)^{7}Be (g.s.) and ^{4}He(α,n)^{7}Be(429 keV) cross sections) shown as triangles and those for ^{7}Li production (sum of ^{4}He(α,p)^{7}Li(g.s.) and ^{4}He(α,p)^{7}Li(478 keV) cross sections) shown as circles. The solid line represents the preiction for the ^{7}Be production cross sections near threshold by multiplying the ^{4}He(α,p) cross sections by the ratio of neutron to proton penetrabilities with a channel radius of 2.4 fm. The dot-dashed line is to guide the eye through the ^{7}Li production cross section.

$^4He(\alpha,p)$ and $^4He(\alpha,n)$: The Structure of ^8Be

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

As is described elsewhere in this Annual Report, we have measured cross sections for the $^4He(\alpha,p)$ and $^4He(\alpha,n)$ reactions at energies between E_α = 39 and 50 MeV to be used in a determination of the contribution to the universal ^7Li abundance from cosmic-ray spallation of the interstellar medium. We have also attempted to relate our results to other data involving the $\alpha+\alpha$ system and to the structure of ^8Be.

In the case of $^4He(\alpha,p)$ we measured differential cross sections for the reaction leading to the ground state of ^7Li and that to its first excited state (478 keV). The ground-state cross sections can be compared to those for the inverse reaction $^7Li(p,\alpha)$ using the detailed balance expression for the case in which identical particles occur in one of the reaction channels[1]. The resulting cross sections are about a factor of two smaller than existing $^7Li(p,\alpha)$ measurements in the relevant energy region[2]. This is consistent with discrepancies found between the measurements of Ref. 2 and more recent measurements at lower energies[3,4].

In this energy region the $^4He(\alpha,p)$ cross sections show considerable structure which can be interpreted as resulting from resonances in the compound nucleus ^8Be. Kumar and Barker[4] have used an R-matrix approach to fit the $^7Li(p,\alpha)$ data up to E_p=7 MeV in terms of 6 levels in ^8Be. These parameters of course also fit our $^4He(\alpha,p)^7Li(g.s.)$ data, but we have also checked to see to what extent they fit the data for the $^4He(\alpha,p)^7Li(478$ keV) reaction. The fit, as shown in Figs. 1 and 2, is not very good, and we are now attempting to determine what changes in the level parameters are necessary to improve it.

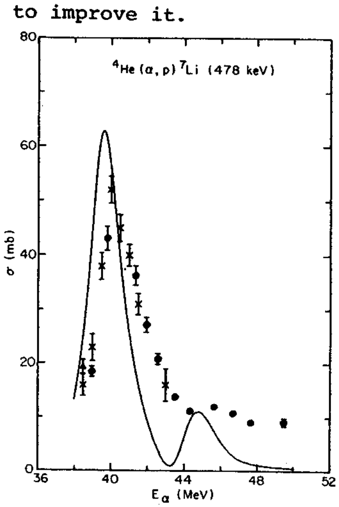

Fig. 1--Comparison of the $^4He(\alpha,p)^7Li(478$ keV) integral cross sections measured in the present study (circles) with those measured by Burchan et al.[6] (triangle) and by Conzett et al.[7] (crosses). The line represents the prediction for this cross section based on the ^8Be level parameters from the R-matrix fits of Kumar and Barker[4] to $^7Li(p,\alpha)$ cross sections.

Below the first three-body threshold in the $\alpha+\alpha$ reaction (39.6 MeV), the sum of the $^4He(\alpha,p)$ and $^4He(\alpha,n)$ cross sections constitute the entire $\alpha+\alpha$ reaction cross section. We have therefore compared our measured reaction cross section with predictions based on $\alpha+\alpha$ elastic scattering phase shift analysis. The proper formula with identical bosons is[5]

$$\sigma_R = 2\pi\lambda^2 \sum_{\substack{\ell=0 \\ \text{even}}}^{\infty} (2\ell+1)\ (1+|e^{2i\delta_\ell}|^2)$$

where δ_ℓ are the complex phase shifts. We find[5] that our measurements and phase shift predictions are in good agreement.

1. W.A. Fowler, G.R. Caughlin, and B.A. Zimmerman, Ann. Rev. Astron. Ap. 5, 525 (1967).
2. G.S. Mani, et al., Nucl. Phys. 60, 588(1964).
3. G.M. Lerner and J.B. Marion, Nucl. Inst. Meth. 69, 115(1969).
4. N. Kumar and F.C. Barker, Nucl. Phys. A167, 434(1971).
5. C.H. King, S.M. Austin, W.S. Chien, and H.H. Rossner, Phys. Lett. 67B, 389(1977).
6. W.E. Burchan, et al., Nucl. Phys. 5, 141 (1958).
7. R.J. Slobodrian, Phys. Lett. 63B, 5(1976).

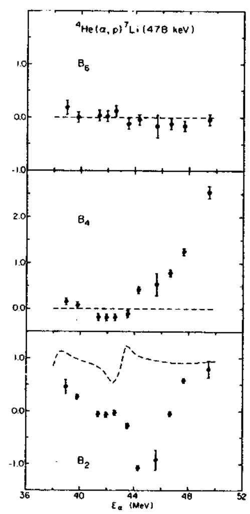

Fig. 2--Angular distribution Legendre coefficients B_L for the $^4He(\alpha,p)$ reaction leading to the first excited (478 keV) state of ^7Li. The dashed lines are predictions for these coefficients based on the ^8Be level parameters from the R-matrix fits of Kumar and Barker[4] to $^7Li(p,\alpha)$ cross sections.

A Constraint on the Mean Baryon Density of the Universe from the Abundance of ^7Li

S.M. Austin and C.H. King

The observed interstellar abundance of ^2H has been used[1,2] to estimate the mean baryon density ρ_b of the Universe. This estimate follows from the facts (1) that there is no plausible source for ^2H other than the primordial big bang and (2) that the production of ^2H in a standard big bang decreases rapidly with increasing ρ_b. If one then assumes that all ^2H was formed in a big bang, the observed abundance[2] of this nuclide requires a value of ρ_b sufficiently low[1] that, for a cosmological constant $\Lambda = 0$, the present expansion of the Universe will continue forever and the Universe is open. A major weakness in this argument is that another source of ^2H may be found, so that it is important to obtain confirming evidence for the above conclusion.

We point out here that ^7Li can be used to place an upper limit on ρ_b, even if other production mechanisms are important, and that this limit also strongly favors an open universe. This possibility arises because the big bang production of ^7Li increases with increasing ρ_b (for $\rho_b > 10^{-31}$) so that an upper limit is obtained by attributing all of the observed ^7Li to the big bang.

For the present argument we have adopted Boesgaard's[4] value of the Li abundance which yields a fractional abundance by mass of ^7Li, $X_7 = 5 \times 10^{-9}$. Assuming the big bang must not synthesize more than this amount then leads[5] to $\rho_b \leq 1.1 \times 10^{-30}$ g/cm^2. As is shown in Fig. 1, this is substantially less than the critical value ρ_c necessary to close a $\Lambda = 0$ Friedman universe.

The existence of mechanisms which destroy ^7Li weakens the limit on ρ_b since the big bang may then have made more ^7Li than is presently observed; conversely, discovery of additional sources of ^7Li strengthens the limit. Astration of primordial material is presumably the most important destruction process. Estimates of the fraction of matter which has passed through stars are typically about 0.5. On the other hand, it has been pointed out recently[3] that infall of primordial material from the galactic halo may be significant and would tend to compensate for the effects of astration for those nuclei produced in the big bang. Other sources of ^7Li are generally rather speculative in nature[3], except for production in the cosmic rays which yields roughly 10% of the observed ^7Li. Since these various effects tend to offset each other, using the observed value of X_7 seems reasonable.

In summary, the simplest and most straightforward assumptions concerning the origin of ^7Li and the nature of the big bang expansion require an upper limit for the present universal density

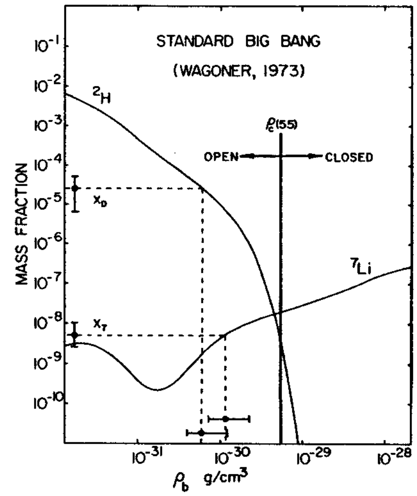

Fig. 1.--Abundances of ^2H and ^7Li produced in a standard big bang (adapted from Wagoner.[5] The present day black body temperature is taken to be 2.90 K.) The vertical line labeled $\rho_c(55)$ is the density necessary to close a Friedman universe with $\Lambda = 0$, if $H_o = 55$ km/sec-Mpc. The point labeled X_D is the mass fraction of ^7Li corresponding to the abundance given by Boesgaard,[4] while that labeled X_D is the mass fraction of ^2H from the summary of ref. 2. (This latter value is smaller than that used by Gott et al., mostly because they include an estimate of the effects of astration). The uncertainty indicated for X_7 is a factor of 2 in either direction while that for X covers the range from a factor of 4 smaller to a factor of two larger. Corresponding values of ρ_b and their uncertainties are also shown. The value of ρ_b determined from the ^7Li abundance is only an upper limit if there are significant sources of Li other than the big bang.

of $\rho_b = (1.1 {+1.1 \atop -0.4}) \times 10^{-30}$ gm/cm^3. Given that the Universe is indeed a Friedman universe with zero cosmological constant, the agreement between the present limit and that based on ^2H strongly supports the conclusion of Gott et al.[1] that the Universe is open and will continue to expand forever.

---

1. J.R. Gott, J.E. Gunn, D.N. Schramm, B.M. Tinsley, Ap. J. 194, 543-553(1974).
2. D.N. Schramm and R.V. Wagoner, Ann. Rev. Nuc. Sci. 27, to be published.
3. H. Reeves, Ann. Rev. Astron. Ap. 12, 437-469(1974).
4. A.M. Boesgaard, Pub. Astron. Soc. Pac. 88, 353-66(1976).
5. R.V. Wagoner, Ap. J. 179, 343(1973).