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Cosmic-Ray Production of ^{6,7}Li by the $\alpha + \alpha$ Reaction

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Total cross sections for the production of ^{6}He, ^{6,7}Li, and ‘Be in the $\alpha + \alpha$ reaction have been measured at bombarding energies of 159, 280, and 620 MeV. The resulting cross sections decrease rapidly with energy. Cosmic ray nucleosynthesis calculations using the new cross sections will produce less ^{6}Li than obtained for the Read-Viola cross sections currently in use.

1. INTRODUCTION

The abundances of the light elements Li, Be, B found in old galactic halo stars have raised questions about the mechanisms that produce them, and whether one can deduce the primordial abundance of ^{7}Li for comparison with the predictions of Big Bang nucleosynthesis. The situation is shown schematically in Fig. 1. The abundances of Be and

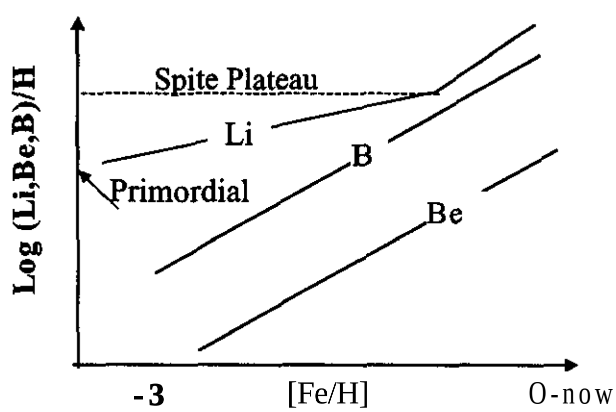

Figure 1. Observed abundances of Li, Be, B (LiBeB)in old galactic halo stars, as a function of the Fe content of these stars. [Fe/H] = $log[(Fe/H)/(Fe/H)_{solar}]$.

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B increase almost linearly with [Fe/H], and show no sign of a plateau at low [Fe/H]. The behavior of Li is different. To first order, the abundance does not depend on [Fe/H] for low [Fe/H]; this is the Spite plateau. It has been taken as evidence that the Li in these old stars has the primordial abundance synthesized in the Big Bang. Recent measurements[1], show that the Li abundance increases slightly with metallicity as shown in exaggerated form in Fig. 1. It seems probable that this increase reflects contributions from other mechanisms, such as production in the cosmic rays. If this is is the case, one will have to extrapolate to earlier times (i.e. lower [Fe/H]) to obtain the primordial abundance, analogously to the procedure one follows to obtain the primordial He abundance. Another issue that must be faced is possible depletion of the primordial ^{7}Li in the stellar convection zone. Since ^{6}Li has now been observed in a few old halo stars, and since it is still more fragile than ^{7}Li, one might be able to use the ^{6}Li abundances to limit the amount of ^{7}Li depletion. Cosmic ray production is the only significant source of ^{6}Li.

A quantitative description of the evolution of Li abundances depends upon the production rates of ^{6,7}Li in the cosmic rays. These in turn depend upon the relevant cross sections for LiBeB formation during interactions of cosmic ray protons and alpha particles with nuclei in the interstellar medium. In the present epoch production of ^{6,7}Li is dominated by the interaction of cosmic ray protons and interstellar C,N,O. However, in the early galaxy ^{6,7}Li production depends sensitively on the cross section for the $\alpha + \alpha \rightarrow ^{6,7}$Li reactions, simply because there are few C,N,O nuclei in the interstellar medium. Unfortunately the cross sections for the reactions leading to ^{6}Li are not known well enough, nor to sufficiently high energy, to permit accurate predictions of ^{6}Li production for a typical cosmic ray spectrum. Uncertainties of at least a factor of two are possible, depending on how one extrapolates the cross sections to high energy.

To reduce this uncertainty, we have measured the production cross sections up to $E_\alpha =$ 620 MeV, using a new technique that greatly reduces the background for these small cross sections. Instead of using a small gas cell and collimators to define the direction of the outgoing particles, the target helium gas fills a large scattering chamber (diameter 235 cm) and the scattering angle is determined by two position sensitive detectors placed one behind the other. Outgoing ^{6}He, ^{6,7}Li and ^{7}Be ions were detected and the cross sections for their production were obtained at 159, 280, and 620 MeV. These data and reevaluated results[2] from lower energy experiments show that the cross sections decrease roughly exponentially between 60 and 620 MeV. As a result, yields are little dependent on reasonable extrapolations to higher energy. The predicted yields of ^{6}Li for a typical cosmic-ray spectrum are smaller than predicted by the summary of Read and Viola[3]. A detailed paper[4] on the present experiment has been submitted for publication.

2. RESULTS

Since ^{6}He and ^{7}Be have lifetimes of 807 msec and 53 days, they decay to ^{6}Li and ^{7}Li quickly on an astrophysical timescales. Consequently it is the sum of the mass-6 cross sections that leads to ^{6}Li and and the sum of the mass-7 cross sections that leads to ^{7}Li. The results for $A = 6$ and $A = 7$ are shown in Figs. 2 and 3. The data for $A = 6$ deviate from an exponential behavior at the highest energies. Adding a constant cross section results in an good description of the data with the following dependence on energy:

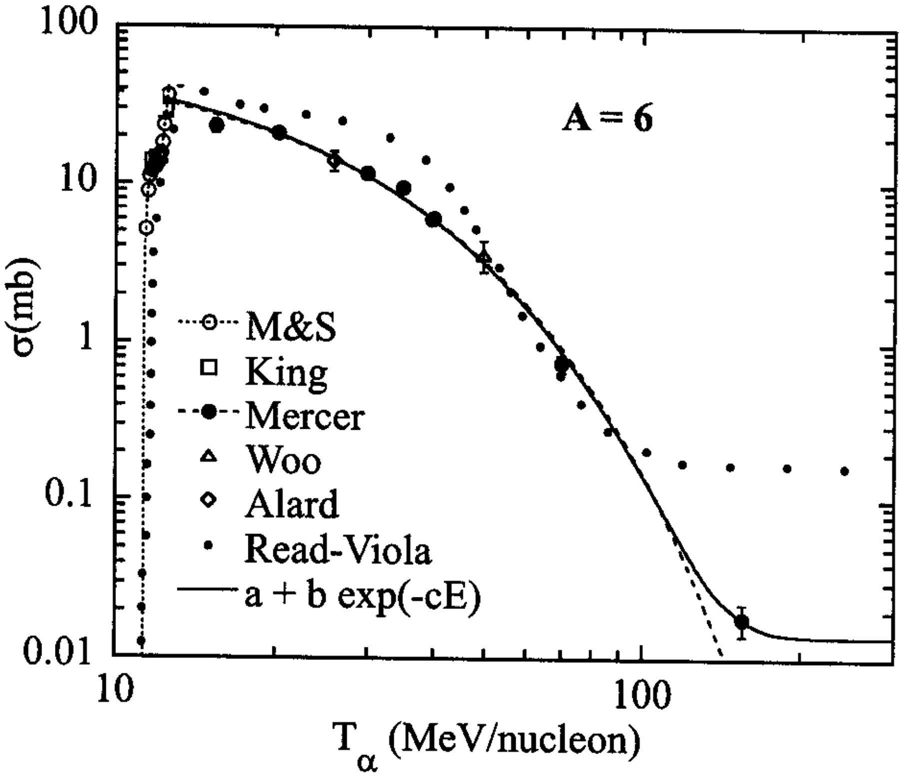

Figure 2. The sums of the cross sections for ^{6}He and ^{6}Li from this experiment are shown as (•) at 159, 280, and 620 MeV The other points for $E_\alpha > 18$ MeV/nucleon are taken from[2]. The small dots are the recommended cross sections of Read and Viola[3]. The dashed line is a weighted exponential fit to the high energy data and the solid curve includes a constant background as shown in the legend.

$\sigma_{mass-6} = 0.014 + 75\exp\left(-0.0159E_\alpha\right)$ mb. It would be desirable to use a form that more accurately reflects the physical processes at high energy, but, to our knowledge, no such description is available for this reaction, and the data are insufficient to fix more than one parameter. The present form should be adequate for applications. There is no evidence for a deviation from exponential behavior for $A = 7$, but there is only an upper limit, not an actual measurement of the cross section, at the highest energy.

3. DISCUSSION AND SUMMARY

Because the cross sections we obtain for production of $A = 6$ in $\alpha + \alpha$ collisions are generally smaller than the recommended cross sections of Read and Viola[3], the production of ^{6}Li in the cosmic rays will be smaller than that predicted in models using the Read-Viola results. To obtain an measure of these effects we have integrated the product of the $A = 6$ cross sections (Fig. 2 and from Read-Viola) and a transported cosmic ray flux (Fig. 2b, curve labeled $\Lambda = 10\mathrm{gm/cm}^2$ in Ref. [5]). The production rate for the present results is half that obtained with the Read-Viola cross sections. Since the production rate of ^{6}Li is only marginally sufficient in some models (see, for example, Ref. [6]) that use

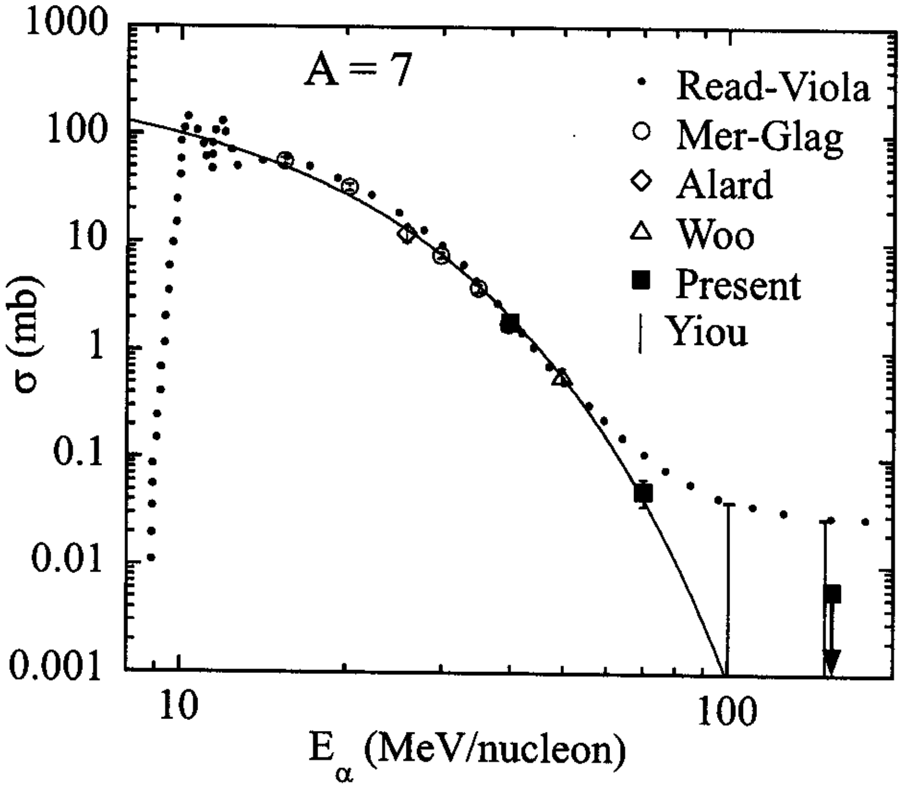

Figure 3. The sum of cross sections for ^{7}Li and ^{7}Be from this experiment are shown as solid squares. The other points for $E_\alpha > 18$ MeV/nucleon are taken from[2]. The small dots are the recommended cross sections of Read and Viola[3] and the solid line is an exponential fit to the data.

the Read-Viola rates, either the models are insufficient, or the stellar depletion of ^{6}Li is small.

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