backward maximum, our curve is too low. Moreover, the calculated height of the backward maximum is energy dependent, whereas experimentally it is found to be nearly constant between 15 and 50 MeV.[10] Finally, the deuteron vector polarization at 14.1 MeV is displayed in Fig. 5. There is only qualitative agreement with the data at 14.95 MeV. The results of Fayard, Lamot, and Elbaz[5] and Doleschall[12] indicate that here part of the differences can be attributed to the use of perturbation theory. The dip for intermediate angles is not deep enough. However, since the experimental minimum is found to be strongly energy dependent, the situation is probably slightly better than shown.[13]

To conclude, with the notable exception of the forward differential cross section where the presence of the repulsion in the local s-wave potentials reduces the effect of the higher partial-wave forces, the sensitivities of the n-d observables are qualitatively the same for the local potentials as for the separable potentials. Furthermore, the pronounced dip near the minimum in the cross section which is found at higher energies using only s-wave potentials is filled in predominantly by the contribution from the d-wave component of the dueteron. As a result, the description with local interactions is in reasonable agreement with the data for the differential cross section over the whole energy range considered.

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$\alpha + \alpha$ Reaction and the Origin of ^{7}Li

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Cross sections are presented for the production of ^{7}Li and ^{7}Be in the $\alpha + \alpha$ reaction between threshold and 140 MeV. Implications of these measurements for the problem of the origin of ^{7}Li in the universe are discussed.

The observed abundances of most stable nuclides can be understood in terms of two main processes: (1) nucleosynthesis during stellar evolution,[1] which applies principally to carbon and heavier elements, and (2) spallation of interstellar matter by galactic cosmic rays,[2] which is most important for the elements with $A < 12$. There are, however, a few nuclides whose abundances are not readily explained by either of these processes. An example is deuterium, where the lack of a reasonable alternative production mechanism has led to the suggestion that most of the present deuterium may have had its origin in the original cosmic explosion, assuming a big-bang model of the universe.[3] Indeed, the observed abundance of deuterium may yield significant information about the characteristics of the big bang, since in present models it provides a severe constraint on the mean baryon density of the universe.[3]

The problem of the origin of ^{7}Li may also prove to have significant implications for models of cosmic evolution. Traditional stellar nucleosynthesis seems to be inadequate to account for ^{7}Li, and in fact nuclear reactions in main-sequence stars appear to deplete rather than produce it.[4] Detailed calculations have indicated that this nuclide is also underproduced in cosmic-ray spallation processes, and, in particular, have predicted a ^{7}Li/^{6}Li abundance ratio which is smaller than the observed ratio by nearly an order of magnitude.[5,6] This result would seem to imply that an additional production mechanism is required for ^{7}Li.

However, the spallation calculations depend on accurate measurements of the cross sections for the nuclear reactions involved. For ^{7}Li, a principal spallation source is the $\alpha+\alpha$ reaction, and prior to the work presented in this Letter a direct measurement of the cross section for ^{7}Li production in this reaction had been made[7] at only two energies (38.5 and 42 MeV). Since ^{7}Be decays to ^{7}Li by electron capture, the cross sections for ^{7}Be formation must also be known, and no successful measurement of this cross section had been made. Spallation calculations[5,6] were thus necessarily based on measured cross sections for the reaction $^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$, using the principle of detailed balance to determine the ^{7}Li ground-state cross section in the $\alpha+\alpha$ reaction. The production of ^{7}Be in its ground state was assumed to have equal cross section, and the channels leading to the particle-stable excited states of ^{7}Li and ^{7}Be (at 478 and 429 keV, respectively) were ignored.[8] In addition, even the $^7\mathrm{Li}(p,\alpha)$ cross sections are problematic, since there is considerable disagreement among existing low-energy measurements[9,10] and only a few isolated measurements have been made at higher energies.[11]

Because of all these uncertainties, no definite conclusion could be drawn concerning the ^{7}Li production in galactic cosmic-ray spallation. In an attempt to clarify this situation, we present in this Letter direct measurements of the cross sections for both ^{7}Li formation and ^{7}Be formation in the $\alpha+\alpha$ reaction. Our measurements indicate that the $\alpha+\alpha$ cross sections assumed in existing spallation calculations have been somewhat overestimated. Thus, since the ^{7}Li production predicted by these calculations was already too low, we conclude that the present models for spallation production cannot account for the observed ^{7}Li abundance and that another mechanism must be sought. For ^{7}Li, as for deuterium, a likely candidate for this mechanism is nucleosynthesis during the big bang.[3]

We determined the cross sections for $\alpha+\alpha \to {}^7\mathrm{Li}+p$ by measuring the angular distributions of the protons in the center-of-mass forward quadrant. The differential cross sections were then integrated to obtain the total cross sections, using the fact that the angular distributions are symmetric about 90° in the center-of-mass system. These measurements were made at eleven energies between the reaction threshold (34.7 MeV for $\alpha+\alpha \to {}^7\mathrm{Li}+p$ and 38.0 MeV for $\alpha+\alpha \to {}^7\mathrm{Be}+n$) and 50 MeV using α particles from the Michigan State University sector-focused cyclotron. The target consisted of a helium-filled gas cell, and the protons were detected in silicon surface-barrier detectors. The average energy resolution obtained for the protons was about 75 keV full width at half-maximum, arising principally from kinematic broadening, so that the proton peaks in the spectrum were well resolved from each other and from the deuteron and α-particle peaks. The ^{7}Li-production cross sections were also measured at 60.2, 92.4, and 140.0 MeV using α particles from the University of Maryland cyclotron. In these latter runs, the proton angular distributions were measured with a Si-NaI ΔE-E counter telescope. The energy resolution of this system was insufficient to resolve the two proton peaks corresponding to ^{7}Li in its ground and 478-keV states, but this is not an important restriction, since the summed cross section for the production of ^{7}Li in its two particle-stable states is the relevant quantity for spallation calculations. The summed cross sections are shown in Figs. 1 and 2 at all the measured energies.

The ^{7}Be-formation cross sections were obtained by directly collecting the ^{7}Be recoils. Since these particles are confined to a narrow forward-angle cone (ranging from 3° maximum laboratory angle

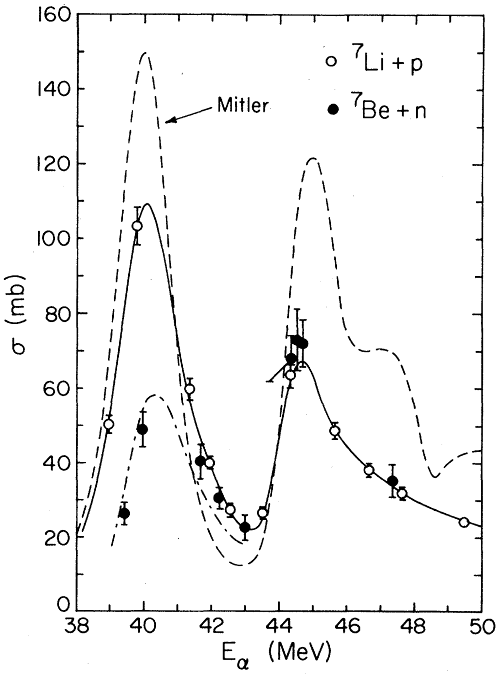

FIG. 1. Cross sections (sum of ground-state and first-excited-state transitions) for the formation of ^{7}Li and ^{7}Be in the $\alpha + \alpha$ reaction below 50 MeV. The dashed curve represents the cross sections (assumed equal for the two reactions) used by Mitler (Ref. 6) in his spallation calculations. The dash-dotted curve shows an estimate of the reduction near threshold of the ^{7}Be formation cross section over that for ^{7}Li formation resulting from the differing neutron and proton penetrabilities. The solid line is to guide the eye.

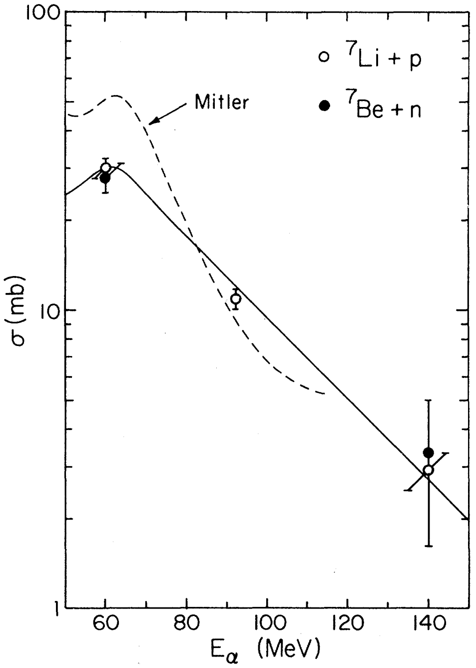

FIG. 2. Cross sections for the formation of ^{7}Li and ^{7}Be in the $\alpha + \alpha$ reaction above 50 MeV. The symbols used have the same meaning as those in Fig. 1.

at 39 MeV to 18° at 140 MeV), they can all be collected in aluminum absorbers placed downstream from the target. We determined the number of ^{7}Be nuclei captured in the foils by measuring the 478-keV γ rays resulting from the 10.3% branch of the decay to the first excited state of ^{7}Li, using a Ge(Li) detector whose absolute efficiency had been calibrated. The amount of ^{7}Be produced by reactions in the windows of the gas-cell target was determined by taking runs with the helium replaced by a hydrogen pressure of equivalent stopping power. From the net ^{7}Be yield we obtained the cross sections shown in Figs. 1 and 2.

Comparisons between our measurements and the cross sections assumed by Mitler[6] in his calculations of ^{7}Li production in $\alpha + \alpha$ spallation are also indicated in the figures. The calculations of Meneguzzi, Audouze, and Reeves[5] utilized a similar excitation function. In the region between threshold and 55 MeV, these cross sections were obtained by applying detailed balance to the ^{7}Li(p, α) measurements of Mani *et al.*,[10] neglecting the contribution from the first-excited state. Although the *relative* excitation function we measured for the cross section leading to the ^{7}Li ground state is in excellent agreement with that of Mani *et al.* for the inverse reaction, we find[12] that the *absolute* normalization of those measurements is too large by approximately a factor of 2. This result is consistent with measurements[9] of ^{7}Li(p, α) cross sections more recent than those of Mani *et al.* Thus, the low-energy ground-state cross section assumed in Refs. 5 and 6 is too large by about a factor of 2. This error is partially compensated in the region between threshold and 43 MeV by a resonance[12] in the cross section for the 478-keV state of ^{7}Li. However, in general the ^{7}Li-production cross sections have been overestimated at the low energies, and as can be seen in Fig. 2, they have been overestimated for the most part at the higher energies as well. On the other hand, our measurements indicate that the ^{7}Be cross sections are essentially equal to those for ^{7}Li, the only marked difference occurring at the lowest energies where threshold effects reduce the ^{7}Be cross section. In summary, these results show that the $\alpha+\alpha$ cross sections which have been used to calculate ^{7}Li production from cosmic-ray spallation are too large. Thus, a mechanism for ^{7}Li formation different from the standard spallation models seems to be required.

Several alternative models have been considered.[13] It has been suggested, for example, that a substantial amount of ^{7}Li could be produced by an unobserved portion of the cosmic-ray spectrum which is peaked at low energies. Spallation might also be induced by moderate-energy projectiles (about 10 MeV per nucleon) produced by shock waves in supernova envelopes. It is not known at present whether such particle fluxes occur with sufficient intensity in nature to account for the ^{7}Li abundance, or whether they can satisfy constraints on interstellar heating (in the case of the cosmic rays) or on the available energy (in the case of supernovae).[13] Another possible source of ^{7}Li production is red-giant stars, where large lithium abundances are sometimes observed. The mechanism for ^{7}Li production in such stars is, however, presently uncertain, and it is an open question whether the ^{7}Li produced in this manner is ejected into the interstellar medium.[13]

In view of these uncertainties, an appealingly simple alternative is that the majority of the present ^{7}Li was created during the big bang,[6,14] and it is suggestive that standard models of this event yield substantial ^{7}Li production.[3] Moreover, the mean baryon density required to generate the observed ^{7}Li abundance during the big bang is reasonably close to that required to generate deuterium, and both of these production processes are quite sensitive to variations in the baryon density.[3] Thus, the universal abundance of ^{7}Li may become, as in the case of deuterium, a means of inferring the nature of the primordial universe.

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