^{2}H Induced Reactions on ^{8}Li and Primordial Nucleosynthesis

M. J. Balbes,[1] M. M. Farrell,[1] R. N. Boyd,[1,2] X. Gu,[1] M. Hencheck,[1] J. D. Kalen,[1] C. A. Mitchell,[1] J. J. Kolata,[3] K. Lamkin,[3] R. Smith,[4] R. Tighe,[5] K. Ashktorab,[6] F. D. Becchetti,[6] J. Brown,[6] D. Roberts,[6] T.-F. Wang,[7] D. Humphreys,[8] G. Vourvopoulos,[8] and M. S. Islam[9]

[1]*Department of Physics, Ohio State University, Columbus, Ohio 43210*
[2]*Department of Astronomy, Ohio State University, Columbus, Ohio 43210*
[3]*Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556*
[4]*Division of Nuclear Medicine, Department of Radiology, Hospital of the University of Pennsylvania, Philadelphia, Pennsylvania 19104*
[5]*Lawrence Berkeley Laboratory, Berkeley, California 94720*
[6]*Department of Physics, University of Michigan, Ann Arbor, Michigan 48109*
[7]*Lawrence Livermore National Laboratory, Livermore, California 94550*
[8]*Department of Physics, University of Western Kentucky, Bowling Green, Kentucky 42101*
[9]*Department of Physics, Ball State University, Muncie, Indiana 47306*
(Received 9 August 1993)

Cross sections for the ^{8}Li$(d,n)^9$Be (ground state) and ^{8}Li$(d,t)^7$Li reactions, both important to primordial nucleosynthesis in the inhomogeneous models, have been measured using a radioactive beam technique. The cross section for the former reaction is found to be small, so it is important only for synthesis of ^{9}Be. The cross section for the latter reaction, however, is found to be large enough to destroy significant quantities of ^{8}Li, and thus could affect predictions of primordial nucleosynthesis yields.

PACS numbers: 25.45.Hi, 27.20.+n, 95.30.Cq, 98.80.Ft

Recent theoretical studies of primordial nucleosynthesis have pinpointed the light nuclides Li, Be, and B as crucial to the testing of our understanding of the processes thereof. The standard model (SM) [1–4] is known to produce fairly good agreement with primordial abundances of nuclides up to mass 7 amu, and to produce very tiny abundances of elements heavier than those. The recently developed inhomogeneous models (IMs) [5–8] predict abundances similar to those of the SM up to ^{4}He for much of their parameter space. However, the IMs predict considerably higher abundances for ^{7}Li and heavier nuclides, suggesting that astronomers can provide definitive tests of the two models. Unfortunately, the predictions of the IMs are considerably less certain than those of the SM, primarily because the IM calculations utilize many thermonuclear reaction rates involving short-lived nuclides, none of which had been measured until very recently. The IMs also contain more parameters than the SM, some of which might be defined by considerations of details of the quark-hadron phase transition, but none of which is yet known with confidence.

The ^{8}Li$(d,n)^9$Be reaction can both produce ^{9}Be and destroy ^{8}Li, and is therefore potentially important in determining the abundances of the light nuclides from the IMs. Note that ^{9}Be also has a number of excited states which could, from ^{8}Li$(d,n)^9$Be* reactions, contribute to the destruction of ^{8}Li, but, because they decay primarily by particle emission, would not make ^{9}Be. The ^{8}Li$(d,t)^7$Li reaction can destroy ^{8}Li, so it could affect the abundances of any nuclides produced via reaction pathways through ^{8}Li. This is particularly important, since the ^{8}Li$(\alpha,n)^{11}$B reaction is thought to be the primary pathway by which nuclides of mass 11 amu or heavier are made. However, the extent to which such nuclides are synthesized [8] scales with the ^{8}Li abundance during primordial nucleosynthesis, determined by the balance between the processes which create it and those which destroy it. Unfortunately experiments involving ^{8}Li are difficult because of the 840.3 ms half-life [9]. Nonetheless, a recent measurement [10] has been made of the cross section for ^{8}Li$(\alpha,n)^{11}$B.

Recent developments have shown that the predictions of the IMs are quite uncertain for the abundances of nuclides ^{7}Li through ^{11}B, due primarily to uncertainties involving late time homogenization [11]. However, it appears that heavier nuclides might be less sensitive to that effect, because of the higher Coulomb barriers for interactions between them and protons. Thus it may be possible to circumvent some of the parameter-associated uncertainties of the IMs by predicting the abundances of ^{12}C and somewhat heavier nuclides. Since their abundances all scale [8] with the ^{8}Li abundance during primordial nucleosynthesis over large regions of the IM parameter space, reactions on ^{8}Li are critical for accurate abundance predictions.

Thus we have attempted to measure cross sections for three of the potentially important reactions on ^{8}Li, ^{8}Li$(d,n)^9$Be, ^{8}Li$(d,t)^7$Li, and ^{8}Li$(d,p)^9$Li, and report on those measurements in this Letter. Because ^{8}Li is short lived, these measurements required an ^{8}Li (radioactive) beam, a recent experimental development. We first describe the experimental setup used, then the basic features of the data obtained. Finally, we discuss the results of the present experiment and give some indication of the effects on predictions of primordial nucleosynthesis which they might bring about.

The D(^{8}Li,^{9}Be)n reaction to the ^{9}Be(g.s.), the D(^{8}Li,^{7}Li)T reaction, and the D(^{8}Li,^{9}Li)H reaction were

0031-9007/93/71(24)/3931(4)$06.00

studied during two week-long runs using the Notre Dame–Michigan–Ohio State radioactive beam facility [12], which operates in the following way. An intense 17 MeV ^{7}Li beam impinging on a 2.3 mg/cm^2 thick primary ^{9}Be target produced ^{8}Li ions and many other species. The ^{8}Li ions were selected by a superconducting solenoid located just after the ^{9}Be target, producing a beam with typical intensity in excess of 10^6 s^{-1}. In some of the runs, the resulting ^{8}Li beam then passed through absorber foils to select the beam energy. Then the beam passed into a scattering chamber where it impinged onto a 0.83 mg/cm^2 thick CD_2 secondary target foil. Four energies from 8.0 to 14.0 MeV (or 1.6 to 2.8 MeV in the c.m.) were studied using this scheme. Since the absorber foils were fairly close to the CD_2 target, they had little affect on the ^{8}Li intensity. However, background event rates, primarily from ^{8}Li scattered from the absorber foils, at the two lowest energies were fairly high. Thus, most of the measurements at those energies were duplicated during the second runs using a newly developed machine tune with a lower primary beam energy and solenoid magnet field and no absorber foil (at 10.0 MeV), or that energy and magnet setting combined with one set of absorber foils (at 8.0 MeV). The results from the two types of measurements were found to agree well. The Li and Be reaction products were detected using two ΔE-E solid state detector telescopes, with the ΔE detectors being about 8 μm thick. Four or five point angular distributions were measured at each energy. The contribution of the C nuclei in the CD_2 foil was determined by background runs with the same beam handling system, but with a C foil at the secondary target. Background from the ^{12}C(^{8}Li,^{7}Li) reaction was typically less than 25% of the total ^{7}Li counts. No background counts in the ^{9}Be region of interest were seen.

In the ΔE versus E spectra, the ^{9}Be group from the D(^{8}Li,^{9}Be) reaction was cleanly separated from contaminants from a small impurity ^{9}Be beam originating upstream in the radioactive beam facility. Although the ^{7}Li peaks from the D(^{8}Li,^{7}Li)^{3}H reaction were not completely separated from the ^{8}Li elastic peak, they were resolved well enough to sum the ^{7}Li peak and estimate the error associated with lost or extra counts. The uncertainty from this procedure is reflected in the quoted statistical errors. Note that the "^{7}Li peak" is for the ^{7}Li ground and first excited states; our system resolution was insufficient to resolve the two peaks. Generally the total statistical errors for the ^{2}H(^{8}Li,^{7}Li)^{3}H reaction fell in the range from 10% to 15% while those for the D(^{8}Li,^{9}Be)n reaction were typically much higher, ranging from 15% to 100% (in cases in which only one event existed in the region of interest). Events from the D(^{8}Li,^{9}Li)p reaction should have been distinguishable from the ^{8}Li elastic peak. However, virtually no events were seen for that reaction at any angle or energy. Thus its cross sections are much smaller than those of either of the other reactions.

The amount of incident beam for each of the $E^{\rm lab}_{^8\rm Li}=14$ MeV measurements was determined by summing the counts in the ^{8}Li-C elastic scattering peak, and using the elastic cross sections of Smith *et al.* [13] to calculate the number of incident ^{8}Li particles. In using those (forward angle) cross sections, the large divergence of the beam ($\pm 2°$) and energy spread (400–600 keV FWHM [13]) had to be taken into account; this was done with a Monte Carlo simulation of the ^{8}Li trajectories through the superconducting solenoid and transport system, onto the CD_2 target, and into the detectors. The same method was used for lower energy measurements, but the elastic scattering cross sections were calculated using the optical model parameters of Smith *et al.* [13] for the 14 MeV cross sections. While the parameters become less appropriate as the incident energy is lowered, the cross section also becomes more closely Rutherford. The Monte Carlo code calculated a standard deviation for the energy of ± 0.4 to ± 0.6 MeV depending on the beam energy and number of absorber foils used. Statistical errors in the Monte Carlo calculations were negligible compared to those of the data. At the most forward detector angle ($\theta_{\rm lab}=10°$), it was not possible to separate the elastically scattered ^{8}Li's from those which were scattered from the entrance slits to the target chamber. For those runs the beam current was calculated from the second detector, which was located at $\theta_{\rm lab}=21°$. For all other runs the determination of the total incident beam from both detectors agreed well. We also used proton scattering, together with known cross sections [14] for protons on ^{1}H and ^{2}H, to determine that the CD_2 target had less than 5% ^{1}H compared to ^{2}H.

The differential cross sections for ^{8}Li(d,t)^{7}Li and ^{8}Li(d,n)^{9}Be(g.s.) were measured from about 20° to 80° in the center of mass. Those for ^{8}Li(d,t)^{7}Li were found to be quite large, tens of mb/sr at forward angles, over the entire energy range studied. An example of such an

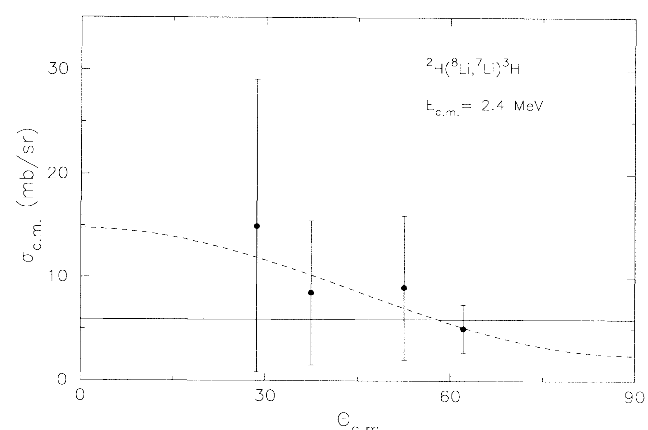

FIG. 1. Angular distributions for the ^{2}H(^{8}Li,^{7}Li) and ^{2}H(^{8}Li,^{9}Be) reactions at a c.m. energy of 2.4 MeV. The solid curve is from a fit using the P_0 term only, whereas the dashed curve is from a fit using both P_0 and P_2 terms.

angular distribution is shown in Fig. 1. More of the details on these measurements will be given in a subsequent paper [15]. Because of both the large kinematic energy shift and the energy spread over the acceptance angle of the detector, the ^{7}Li reaction peak was not resolvable from the ^{8}Li scattered beam at back angles, thus preventing measurement of the back angle differential cross sections. Although the differential cross sections appeared to resemble direct nuclear cross sections by dropping off sharply with angle, we could not tell from our data if that is the case, or if the cross sections might be symmetric about 90°. Thus we fitted the angular distributions with Legendre polynomial expansions, assuming the angular distributions to be symmetric about 90°, to determine the total cross sections. Fits were made with P_0 only, and with P_0 and P_2 terms. In most cases, the values obtained for the coefficient of P_0 in the two fits agreed very well. That difference was included (in quadrature with the statistical uncertainties) as a systematic uncertainty in the error bars shown in Fig. 2. Since we were not able to measure cross sections at back angles with the detectors used, we assumed that the back angle cross sections contributed half that for the forward angles. If either of the extreme cases of no back angle contribution or symmetry about 90° prevailed, our estimate would then be in error by no more than 33%.

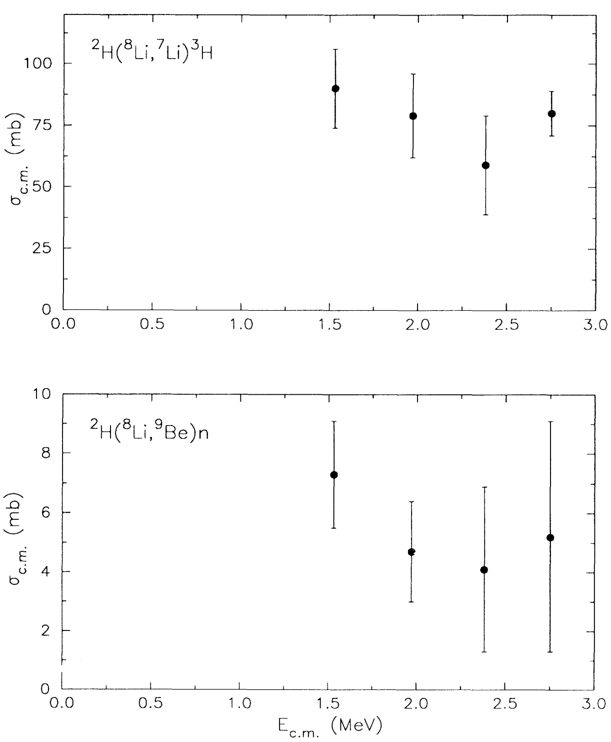

FIG. 2. Excitation functions for the ^{8}Li(d,t)^{7}Li and ^{8}Li(d,n)^{9}Be(ground state) reactions. Error bars indicate statistical and systematic uncertainties for each datum. There is also a possible systematic error of order 33% due to the symmetry or lack thereof about 90°.

The excitation functions for ^{8}Li(d,t)^{7}Li and ^{8}Li-(d,n)^{9}Be are shown in Fig. 2. The former reaction was studied previously at the highest energy [13]; the results obtained in that study are in agreement with the present result. It can be seen that the lower energy ^{8}Li(d,t)^{7}Li cross section rises, in contrast to the expected behavior at low energies, apparently due to a broad resonance. This structure can be identified with a resonance observed previously [16] at an excitation energy of around 24 MeV. The presence of this structure emphasizes the need to measure cross sections at energies below 1.6 MeV. Unfortunately, they cannot be obtained with the experimental configuration used in the present experiment.

The cross sections for ^{8}Li(d,n)^{9}Be(g.s.) are considerably smaller than those for ^{8}Li(d,t)^{7}Li. The total cross sections for the former reaction are found to agree to within a factor of about 2 with those determined from the inverse reaction [17]. Despite its small cross section, ^{8}Li(d,n)^{9}Be(g.s.) might be significant in synthesizing ^{9}Be. Recent experiments [18] to determine the importance of the ^{7}Li(t,n)^{9}Be reaction, thought [19] to be the dominant reaction path for synthesizing ^{9}Be, have shown that cross section to be smaller than originally thought. Thus ^{8}Li(d,n)^{9}Be(g.s.) may produce a significant fraction of the ^{9}Be synthesized in some regions of the IM parameter space. Note also that, although ^{8}Li(d,n)-^{9}Be(excited states) would not synthesize any ^{9}Be, it could be very important as a ^{8}Li destruction mechanism; this reaction is presently under study [20]. Because the cross section upper limit observed for ^{8}Li(d,p)^{9}Li is so small, it could not be important either for making ^{9}Be (from β decay of ^{9}Li), or for destroying ^{8}Li.

The astrophysical S factors for the ^{8}Li(d,t)^{7}Li and ^{8}Li(d,n)^{9}Be(g.s.) reactions at each energy were calculated from the measured excitation functions according to the standard prescription [21]. The best estimate of the S factor for each reaction, which was assumed to be energy independent (in the absence of sufficient data to define the possible resonance structure), was then calculated via a weighted averaging of the four measured values. This procedure resulted in a reaction rate of

$$N_A\langle\sigma v\rangle = 9.63\times 10^6 S(E_0) T_9^{2/3} \exp(-10.324 T_9^{-1/3}) \times (1.0+0.0404 T_9^{1/3})\ \mathrm{cm^3 s^{-1}},$$

where T_9 is the temperature in 10^9 K. $S(E_0)$ is the astrophysical S factor, given by $S(E_0)=1760\pm 410\pm 480$ keV b for the ^{2}H(^{8}Li,^{7}Li)t reaction, and $S(E_0)=98 \pm 47\pm 32$ keV b for the ^{2}H(^{8}Li,^{9}Be(g.s.))n reaction, where the first quoted error is the standard deviation in the S-factor excitation function from a flat line (thus implicitly including the statistical and systematic errors represented by the error bars in Fig. 2). The second quoted error represents the 33% systematic error due to the uncertainty in the back angle behavior of the cross section angular distributions.

The effect of the strong ^{8}Li(d,t)^{7}Li reaction on the predicted number abundance of ^{8}Li during primordial nucleosynthesis in the IMs, and hence on the predicted abundances of nuclides heavier than ^{11}B, can be estimated qualitatively by examining the processes which determine the ^{8}Li abundance by making it or destroying it. The creation and destruction rates due to reactions depend not only on the reaction rates but on the densities of the interacting nuclides as well. Since the densities depend critically on the IM parameters, so will the creation and destruction rates. Some indication of the importance of the $^8\mathrm{Li}(d,t)$ reaction to the ^{8}Li abundance can be obtained, however, by comparing the rate at which it destroys ^{8}Li to those for ^{8}Li β decay and $^8\mathrm{Li}(\alpha,n)^{11}\mathrm{B}$. Over some of the parameter space of the IMs, the density of ^{4}He becomes high enough [22] that the $^8\mathrm{Li}(\alpha,n)$ reaction apparently can dominate over β decay in the destruction of ^{8}Li. While the cross section [9] for $^8\mathrm{Li}(\alpha,n)$ is larger than that for $^8\mathrm{Li}(d,t)$ at energies above 1 MeV, that for the former reaction falls off more rapidly at low energy due to its larger Coulomb barrier. Since, in some regions of the IM parameter space, the ^{2}H abundance [22] can come within an order of magnitude of that for ^{4}He, the $^8\mathrm{Li}(d,t)$ reaction appears to be competitive with the $^8\mathrm{Li}(\alpha,n)$ reaction in destroying ^{8}Li in environments in which reactions dominate that destruction. Hence it may be important to include it in future considerations of the IMs.

Although the abundance predictions of the standard model and the inhomogeneous models of primordial nucleosynthesis can vary by a large amount for nuclides such as ^{7}Li, ^{9}Be, and ^{11}B, it is difficult to discriminate between the two models. The difficulties in interpretation lie to a large extent with recently discovered effects [11] in the IMs, which appear to be adding to the confusion of the predicted abundances, even while elucidating some interesting effects associated with the early Universe. Hence it is important to predict abundances of the nuclei heavier than C, as they may ultimately turn out to be much more robust to the uncertainties of the IMs. These abundances rely critically on the reactions which involve ^{8}Li. The recent ^{8}Li radioactive beam experiments have demonstrated that information about the cross sections which are important to primordial nucleosynthesis can be measured with the accuracy needed.

This work was performed with the support of the National Science Foundation under Grants No. PHY89-20606, No. PHY92-21669, No. PHY91-00688, No. PHY91-00708, and No. PHY89-11831, and by the Department of Energy through LLNL under Contract No. W-7405-ENG-48.

[1] R. V. Wagoner, W. A. Fowler, and F. Hoyle, Astrophys. J. **148**, 3 (1967).
[2] D. N. Schramm and R. V. Wagoner, Astrophys. J. **148**, 37 (1977).
[3] T. P. Walker, G. Steigman, D. N. Schramm, K. A. Olive, and H. Kang, Astrophys. J. **376**, 51 (1991).
[4] M. J. Balbes, R. N. Boyd, and G. J. Mathews, Astrophys. J. (to be published).
[5] J. H. Applegate, C. J. Hogan, and R. J. Scherrer, Astrophys. J. **329**, 592 (1988).
[6] C. Alcock, G. M. Fuller, and G. J. Mathews, Astrophys. J. **320**, 439 (1987).
[7] R. Malaney and W. A. Fowler, Astrophys. J. **333**, 14 (1988).
[8] T. Kajino and R. N. Boyd, Astrophys. J. **359**, 267 (1990).
[9] K. E. Sale, T.-F. Wang, R. N. Boyd, G. J. Mathews, D. W. Heikkinen, M. L. Roberts, M. S. Islam, and P. B. Corn, Phys. Rev. C **41**, 2418 (1990).
[10] R. N. Boyd, I. Tanihata, D. Hirata, N. Inabe, T. Kubo, T. Nakagawa, T. Suzuki, M. Yonokura, X. X. Bai, K. Kimura, S. Kubono, S. Shimoura, and H. S. Xu, Phys. Rev. Lett. **68**, 1283 (1992).
[11] C. Alcock, D. Dearborn, G. M. Fuller, G. J. Mathews, and B. S. Meyer, Phys. Rev. Lett. **64**, 2607 (1990).
[12] J. J. Kolata, A. Morsad, X. J. Kong, R. E. Warner, F. D. Becchetti, W. Z. Liu, D. A. Roberts, and J. W. Janecke, Nucl. Instrum. Methods Phys. Res., Sect. B **40/41**, 503 (1989).
[13] R. J. Smith, J. J. Kolata, K. Lamkin, A. Morsad, F. D. Becchetti, J. A. Brown, W. Z. Liu, J. W. Janecke, D. A. Roberts, and R. E. Warner, Phys. Rev. C **43**, 2346 (1991).
[14] A. S. Wilson, M. C. Taylor, J. C. Legg, and G. C. Phillips, Nucl. Phys. **A130**, 624 (1969); N. Jarmie, R. E. Brown, R. L. Hutson, and J. L. Detch, Phys. Rev. Lett. **24**, 240 (1970); D. C. Kocher and T. B. Clegg, Nucl. Phys. **A132**, 455 (1969); B. Cork and W. Hartsough, Phys. Rev. **94**, 1300 (1954).
[15] M. J. Balbes *et al.* (to be published).
[16] F. Ajzenberg-Selove, Nucl. Phys. **A490**, 1 (1988).
[17] W. Scobel, Z. Naturforsch. **24**, 289 (1969).
[18] C. R. Brune, R. W. Kavanagh, S. E. Kellogg, and T. R. Wang, Phys. Rev. C **43**, 875 (1991); S. Barhoumi, G. Bogaert, A. Coc, P. Aguer, J. Kiener, A. Lefebvre, J.-P. Thibaud, F. M. Baumann, H. Freiesleben, C. Rolfs, and P. Delbourgo-Salvador, Nucl. Phys. **A535**, 107 (1991).
[19] R. N. Boyd and T. Kajino, Astrophys. J. **336**, L55 (1989).
[20] K. Lamkin (private communication); J. J. Kolata *et al.* (private communication).
[21] C. Rolfs and W. S. Rodney, *Cauldrons in the Cosmos* (University of Chicago Press, Chicago, 1988).
[22] L. H. Kawano, W. A. Fowler, R. W. Kavanagh, and R. A. Malaney, Astrophys. J. **372**, 1 (1991).