Measurement of the ^{8}Li(α,n)^{11}B Reaction Cross Section at Energies of Astrophysical Interest

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(Received 16 September 1991)

The cross section for the ^{8}Li(α,n)^{11}B reaction, which is crucial to predictions of primordial nucleosynthesis in inhomogeneous models, has been measured using the radioactive-beam facility of the Institute for Physical and Chemical Research (RIKEN). The reaction cross section to all allowed ^{11}B states was found to be larger than that to just the ^{11}B ground state by about a factor of 5.

PACS numbers: 25.55.Hp, 95.30.Cq, 98.80.Ft

The standard (homogeneous) model (SM) [1] of primordial nucleosynthesis has been known for some time to give reasonable predictions of the abundances of the nuclides up to ^{4}He (although recent work [2] on ^{4}He has raised questions about the agreement between theory and observation), and arguably valid predictions [3] for ^{7}Li as well. However, consideration of density inhomogeneities, possibly resulting from the quark-hadron phase transition thought to have occurred 10^{-5} s after the big bang, has led to a set of alternate models, the inhomogeneous models (IMs) [4,5]. In the IMs, the abundances predicted for light nuclides are similar to those predicted by the SM, but those for ^{7}Li, ^{9}Be, ^{11}B, and heavier nuclides are considerably higher for most of the IM parameter space. Unfortunately, the abundance of ^{7}Li, which is fairly easily measured by astronomers, is difficult to interpret [6-9]. Recent studies [10,11] of ^{9}Be, however, have pushed its abundance in metal poor stars to potentially interesting levels [12]. But ^{11}B and heavier nuclides may ultimately provide important tests of primordial nucleosynthesis; indeed the relative insensitivity [13] of the predicted ^{11}B abundance to the IM parameters may make it an ideal test of those models. Furthermore, a recent observation [14] has shown ^{11}B can be detected in metal poor stars, using the Hubble Space Telescope, at levels relevant to predictions of primordial nucleosynthesis [5].

A critical reaction in predicting abundances of ^{11}B and heavier nuclides in the IMs is ^{8}Li(α,n)^{11}B, as ^{11}B is the nuclide through which most heavier nuclides must pass, and that reaction apparently regulates the dominant pathway by which ^{11}B is made [5]. Observation of this reaction, however, is complicated by the 840.3-ms half-life [15] of ^{8}Li. A recent measurement [16] of the inverse reaction ^{11}B(n,α)^{8}Li gives the ground-state-ground-state cross section for ^{8}Li(α,n)^{11}B. However, several ^{11}B excited states can be populated in ^{8}Li(α,n)^{11}B, so inference of the cross section of interest from measurement of the inverse reaction may underestimate the actual value by a large factor. Thus we have measured the cross section for ^{8}Li(α,n)^{11}B directly, using an ^{8}Li radioactive beam. We report on the results of that experiment in this Letter. Some of the present results have been presented at conferences [17,18].

A sketch of the apparatus used in this experiment is shown in Fig. 1. The ring cyclotron of the Institute for Physical and Chemical Research (RIKEN) was used to produce a beam of ^{14}N ions at an energy of 80A MeV, which was directed onto a thick Be target located at the entrance to the RIKEN projectile fragment separator (RIPS) [19]. The RIPS selected, focused, and energy degraded the ^{8}Li ions, which then passed through a solid-state detector to insure their identification (a small impurity beam of ^{11}B ions was also present). The resulting ^{8}Li beam had an intensity of about 10^3 ions s^{-1} and an energy from roughly 10 to 20 MeV. Because of the large beam energy spread a channel plate time-of-flight (TOF) system [20] was used to tag each ion and determine its energy.

Following the TOF system the ^{8}Li ions passed through a thin entrance window into the multisampling ionization chamber (MUSIC) [21], a detector which maps out trajectories of ions passing through it and determines their energy losses ΔE in 5-cm increments along their trajectories. The active volume of the MUSIC encloses a uniform (vertical) electric-field region. The ΔE measurements are made by observing the amount of charge created under each of ten cathode plates located above the active detector volume. Position in the vertical plane is determined by measuring the drift time of the ions created in the active volume to the cathode plates. Position in the horizontal plane is measured by ten resistive wires which run the length of the MUSIC. The detector gas used for the MUSIC was ^{4}He with a 3% admixture of butane (to speed up the signals) at 0.2 atm pressure; the ^{4}He thus served as both detector gas and target. Events from ^{4}He(^{8}Li,^{11}B)n were identified in principle by ob-

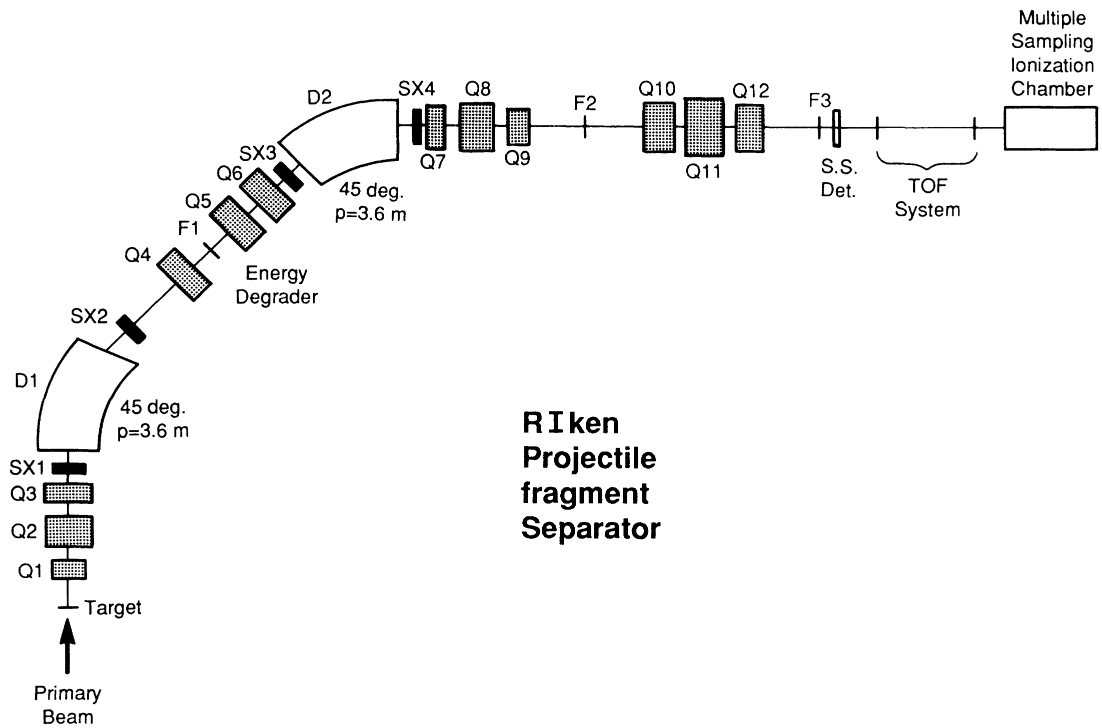

FIG. 1. Schematic drawing of the facility at RIKEN used to produce the ^{8}Li beam and study the ^{4}He(^{8}Li,^{11}B)n reaction. The various elements are denoted by the symbols Dj (dipole magnet), Fj (focus point), Qj (magnetic quadrupole), or SXj (magnetic sextupole).

serving the change in $\Delta E/\Delta x$ which accompanied their conversion from ^{8}Li to ^{11}B at the point at which a change in the trajectory was also observed. Because of event rate limitations of the MUSIC, the 10^{-3}-s^{-1} rate of incident ^{8}Li, rather low by present radioactive-beam standards, was well matched to the rate at which the MUSIC could operate.

However, ^{4}He(^{8}Li,^{11}B)n to some ^{11}B excited states, at the energies we studied, could produce ^{11}B ions with very small energy, thus making the identification of ^{11}B ions by their change in $\Delta E/\Delta x$ difficult. Thus simulations were run to see if the reaction events of interest could indeed be distinguished from other events, notably from ^{1}H(^{8}Li,$\alpha\alpha$)n and elastic scattering. The MUSIC signals were calculated over the range of energies studied for ^{4}He(^{8}Li,^{11}B)n to all ^{11}B states for the full range of scattering angles. The same was done for elastic scattering and for ^{1}H(^{8}Li,$\alpha\alpha$)n events. The ^{4}He(^{8}Li,^{11}B)n events were found to be readily distinguishable from other possible events except at low energies, below 1.5 MeV in the center of mass, where such distinctions could not be made.

Each event, consisting of ten ΔE, ten cathode-plate drift time, and ten position-wire signals, and signals from the upstream TOF system and solid-state detector, was recorded on magnetic tape; about fifty tapes, each with about 0.7×10^6 events, were ultimately obtained. Since every incident ^{8}Li ion was analyzed in the MUSIC, a way of filtering out the many trivial events from the ^{4}He(^{8}Li,^{11}B)n and other "anomalous" events was devised. The ΔE signals for ^{8}Li ions which went through, or stopped in, the MUSIC without interacting lie on a densely populated locus of points. Since events in which ^{8}Li ions elastically scatter or undergo a reaction lie off that locus, they can be identified. Thus gates could be set to select anomalous events from each tape; this procedure yielded roughly 200 such events per tape. The ΔE histogram for each such event was then compared to that for a Bragg curve for an incident ^{8}Li of that energy. The discrepancy from that curve, e.g., anomalous energy loss or apparent nonconservation of energy [for ^{8}Li(α,n)^{11}B events in which the neutron carried off most of the final-state energy] provided the identification of the event. After each of the 1500 true ^{4}He(^{8}Li,^{11}B) events was identified, the position information from the MUSIC identified the point at which the reaction event occurred to an accuracy of about 2 cm. When combined with TOF and energy-loss information [22], this determined the energy at which the event occurred, thus allowing reconstruction of the excitation function for the ^{8}Li(α,n)^{11}B reaction to all ^{11}B states.

An additional test of our ability to distinguish reaction events of interest from other anomalous events was provided by several runs made with a 20% admixture of butane in the MUSIC. At center-of-mass energies above 1.5 MeV, the results obtained for the ^{4}He(^{8}Li,^{11}B)n cross section were consistent with those having a lower butane fraction.

The excitation function determined from this experiment is presented in Fig. 2. Also indicated in that figure is the ground-state–ground-state excitation function inferred from the inverse reaction study [16]; it can be seen that the cross section to all possible ^{11}B states exceeds that to just the ground state by a fairly constant factor of about 5 for the data shown. Since we cannot distinguish reaction events of interest from other types of events at low energies, the data below 1.5 MeV from this experiment are not shown (the cross section inferred from those data rises sharply below 1.5 MeV). Those above 1.5 MeV, however, are thought to give a reliable indication of the factor by which the excited ^{11}B states enhance the ^{8}Li$(\alpha,n)^{11}$B reaction cross section from that to just the ^{11}B ground state. Note that this enhancement resulting from ^{11}B excited-state contributions is consistent with a recent study [23] of neutron decay widths of excited states in ^{12}B.

Uncertainties on the data points are of two types, and arise from several sources. The first type is for the magnitude of the observed cross sections. The energy bins were chosen to be about 800 keV in the laboratory frame, resulting in roughly 40 counts per energy bin, or about 15% statistical uncertainties. Additional uncertainty also exists from possible event confusion. When two interpretations for an event were possible, that event was included as half a ^{4}He(^{8}Li,^{11}B)n event, and the uncertainty was increased by half an event.

The second type of uncertainty is in definition of the energy at which reaction events occur. Contributors to this are (a) uncertainty in the TOF determination, (b) uncertainties in energy losses (including straggling), both through upstream foils and in the values measured in MUSIC, and (c) uncertainty in identifying the point at which a reaction event occurs. (a) The TOF system was calibrated both with an α source and with a beam of well-defined energy; the resulting uncertainty in TOF is 0.8 ns (for a 1-m flight path), producing a typical energy uncertainty at the entrance to the MUSIC of 100 keV (laboratory frame). This is negligible. (b) Uncertainties in energy losses depend on where reaction events occur in the MUSIC. Since two reaction events at the same energy can occur on two ^{8}Li ions which have lost very different amounts of energy, and straggling varies as the square root of the product of the ion's energy and its energy loss [24], the two ions can have undergone much different amounts of energy straggling. However, since the relative effect of some thickness nonuniformity in the MUSIC entrance foil will be larger for the ion which loses less energy, it will increase the lower energy ion's straggling to about the level of that of the higher energy ion. Thus we have taken the straggling [24] to be 300 keV in the laboratory frame for all ions. (c) Finally, determination of the location of the reaction event contributes roughly 400 keV to the energy uncertainty. Addition of these effects in quadrature produces a total energy uncertainty of about 170 keV in the center-of-mass frame.

Although it would be desirable to extend the present data down to the energy at which ^{8}Li(α,n) operates during primordial nucleosynthesis, somewhat below 1.0 MeV, the event ambiguity at low energies prevents this. However, the present fairly constant ratio between the total cross section to all ^{11}B states and that to just the ground state, and the fact that our data do extend somewhat into the resonance structure [15] which dominates that cross section at low energies, suggest that the rate for this reaction should be increased by our observed factor of 5 from that suggested by the inverse reaction. The ^{8}Li$(\alpha,n)^{11}$B(g.s.) astrophysical S factor [16] was parametrized by a sum of ten Gaussian terms (corresponding to peaks observed in the S factor, which were centered at energies ranging from 0.38 to 4.25 MeV), then multiplied by the enhancement factor of 5 determined in the present experiment to account for reactions to all ^{11}B states. The reaction rate was then computed from that S factor, and subsequently fitted to produce the reaction rate for ^{8}Li(α,n) to all ^{11}B states of

$$N_A\langle\sigma v\rangle = T_9^{-3/2}[5.505\times10^6\exp(-4.410/T_9)+4.596\times10^8\exp(-6.847/T_9)] + 1\times10^{13}T_9^{-2/3}\exp(-19.45/T_9^{1/3})[2.02T_9^{1/3}+17.71T_9^{2/3}+17.65T_9^{1}+3.57T_9^{4/3}]\ \mathrm{cm^3\,s^{-1}\,mole^{-1}},$$

where N_A is Avogadro's number and T_9 is the temperature in units of 10^9 K. Note that only the 0.38- and 0.59-MeV peaks in the S factor made significant contributions to the reaction rate. This provides a good parametrization from T_9 of 0.2 to 2.0.

What effect will this increase in the ^{8}Li$(\alpha,n)^{11}$B reaction rate have on predictions of the IMs? That reaction is the dominant one by which ^{11}B is made for much of the parameter space of the IMs. Since all of the nuclides heavier than 11 amu pass through ^{11}B on their way to higher masses, the heavy element abundances might thus be expected to increase with this reaction rate, provided β decay of ^{8}Li is the dominant ^{8}Li destruction mechanism. However, the present rate, together with densities typical of primordial nucleosynthesis [4–6], suggests this is the case only over part of the IM parameter space. Thus detailed IM network calculations need to be performed in order to determine the effect of the enhancement in the ^{8}Li$(\alpha,n)^{11}$B reaction rate on the abundances of ^{11}B and all heavier nuclides.

This work was supported in part by the National Science Foundation through Grant No. PHY 8920606. One of the authors (R.N.B.) thanks RIKEN for its support and hospitality during his stay there. The contributions of M. Fujimake in redesigning and modifying MUSIC, of

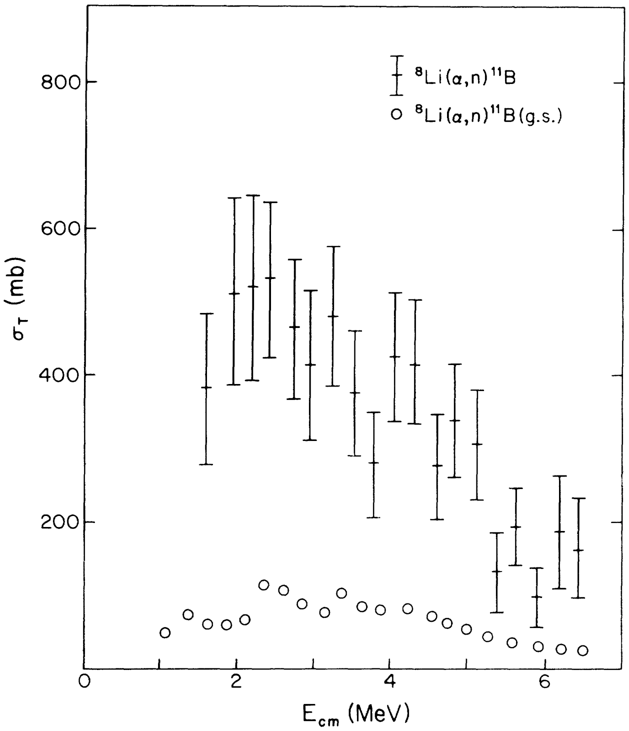

FIG. 2. Total cross section for the $^8\text{Li}(\alpha,n)^{11}\text{B}$ reaction (points with error bars) as a function of center-of-mass energy. The dots are for a representative sampling of the data for the cross section to just ^{11}B(g.s.), as inferred from the inverse reaction data of Paradellis *et al.* [16].

Y. Yano and the RIKEN accelerator staff for insuring smooth operation of the accelerator, and of C. A. Mitchell with computational assistance are noted. Finally, the interest and support of M. Oda throughout this project are gratefully acknowledged.

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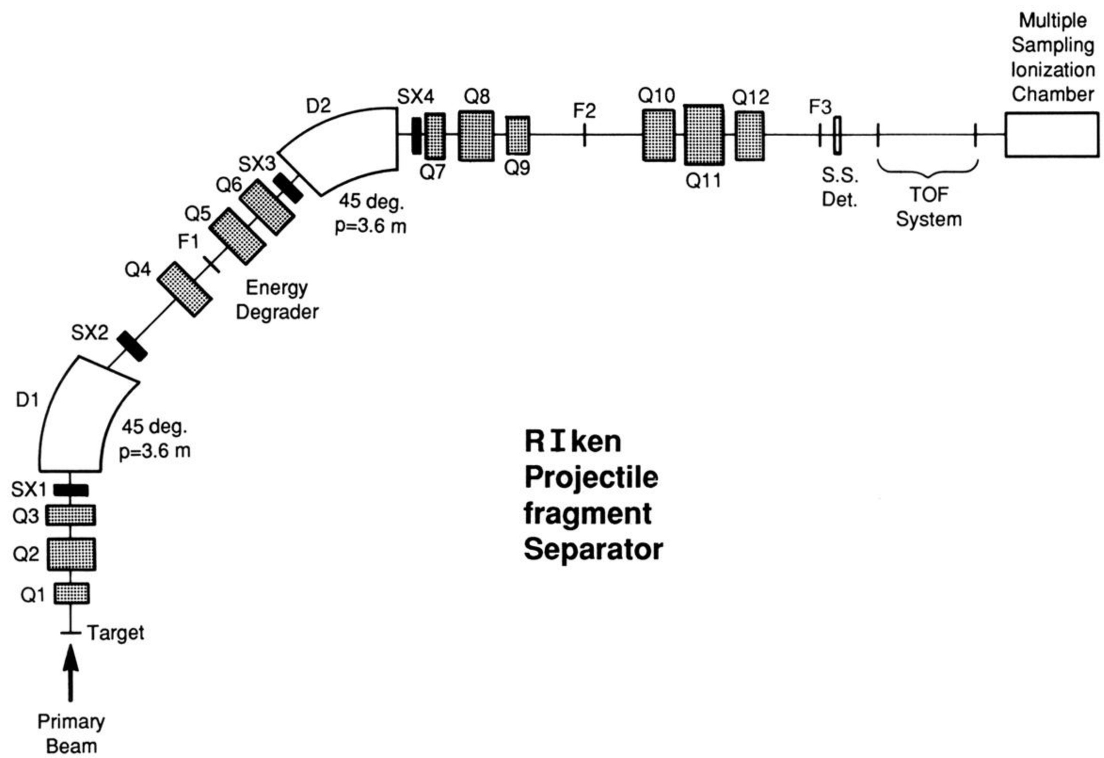

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