Nucleosynthesis of Li, Be, and B: contributions from the $p + {}^{16}O$ reaction at 50–90 MeV

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Cross sections fo the production of $A = 6$, 7, 9, 10, and 11 isobars in the reaction of 50–90 MeV protons with oxygen are reported. Product masses were identified by time-of-flight techniques using either a channel-plate fast-timing device or rf fast timing. Mass, kinetic energy, and angular distributions are reported for the products. The measured cross sections are applied to theories of LiBeB nucleosynthesis which involve galactic–cosmic-ray or stellar-flare reactions as a source of these elements. Both of the models underproduce the observed ${}^{7}Li/{}^{6}Li$ ratio by an order of magnitude, which supports previous conclusions that an additional source of ${}^{7}Li$ is required for its synthesis. However, the models give reasonable agreement for the ${}^{11}B/{}^{10}B$, ${}^{6}Li/Be$ and $B/{}^{6}Li$ ratios, although the galactic ray model predicts a ${}^{11}B/{}^{10}B$ ratio that is low by a factor of 2. In addition the $B/{}^{6}Li$ ratio is consistent only with a low value for the natural boron abundance.

[NUCLEAR REACTIONS ${}^{16}O(p,HI)$; HI Mass numbers $A = 6$, 7, 9, 10, and 11; $E = 50$, 55, 65, 75, 90 MeV; ${}^{7}Li$, ${}^{7}Be$, ${}^{10}Be$, ${}^{10}B$, and ${}^{10}C$ at 90 MeV; measured σ, $\sigma(\theta)$, and $\sigma(E)$; astrophysical implications of data are discussed.]

I. INTRODUCTION

During the past decade experimental and theoretical efforts have combined to provide a much better understanding of the processes whereby the elements Li, Be, and B (LiBeB) are synthesized in nature.[1-9] Whereas the elements carbon and beyond are accounted for in terms of stellar evolution cycles, LiBeB are thought to have their origin in nonequilibrium cosmological phenomena.[10] This requirement is imposed by the loosely-bound nature of ${}^{6}Li$, ${}^{7}Li$, ${}^{9}Be$, ${}^{10}B$, and ${}^{11}B$—which are unstable to destruction by (p,α) reactions at the temperatures encountered in stellar interiors. Among the proposed mechanisms for LiBeB synthesis, interactions between galactic cosmic rays (GCR) and interstellar matter seem highly plausible, since the known properties of both the GCR particle flux and the interstellar medium are consistent with such production.[11-13] Other suggested possibilities include production via energetic solar-flare interactions,[14-17] during supernova explosions[18] or on the surface of neutron stars.[19] In addition, the isotope ${}^{7}Li$ may be synthesized in significant quantities during the big bang[20,21] or as the result of the ${}^{4}He({}^{3}He,{}^{7}Be)$ reaction during He shell flashes.[22]

The primary nuclear reactions which give rise to the cosmic abundances of LiBeB in these phenomena involve the interactions of protons and α particles—the primary constituents of the galaxy—with carbon, nitrogen and oxygen nuclei—the next most abundant species. The $\alpha+\alpha$ reaction is also an important source of ${}^{7}Li$ and ${}^{6}Li$. Thus, in order to understand the synthesis process(es), excitation functions for the production of LiBeB in reactions of the type $p+$CNO, $\alpha+$CNO and $\alpha+\alpha$ must be measured. The energy range must extend from the threshold region to several GeV in order to test synthesis models which are sensitive to different energy distributions for the colliding species. The present status of the data is as follows: (1) below 45 MeV the $p+$CNO reactions have been well studied at Michigan State (MSU) and the University of Washington[5,7]; (2) the MSU group has measured ${}^{7}Li$ (and ${}^{7}Be$) production in the $\alpha+\alpha$ reaction below 50 MeV (Ref. 6); (3) cross sections for the $p+{}^{12}C$ reaction at 45–100 MeV and $A=7$ production from the $\alpha+\alpha$ reaction at 60–140 MeV have been determined at the University of Maryland[6,9]; and (4) the important high-energy tails of the $p+$CNO excitation functions have been obtained at the Orsay Laboratory.[8]

Incorporation of the existing data into the GCR model indicates that the absolute abundances of ${}^{6}Li$, ${}^{9}Be$, ${}^{10}B$, and ${}^{11}B$ can be reproduced reasonably well.[11-13] However, the ${}^{11}B/{}^{10}B$ ratio is low by a factor of about two in the GCR model, although it can be reproduced in other models. A more serious anomaly is that ${}^{7}Li$ is underproduced by a factor of about 10 in most models. This suggests that ${}^{7}Li$ must have another source in nature—one of the most plausible of which is the big bang.[1,6] In addition to the intrinsic problem of understanding LiBeB synthesis, this latter possibility suggests that a thorough understanding of post-big-bang production of ${}^{7}Li$ may also shed new light on the parameters of the big bang. These in turn can be used to set limits on the fundamental nature of the universe, e.g., whether it is open or closed.[23–25]

In order to gain as complete an understanding of LiBeB synthesis as possible, additional data are required. Excitation functions of particular importance are (1) $\alpha(\alpha, A=6,7)$; (2) $p(^{16}O, \text{LiBeB})$; and (3) $\alpha(\text{CNO}, \text{LiBeB})$. Sparse data exist for the $\alpha + \text{CNO}$ reactions.[8,27] However, these are of lesser importance due to the low relative abundances[26] of the projectile-target combinations and additional data from these reactions probably will have only a minor effect on the interpretation of the data. The $\alpha+\alpha$ reaction is important because of the high relative abundance of the target-projectile combination in nature.[26] This reaction is currently being measured at the University of Maryland and will be reported in a future paper. The same abundance arguments apply to the $p+{}^{16}O$ reaction, since protons are the most abundant of nature's nuclei and ^{16}O has the highest abundance of the CNO nuclei. The $p+{}^{16}O$ reaction has been measured in the threshold region,[5] but little data previously existed at higher energies. This paper discusses the measurement of these cross sections in the energy region spanning the peak of the excitation function up to the asymptotic high-energy region.

II. EXPERIMENTAL PROCEDURES

The experiments were performed at the University of Maryland Cyclotron using beams of 50-, 55-, 65-, 75-, and 90-MeV protons. Beams of 100–300 nA intensity were passed through a 30° bending magnet and focussed onto a gas target cell in a 76-cm-diameter scattering chamber. The beam profile on target was typically 1.5 mm $\times$ 3 mm and was periodically checked for stability using a remote controlled scintillator viewed by a TV camera. Because of the necessity to detect very low-energy heavy recoil nuclei in this experiment ($A=6$–16), a special gas target cell, similar to one designed by Laumer,[28] was constructed to contain the natural O_2 target gas. The principal cell window consisted 11 μm Havar foil. In order to observe the reaction products with minimum energy degradation due to the target gas and window thickness, a sleeve was inserted into one segment of the cell which provided a thin-window element. Windows consisted of laminated sheets of Formvar S with a total thickness of 20–30 $\mu g/cm^2$. Typical O_2 gas pressures were 100 torr.

The primary fragments of interest in these experiments are those particle-stable nuclei with $A=6$–7 and 9–11, which on an astrophysical time scale lead to the stable nuclei ^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, and ^{11}B. Atomic number identification is not needed since only one stable isobar exists for these mass numbers, although for cosmic-ray dating the isotope ^{10}Be is of interest and we have attempted to Z identify this nuclide in the 90 MeV experiment. Time-of-flight mass identification has been employed in these cross-section measurements. However, detection of the products is complicated by the fact that they originate largely via three-body breakup and more complicated mechanisms, which produce continuous energy spectra peaked near 1–4 MeV. For the 50–75 MeV experiments, a time-of-flight telescope was used which consisted of timing signals provided by a channel-plate fast-timing device (CPFTD) and a 75 μm ΔE detector. A 700 μm E detector was placed behind the 75 μm detector and was used for particle identification of any fragments which penetrated the ΔE detector. All energy detectors were totally depleted semiconductor devices. The timing resolution for this system was 250–300 ps, which permitted discrete A identification up to $A=16$ with a flight path of 20–25 cm. The channel-plate system is described in detail elsewhere.[29] For the 90-MeV run, the time-of-flight measurements were performed using rf timing techniques in conjunction with a

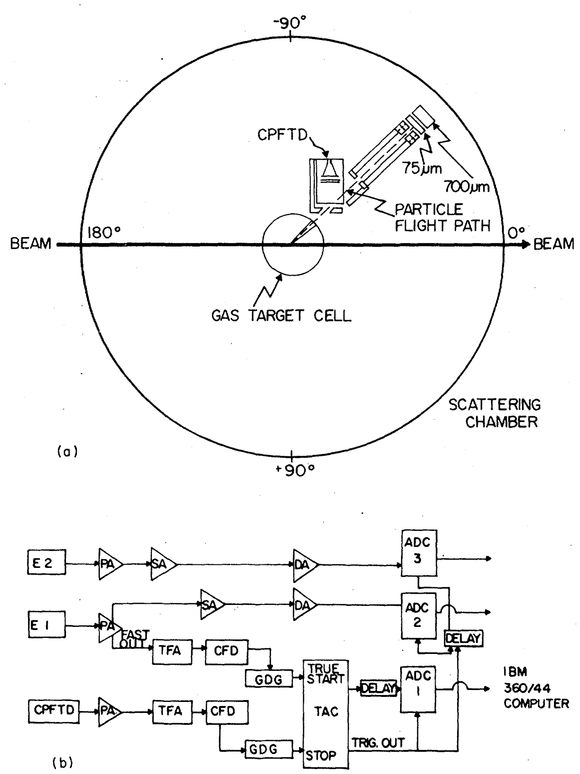

FIG. 1. (a) Scattering chamber configuration for time-of-flight studies with channel-plate fast-timing device (CPFTD) and (b) associated electronic block diagram.

15 μm ΔE and 75 μm E detector telescope, as described in a previous paper.[9]

A diagram of the scattering chamber and electronics is shown in Fig. 1. Using standard commercial electronics, fragments with energies greater than about 0.1–0.2 MeV/nucleon could be detected. Timing signals from the CPFTD were derived from secondary electrons emitted when the fragment of interest passed through a 30 μg/cm^2 carbon foil. The electrons were accelerated through a potential of 1200 V onto two microchannel plates in series, which provided a net gain of 10^5–10^6. The charge was collected on an anode cone, amplified by a fast preamplifier and amplifier. The fast signals for the time-to-amplitude converter (TAC) were then generated by a constant-fraction timing discriminator. Fast-timing signals from the ΔE detector were derived from a fast time-pickoff unit and processed with a timing-filter amplifier and constant-fraction timing discriminator. Both fast signals were then fed into a TAC (operating in the inverted timing mode) and processed on line with an IBM 360/44 computer. Standard linear electronics were used for the energy signals. Measurements at each energy were performed over an angular range of 15° to 135° in the laboratory system in angular increments of 15°. The data were then analyzed to yield mass distributions, angular distributions, energy distributions and total cross sections for the $A = 6$–11 products.

III. EXPERIMENTAL RESULTS

Mass distributions for products emitted at 30° in the 55-MeV $p + {}^{16}$O reaction are presented in Figs. 2(a)–2(c) for energy cuts of 2–4, 4–6, and 9–11 MeV. In general the mass resolution is 0.3 u or better and the errors in yield due to contamination from adjacent mass numbers is small. Figure 2(a) demonstrates the degradation of the mass spectrum at very low fragment energies, where $d^2\sigma/d\Omega dE$ reaches its maximum for all products. Integration of each mass spectrum was performed manually in order to minimize errors due to nonlinearities in the timing. The fragment Z distributions obtained at 90 MeV represented only a fraction of the yields for these isotopes due to the failure to identify those fragments which stopped in the 15 μm detector. In order to correct for the missing low-energy yield for a given Z, A fragment, we assumed the spectral shapes to be identical to those of the corresponding A as determined by the time-of-flight data at 75 MeV. For ^{7}Li and ^{7}Be this assumption should introduce little error because of the similarity of the exit channels for these two nuclei. For ^{10}Be and ^{10}B greater uncertainties exist.

In Fig. 3 energy spectra are plotted for $A = 7, 11$, and 16 isobars observed at 30° in the laboratory system for the 55-MeV $p + {}^{16}$O reaction. This figure demonstrates the sensitivity of the cross section to the low-energy part of the spectrum due to the large yield of such products. The missing cross section below the low-energy cutoff in the energy spectrum was evaluated as follows. The differential cross section in the unobserved region was assumed to be constant and identical to that at the maximum in $d^2\sigma/d\Omega dE$; one-half the cross section evaluated in this region was then added to the measured yield. An error identical to this amount was added in quadrature to the other sources of error in determining the total errors. This is the major source of the experimental errors quoted for the data, which also include counting statistics and uncertainties in target gas pressure, beam current integration, and detector and gas cell geometries. Comparison of all measured angles demonstrates that the shapes of the energy spectra change little as a function of bombarding energy. The weakly populated two-body final states observed in the 55-MeV data of Fig. 3 arise from the ^{16}O$(p, {}^7$Li$){}^{10}$C and ^{16}O$(p, {}^7$Be$){}^{10}$B reactions. These states disappear at higher bombarding energies. This feature of the data demonstrates the importance of three-body and more complicated mechanisms in the formation of the products of interest. Note in Fig. 3 that the ^{16}O(p, p') and ^{16}O(p, n) reactions are also clearly identified, indicating the value of the CPFTD for use in spallation studies of low-energy residual nuclei formed in these reactions.

The laboratory angular distributions for the products are given in Fig. 4(a) for $A = 7, 9$, and 11 isobars at 65 MeV and in Fig. 4(b) for $A = 7$ at 50, 55, 65, 75, and 90 MeV. The angular distributions do not exhibit significant structure, as would be expected of multibody breakup reactions. Table I lists the total cross sections obtained from integration of the laboratory angular distributions for the $A = 6$, 7, and 9–11 products measured in these reactions. The corresponding excitation functions, which include the low-energy data of Laumer *et al.*,[5] and higher-energy results obtained by Yiou, Raisbeck and co-workers,[8] are plotted in Fig. 5.

For $A = 10$ and 11 isobars our data join smoothly with both the low-energy results of Ref. 5 and the higher-energy points of Ref. 8. Beyond an energy of 135 MeV the $A = 10$ and 11 cross sections appear to be independent of energy, as evidenced by the agreement with the data of Lindstrom *et al.*,[29a] for 2.1 GeV/nucleon ^{16}O bombardment of ^{1}H. Comparison of the $A = 10$ and 11 excitation func-

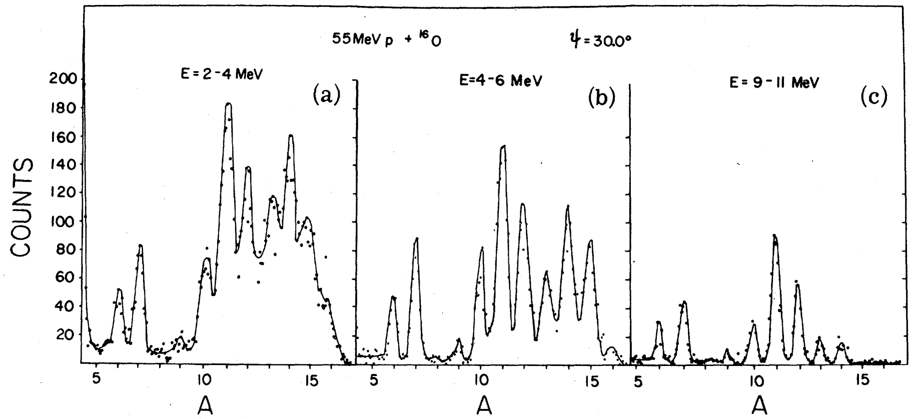

FIG. 2. Mass spectra obtained with CPFTD for 55-MeV protons incident on oxygen at 30° in the laboratory system. Energy cuts refer to (a) 2–4 MeV bin, (b) 4–6 MeV bin, and (c) 9–11 MeV bin in two-dimensional spectra Et^2 versus E.

tions with the $p + {}^{12}C$ results[9] shows an approximate similarity, with the ^{16}O yields generally slightly lower than those for ^{12}C; at high energies the yields from ^{12}C become about a factor of two larger than from ^{16}O (Ref. 29a) and both are independent of energy.

In the case of $A = 9$, our results define the threshold and peak regions of the excitation function which can be extrapolated smoothly to the measurements of Ref. 8 at 135 MeV. However, Ref. 29a reports a cross section for $A = 9$ that is a factor of three larger than Ref. 8, indicating that the ^9Be cross section increases with increasing bombarding energy or that an experimental discrepancy may exist. In support of the former argument, it is well known that for $p + {}^{12}C$ the cross section for $A = 9$ increases slowly with energy from threshold up to 28 GeV.[9] In contrast with the $p + {}^{12}C$ system, the present data show a distinct peak in the ^{16}O excitation function and its magnitude in a factor of 3–4 larger. The explanation for this behavior is not obvious.

In the $A = 6$ and 7 data there is a hint of possible structure near 40 MeV, perhaps due to the opening of other reaction channels such as $(p, p\alpha)$ followed by ^{12}C breakup; however, within the limits of error the data can also be interpreted in terms of a smoothly-rising excitation function. The high-energy portions of the $A = 6$ and 7 excitation functions appear to decrease smoothly until ~150 MeV and for $A = 6$ is constant with energy thereafter.[8,29a] However, for $A = 7$ the high-energy limit of Ref. 29a is about 50% larger than the data of Ref. 8, again suggesting a possible increase in cross section with bombarding energy. In comparison with the $p + {}^{12}C$ system, the $A = 6$ and 7 yields are about 50% higher in the peak of the excitation function, whereas at high energies these cross sections are nearly identical for both ^{12}C and ^{16}O targets.[9,29a]

The excitation functions are in moderately good agreement with the semiempirical predictions of

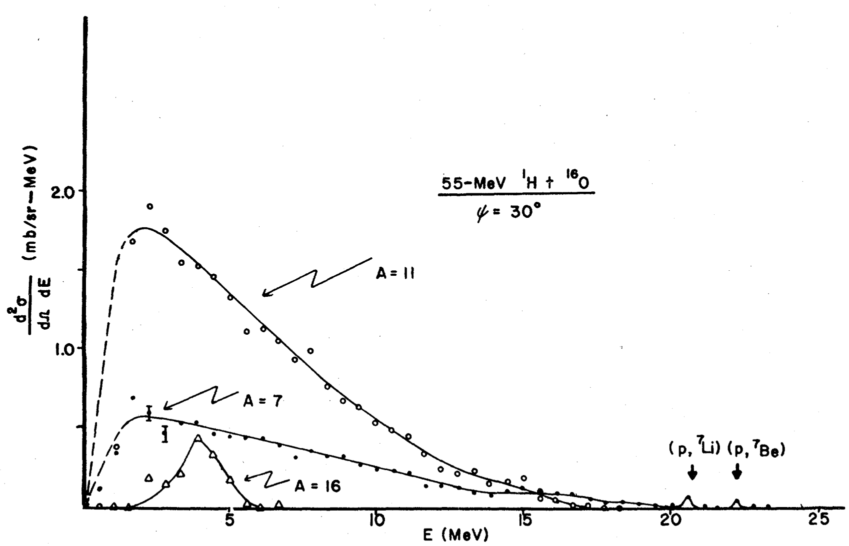

FIG. 3. Energy spectra for $A = 7$, 11, and 16 mass lines for 55-MeV proton bombardment of oxygen at 30° in the laboratory system.

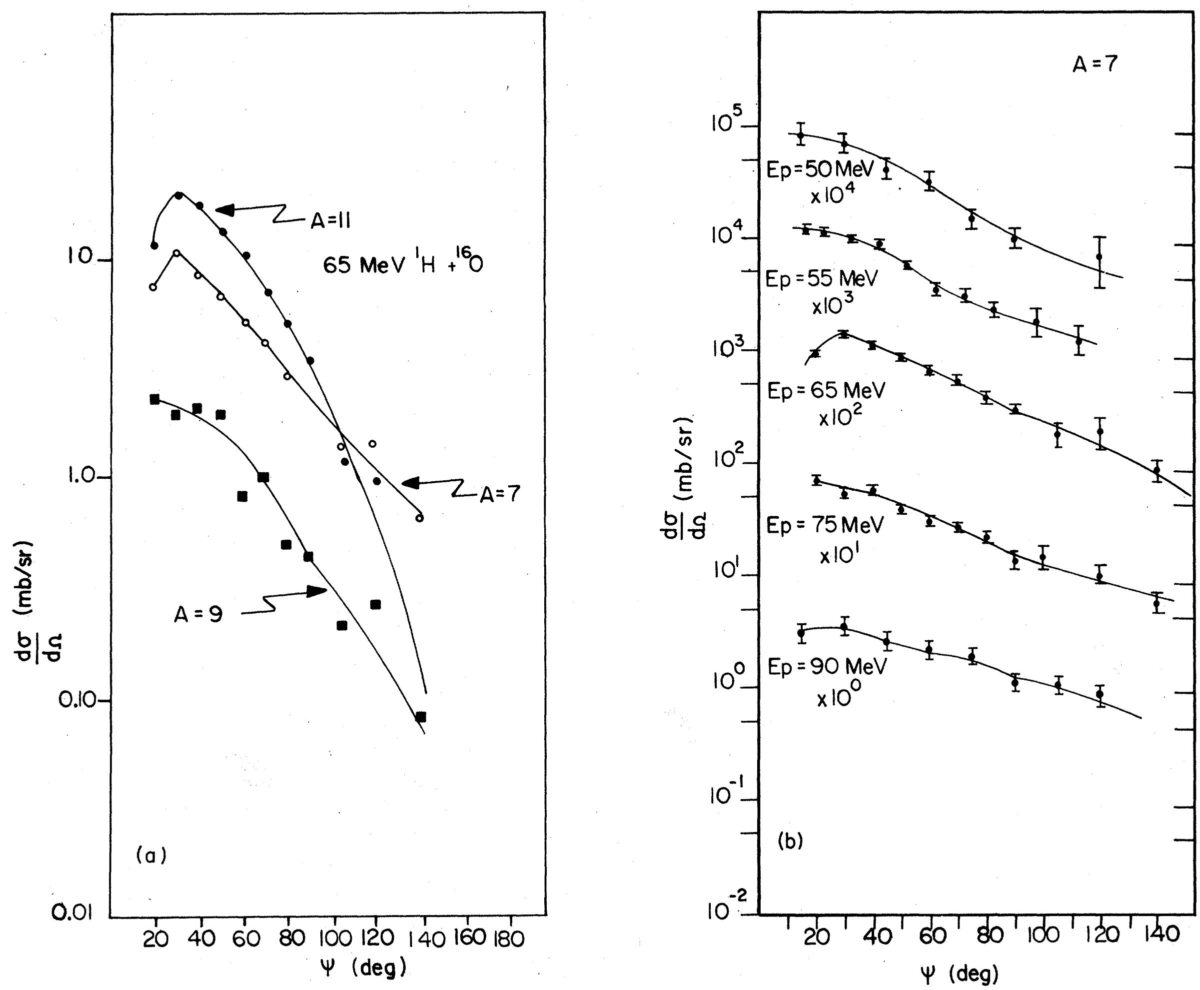

FIG. 4. Angular distributions for (a) $A=7$, 9, and 11 isobars produced in bombardment of oxygen with 65-MeV protons, and (b) $A=7$ isobars for bombarding energies of 50, 55, 65, 75, and 90 MeV.

TABLE I. Cross sections for production of LiBeB isobars from bombardments of oxygen with 50–90 MeV protons.

	Cross section (mb)				
Energy (MeV)	$A=6$	7	9	10	11
50	17.6±3.1	26.9±3.6	3.6±0.9	19.7±2.8	73.4± 8.9
55	23.0±3.1	42.7±4.8	7.9±1.3	33.8±4.5	86.9±10.6
65	28.5±3.3	54.8±6.3	10.0±1.4	34.3±4.7	72.0±10.0
75	24.0±2.9	35.0±4.2	7.2±1.2	31.8±3.8	60.4± 8.9
90	17.9±3.6	19.9±4.0	6.2±1.2	18.8±3.8	45.6± 9.1
		9.7(^{7}Li)		1.8(^{10}Be)	
		10.2(^{7}Be)		9.5(^{10}B)	
				7.4(^{10}C)	

Shapiro and Silberberg,[30] but are 2–3 times higher than the estimates of Laumer.[5] Comparison with cascade-evaporation codes is also not satisfactory. In order to understand these reactions more completely we are presently developing a two-step cascade-deexcitation code.[31] The cascade step involves a modification of earlier Monte Carlo calculations[32] to include deuteron and α particle clusters. The deexcitation step replaces evaporation with a Fermi breakup mechanism which permits multibody final states.[33] A comparison of this calculation with these data will be presented in a subsequent publication. For the remainder of this paper, we discuss the importance of these data to the question of LiBeB nucleosynthesis.

IV. IMPLICATIONS FOR LiBeB NUCLEOSYNTHESIS

A. Review of mechanisms for LiBeB synthesis

As has been mentioned in the introduction, nucleosynthesis during stellar evolution does not contribute to the observed abundances of LiBeB.[10]

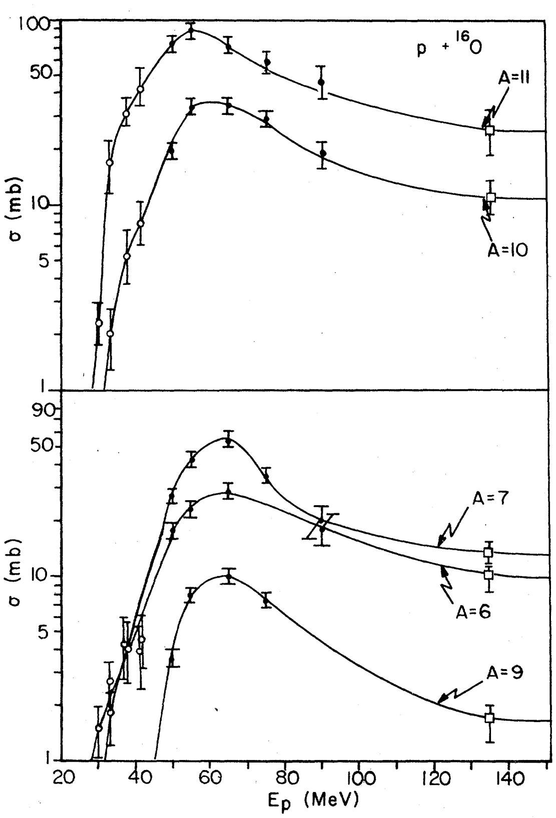

FIG. 5. Excitation functions for $A = 6$, 7, 9, 10, and 11 isobars formed in reactions of protons with oxygen. Data below 50 MeV refer to data from Michigan State University (Ref. 5), those above 90 MeV were obtained at Orsay (Ref. 8), and the 50–90 MeV data represent the present work.

Consequently, several alternative mechanisms have been hypothesized to account for the origin of these elements. The validity of these models is tested by their ability to reproduce the experimental abundance ratios,[26] listed in Table II.

The situation with respect to the experimental abundances of these elements and the various theories of nucleosynthesis has been reviewed extensively by several authors.[1–4] As far as the isotopic ratios are concerned, the $^7Li/^6Li = 12.5$ and $^{11}B/^{10}B = 4.1$ ratios appear to be universally constant. The elemental ratios, however, are less certain. While the $^6Li/Be = 4.5$ ratio appears to be relatively reliable, the $B/^6Li$ ratio is subject to much greater uncertainties and the range of quoted values[26,34] extends from about 2 to 95. Recent measurements[35,36] indicate a value of $B/^6Li \approx 14$, but the reader should be aware that considerable debate continues concerning this value. In Table II we quote the ratios for $^6Li/Be$ and $B/^6Li$ in order to eliminate the contribution of ^7Li, which is known to be anomalous in most model calculations.

The proposed models for light-element nucleosynthesis invoke either a low-density or dynamic environment in which the light nuclei, once formed, have a finite probability for survival on a cosmological time scale. The large enhancement of LiBeB in the GCR flux (LiBeB/CNO ≈ 1) suggests that this mechanism must certainly be important. This model has been investigated by several authors[5–9,11–13] and seems to do reasonably well in predicting the absolute abundances of ^6Li, ^9Be, ^{10}B, and ^{11}B. However, the $^7Li/^6Li$ ratio is low by an order of magnitude and $^{11}B/^{10}B$ is low by about a factor of two. Numerous analytical

TABLE II. LiBeB production ratios for various particle spectra described in Eqs. (1)–(3). All ratios are based on Ref. 26, except the $B/^6Li$ ratio in which the lower limit is given by Ref. 34 and the upper limit by Ref. 26.

$\phi(E)$	$^7Li/^6Li$	$^{11}B/^{10}B$	$^6Li/Be$	$B/^6Li$
Experiment	12.5	4.1	4.5	2–95
$(E+E_0)^{-2.6}$	1.3	2.0	4.3	3.6
$R^{-M(R)}$	1.4	2.2	8.0	2.1
E^{-1}	1.2	2.4	9.0	2.1
E^{-2}	2.0	3.8	15	1.8
E^{-3}	3.0	6.0	19	2.2
E^{-4}	3.8	8.4	21	3.9
$k(E+E_0)^{-2.6} + k'E^{-3}$	2.7	4.1	12	2.5

and numerical spectral shapes have been suggested for the GCR flux, the conventional form[37] of which is

$$\phi(E)=k(E_0+E)^{-2.6}\ , \tag{1}$$

where E_0 is the particle rest mass, E is the particle kinetic energy per nucleon, and $k=12.5$ from a fit to the high-energy GCR proton flux. Another form involves a power law in magnetic rigidity[38]

$$\phi(E)=kR^{-M(R)}\ , \tag{2}$$

where $R=pc/ze$ and $M(R)$ is chosen to insure that $\phi(E)$ flattens out at lower energies. This form for $\phi(E)$ enhances the effect of the α-particle and higher-Z-induced reactions. In testing the GCR model, a major problem is encountered due to uncertainties in the low-energy region of the GCR spectrum which is not known because of solar modulation.[39] Recent measurements have indicated that an intense low-energy component may be present in the GCR spectrum[40] and we investigate this possibility below to see if the LiBeB isotopic ratios can be rationalized within such a framework.

Another model, which was originally suggested to account for LiBeB formation, proposed that intense flare activity associated with the early phases of stellar condensation generates LiBeB via reactions in which protons and α particles collide with CNO nuclei already present in the stellar nebula.[14–17] In order to account for the particle spectrum associated with stellar flares, a power law in kinetic energy or kinetic energy per nucleon is usually assumed[41] where

$$\phi(E)\propto E^{-\gamma}\ . \tag{3}$$

The value of γ is typically in the range of 1.5–5; $\gamma\approx 3$ is consistent with solar-flare activity. An objection to this mechanism has been raised by Ryter[42] on the grounds that it would require too large a fraction of the star's gravitational energy. However, Canal[43] has argued that α-particle reactions may relax this constraint. This model has also been inadequate to explain the ^{7}Li/^{6}Li abundance ratio, although for $\gamma\approx 2$, the ^{11}B/^{10}B ratio can be fit and the ^{6}Li/Be and ^{6}Li/B ratios are reasonable.

It has also been suggested that supernova shock waves which accelerate particles to energies of up to 40 MeV/A may provide the source for LiBeB.[18] Bodansky[7] has shown that for a δ function particle spectrum,

$$\phi(E)\propto\delta(E)\ , \tag{4}$$

all abundances can be reproduced with an energy of ≈10–15 MeV/nucleon. However, a number of objections to this mechanism have been raised[1,44] which make it seem implausible that this can be a major mechanism for LiBeB synthesis. Another model that has recently been proposed involves the $\alpha+\alpha$ reaction on the surface of pulsars.[19] This mechanism enhances the ^{7}Li/^{6}Li ratio; however, new cross section data for the $\alpha+\alpha$ reaction may make it less attractive.[45]

In view of the underproduction of ^{7}Li in most models, additional sources of ^{7}Li must also be considered. One such possibility is cosmological synthesis in the big bang. Wagoner has shown that nucleosynthesis in the big bang can produce meaningful quantities of ^{7}Li while the yields of the other LiBeB nuclides are quite low.[20,21] Another possible galactic source of ^{7}Li involves formation via the $\alpha(^3\mathrm{He},\gamma)^7\mathrm{Be}$ reaction during helium-shell flashes in red giant stars. Rapid convective mixing is proposed to bring the ^{7}Be to the surface of such stars before it can be destroyed. Attempts to evaluate the production rates and ejection probabilities have met with difficulties.[46–48] Production of ^{7}Li in nova explosions via a similar mechanism has also been suggested recently.[49]

B. Current model predictions

In this section the GCR and flare models for LiBeB nucleosynthesis are evaluated in the light of the new cross section data presented above. Formation of LiBeB in supernova shock waves, on the surface of pulsars, in red giant He-shell flashes, or in nova explosions is not considered. Since these mechanism involve LiBeB synthesis at low energies, the present data do not materially alter previous conclusions.

In order to evaluate models for nucleosynthesis, the following rate equation is solved:

$$\frac{dN_L}{dt}=\sum_{i,j} N_i\int_{E_0}^{\infty}\sigma_{ijL}(E)\,\phi_j(E)S(E,i,j,L)dE\ . \tag{5}$$

This equation accounts for the sum of all L-element ($L=$ LiBeB) production processes from all combinations of interaction between targets, i, and projectiles j. For the purpose of these comparisons we have considered reactions between protons and α particles with carbon, nitrogen, and oxygen nuclei (including the inverse reactions), as well as the $\alpha+\alpha$ reaction. The target abundances, N_i, were taken to be representative of the interstellar medium, i.e., H/He = 10; He/C = 187 and C/N/O = 3.2/1/5.7, based upon the compilation of Cameron.[26] The experimental cross section data are given by $\sigma_{ijL}(E)$, which represents the probability of forming a given L isotope in the interaction of a given projectile j with nucleus i. The cross section data were based upon Table I and published values given in Refs. 5–9, 27, and

45 and compilations contained therein. The particle flux appropriate to each model is given by $\phi_j(E)$. The factor $S(E, i, j, L)$ is the fraction of the species L which slows down in the galactic disk to become a part of the interstellar medium. We approximate this quantity according to the procedure in Ref. 12 with an exponential,

$$S(E,i,j,L) = e^{-R(E_L)/\Lambda} ,$$

where $R(E_L)$ is the range of the species L at an energy E_L in g/cm^2 of H. Λ is the mean cosmic-ray path length (taken here to be 5 g/cm^2 H). We estimate the energy E_L as the same energy per nucleon as the compound nucleus would have in the reaction. The integration over energy is carried out from the reaction threshold energy E to 20 GeV, beyond which there is essentially no contribution to Eq. (5).

For most of the excitation functions the cross sections are constant above about 100 MeV/nucleon; hence, in those cases where high-energy data are absent, it is assumed that the high-energy cross sections are constant at the 100-MeV value. With the inclusion of the present data in the calculations, the excitation functions for most of the significant reactions are now well defined. Exceptions are the $\alpha+\alpha$ reaction—of major importance to the $A=6$ and 7 yields—and α + CNO reactions. The latter are primarily of interest for fluxes which are proportional to the projectile kinetic energy per nucleon. Recent $\alpha + {}^{12}C$ data[27] indicate that the cross-section ratios for α-induced reactions are nearly identical to those for proton-induced reactions; e.g., $\sigma(A=7)/\sigma(A=6) \approx 1.6 \pm 0.2$ in the energy region 68–800 MeV and $\sigma(A=11)/\sigma(A=10) \approx 3.0 \pm 0.2$ between 100–160 MeV. Hence, we conclude that the α + CNO reactions are not likely to alter the present ratio calculations in a significant way. In employing Eqs. (1) and (2) for the GCR particle fluxes, $\phi_j/\phi(H)$ are those given by Mitler[13]; i.e., $\phi(\mathrm{H})/\phi(\mathrm{He}) = 10$, $\phi(\mathrm{He})/\phi(\mathrm{C}) = 56$ and $\phi(\mathrm{C})/\phi(\mathrm{N})/\phi(\mathrm{O}) = 3.7/1/3.6$.

The calculated results for a selection of particle spectra are summarized in Table II. Several conclusions are immediately obvious from examination of this table. First, it is clear that neither the GCR nor the stellar-flare models can successfully describe all of the observed isotopic and elemental ratios. In fact, the new cross-section data have served to accentuate, rather than decrease, the deviations between the model calculations and the experimental abundance ratios. In particular, the ^{7}Li/^{6}Li ratio is generally low by an order of magnitude in all models. The ^{7}Li/^{6}Li values predicted by these calculations are lower than previously reported due to the inclusion of preliminary data for $A=6$ and 7 cross sections in the $\alpha+\alpha$ reaction.[45] The new results indicate enhanced ^{6}Li production from the $\alpha(\alpha,pn)$ ^{6}Li reaction compared to empirical estimates used in earlier analyses. Available data for the α + CNO systems—although fragmentary—yield ^{7}Li/^{6}Li ratios very similar to those for the p + CNO reactions.[8,27] However, it is clear from Table II that an additional source of ^{7}Li is required to account for the natural ^{7}Li/^{6}Li isotopic ratio.

Examination of the results for the GCR spectra [Eqs. (1) and (2)] in Table II demonstrate that the experimental values for the ^{11}B/^{10}B, ^{6}Li/Be, and B/^{6}Li ratios are approximately reproduced. Nonetheless, the fact that the ^{11}B/^{10}B ratio is low by about a factor of two may well be significant. All of the salient cross-section data are now included in the calculation for these isotopes and given the rather complete systematics that now exist for the p + CNO reactions and partial data for the α + CNO systems, it seems highly unlikely that further measurements of the α + CNO reactions will alter the ^{11}B/^{10}B ratio significantly. Since this measured isotopic abundance ratio can be considered as highly accurate, one is led to the conclusion that the GCR spectra underproduce ^{11}B by a factor of two. The elemental ratios are subject to much greater errors. Thus, the ^{6}Li/Be ratio can be considered to represent satisfactory agreement between experiment and model calculations; the same is true for the B/^{6}Li ratio, but only if the lower B abundance ratio is assumed.

Given our knowledge of the GCR flux, the composition of the interstellar medium, and the approximate agreement with the data, one must conclude that this mechanism is a significant one for production of ^{6}Li, ^{9}Be, ^{10}B, and ^{11}B. In Table II we list the absolute abundances (relative to Si = 10^6) for the LiBeB isotopes calculated from integration over a period of 10^{10} yr. Both the GCR flux and the composition of the interstellar medium were assumed to be constant with time in these calculations. This is probably a good first order assumption since in the early universe the GCR flux may have been more intense, but this would be offset to some extent by lower CNO abundances in the interstellar medium. This reasoning does not apply to the $\alpha+\alpha$ reaction, however, if ^{4}He is of big bang origin. It is observed in Table III that the absolute abundances agree rather well for all isotopes except ^{7}Li. Hence, we substantiate the earlier conclusions of Refs. 11–13 and conclude that the GCR mechanism must be a major one for LiBeB nucleosynthesis. The anomalous ^{11}B/^{10}B ratio and low B/^{6}Li ratio may imply that either an additional source of B or modification of the GCR particle spectrum is necessary. This latter point is discussed below.

TABLE III. Absolute abundance calculated for GCR spectrum and integrated over 10^{10} years (based on Si $=10^6$).

	^{6}Li	^{7}Li	^{9}Be	^{10}B	^{11}B
Experiment	3.7	46	0.81	1.3–69	5.4–280
$k(E+E_0)^{-2.6}$	4.9	6.5	1.2	5.9	11.9

Comparison of the results for various flare spectra in Table II indicate that (except for ^{7}Li/^{6}Li) all of the ratios can be fit satisfactorily with a power law spectrum in energy/nucleon with $\gamma \approx 2$. In this case the ^{11}B/^{10}B anomaly disappears, although again the calculations only agree for a low value of the B abundance. The calculated ^{6}Li/Be ratio is also somewhat large, but is probably within the limits of experimental error. It is noted in Table II that for rather soft spectra (large γ) a substantially enhanced ^{11}B/^{10}B ratio is obtained. This suggests that the discrepancy in this isotopic ratio for the GCR spectrum could be overcome if an intense low-energy component were present in the GCR flux.[39a,39b] For example, if the GCR spectrum contained a $\gamma \approx 3$ component which contributed an amount of LiBeB roughly equivalent to the GCR flux, the ^{11}B/^{10}B ratio would be reproduced by the calculations without seriously influencing any of the other ratios. Such a possibility is suggested by recent satellite measurements of the GCR flux.[40] In Table II we also include results for such a spectrum with a functional form

$$\phi(E) = k(E+E_0)^{-2.6} + k'E^{-3} \tag{6}$$

to illustrate this point. Values of $k=12.5$ and $k' = 2.2\times10^{-3}$ were used in the calculation.

V. CONCLUSIONS

The present measurements of the cross sections for LiBeB production in the $p+{}^{16}$O system complete the set of p + CNO excitation functions necessary for interpretation of models of LiBeB nucleosynthesis. Analysis of the galactic-cosmic-ray and stellar-flare models for synthesis of LiBeB are not substantially altered from previous conclusions presented in Refs. 11–13 by the inclusion of the new data—primarily because the excitation functions for the products of the $p+{}^{16}$O reactions are essentially the same as those for the products of the $p+{}^{12}$C and $p+{}^{14}$N reactions, except for threshold effects.

All of the model calculations underproduce ^{7}Li by an order of magnitude. The remaining ratios—^{11}B/^{10}B, ^{6}Li/Be, and B/^{6}Li—can all be approximately reproduced by either a galactic-cosmic-ray mechanism or a flare spectrum with $\gamma \approx 2$. Furthermore, the absolute abundances can be adequately described by the GCR model. Hence, the need for more elaborate mechanisms for synthesis of those nuclides does not seem imperative. Nonetheless, several problems remain. The GCR model predicts a ^{11}B/^{10}B ratio that is a factor of two low; this discrepancy appears to be significant in view of the present completeness of the data for the boron isotopes. One possible explanation is that there is a low-energy component in the GCR flux that enhances the ^{11}B/^{10}B ratio because of the differences in the threshold for these reaction products. This explanation could yield satisfactory results for ^{11}B/^{10}B and ^{6}Li/Be, but would be consistent with B/^{6}Li only for the low boron abundance.

If it should turn out that the high boron abundance quoted in Cameron[26] is correct, then a serious reevaluation of the entire LiBeB problem will be necessary. The high B abundance would imply that neither the galactic-cosmic-ray nor the flare spectra mechanisms are significant sources of ^{10}B and ^{11}B production. Since ^{7}Li is already accepted as being anomalous, this would leave a generally chaotic pattern for the understanding of LiBeB nucleosynthesis processes and would suggest a serious reevalutation of mechanisms which emphasize monoenergetic fluxes of particles with an energy corresponding to the threshold region for the salient reactions. Hence, a definitive understanding of the boron abundance problem also seems essential to a general test of LiBeB nucleosynthesis.

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