THE ASTROPHYSICAL JOURNAL, 468:199–206, 1996 September 1

LiBeB PRODUCTION BY NUCLEI AND NEUTRINOS

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Received 1995 December 6; accepted 1996 March 20

ABSTRACT

The production of LiBeB isotopes by nuclear and neutrino spallation are compared in the framework of Galactic evolutionary models. As motivated by γ-ray observations of Orion, different possible sources of low-energy C and O nuclei are considered, such as supernovae of various masses and WC stars. We confirm that the low-energy nuclei (LEN), injected in molecular clouds by stellar winds and Type II supernovae originating from the most massive progenitors, can very naturally reproduce the observed Be and B evolution in the early Galaxy (halo phase). Assuming the global importance of the LEN component, we compute upper and lower bounds to the neutrino process contribution corresponding to limiting cases of LEN particle spectra. A consistent solution is found with a spectrum of the kind proposed by Ramaty et al., e.g., flat up to $E_c = 30$ MeV nucleon^{-1} and decreasing abruptly above. This solution fulfills the challenge of explaining, at the same time, the general Be and B evolution and their solar system abundances, without overproducing ^{7}Li at very low metallicities, and the meteoritic ^{11}B/^{10}B ratio. In this case, neutrino spallation is constrained to play a limited role in the genesis of the solar system ^{11}B. Galactic cosmic rays (GCRs) become operative late in the evolution of the disk ([Fe/H] > -1), but their contribution to the solar abundances of ^{9}Be, ^{10}B, and ^{11}B is not dominant (35%, 30%, and 20% respectively). Thus, with this LEN spectrum, GCRs are *not* the main source of ^{9}Be and B in the Galaxy. The most favorable case for neutrinos (adopting the same kind of spectrum) has $E_c = 20$ MeV nucleon^{-1}. Even in this case, the neutrino yields of Woosley & Weaver must be reduced by a factor of 5 to avoid ^{11}B overproduction. Furthermore, this solution leads to a high B/Be ratio at [Fe/H] $= -2$, difficult to reconcile with the observations, unless specifically non–local thermodynamic equilibrium corrections to the boron abundance are large. On the other hand, if neutrino spallation does play an important role in the production of Galactic ^{11}B, then LEN processes are relegated to a more local phenomenon. However, in this case, unless neutrino spallation can also produce ^{9}Be (and to some extent ^{10}B and ^{6}Li), a new source of primary ^{9}Be must be found.

Subject headings: cosmic rays — galaxies: evolution — nuclear reactions, nucleosynthesis, abundances

1. INTRODUCTION

Since the 1970s, it has been known that spallation reactions between high-energy nuclei in the Galactic cosmic rays (GCRs) and the interstellar medium are an important source of Li, Be, and B (LiBeB) isotopes. However, this mechanism is known to be incomplete, as indicated by the well-established failure of GCR production to reproduce the ^{7}Li abundance in Population I stars and by the meteoritic ^{11}B/^{10}B isotopic ratio, and as shown more recently by the linear (rather than quadratic) proportionality between Be (and B) and Fe in the early Galaxy (Population II). Thus, there is a need for an additional source of LiBeB. Partly in response to this need, two new sources of LiBeB, and particularly ^{11}B, have been recently proposed:

1. The synthesis of ^{7}Li and ^{11}B by neutrino spallation in the helium and carbon shells of supernovae (Woosley et al. 1990; Olive et al. 1994; Timmes, Woosley, & Weaver 1996)—the so-called "ν-process."
2. The breakup of low-energy nuclei (LEN) injected in molecular clouds, as suggested by the γ-ray line emission detected in Orion (Bloemen et al. 1994; Cassé, Lehoucq, & Vangioni-Flam 1995; Ramaty, Kozlovsky, & Lingenfelter 1995, 1996a, 1996b; Fields et al. 1996).

With the addition of these processes, spallation now depends on three sources related to high-energy (>500 MeV nucleon^{-1}) and low-energy (<30 MeV nucleon^{-1}) nuclei and to neutrinos (<8 MeV). The effect of the ν-process on LiBeB evolution has been considered by Olive et al. (1994). These authors followed Prantzos, Cassé, & Vangioni-Flam (1993) in assuming that GCRs were more efficiently confined in the early Galaxy. By itself, such an "overconfinement" model reproduced crudely the Be and B evolutions (but not perfectly, see Tayler 1995). The most recent data confirm the linearity of both the B and ^{9}Be versus Fe correlations (Duncan et al. 1996; Rebull et al. 1996). As such, they are indeed difficult to reconcile with the overconfinement model, especially at very low metallicity, where the calculated slope is 2. Moreover, the ^{11}B/^{10}B ratio always remains unavoidably close to 2.5, the usual GCR value. To obtain a solar boron isotopic ratio of ^{11}B/^{10}B $= 4.05 \pm 0.05$ (Shima & Honda 1962; Chaussidon & Robert 1995), Olive et al. (1994) introduced neutrino spallation, which enhances ^{11}B (and not ^{10}B) and therefore can give the right boron isotopic ratio in the solar system. Since this process produces negligible amounts of ^{9}Be, one has to invoke a separate production of this isotope by nuclear spallation.

Recently, the ν-process yields have been updated (Woosley & Weaver 1996), and more importantly, the

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Bloemen et al. (1994) discovery of unexpected γ-ray emission from Orion has provided strong evidence for a LEN component. The Orion γ-radiation is consistent with line emission from $^{12}C^*$ and $^{16}O^*$ and, as such, can only be plausibly explained by a large flux of low-energy nuclei enriched in C and O. Given this observational evidence for LEN, and its ability to copiously produce LiBeB, the combined effect with neutrino spallation should be reconsidered. In this paper, we will explore constraints on the relative contribution of all three Galactic LiBeB sources: GCRs, LEN, and the ν-process. We will show that one can significantly constrain the relative contribution of the different sources by exploiting the particularities of each process and the interplay of these components in LiBeB evolution.

The paper is organized logically as follows: we first introduce the three components of LiBeB production and discuss the available free parameters for each. In particular, since the origin of the LEN is still debated, as are the corresponding LEN source abundances, we introduce various C- and O-enriched compositions related to stellar winds and supernovae of different masses. Next, the parameters for the different production mechanisms are constrained by comparing them to the available observational and solar system data on LiBeB evolution. These data consist of the history of the elemental abundances (observed as a function of metallicity [Fe/H]) and of the solar system isotopic abundances and their ratios. Specifically, the adopted solutions are bound by observational requirements: (1) to avoid Li overproduction at low metallicity (i.e., preserve the Spite plateau, e.g., Spite & Spite 1993); (2) to reproduce the quasi-linear relationship between Be/H and B/H versus [Fe/H], at least up to [Fe/H] < -1; (3) to reproduce the solar Be/H abundance; and (4) to generate a $^{11}B/^{10}B$ ratio such that, after mixing with the GCR products ($^{11}B/^{10}B = 2.5$) and the neutrino-induced ^{11}B, we get the observed meteoritic value of $^{11}B/^{10}B = 4.05 \pm 0.05$ (Chaussidon & Robert 1995).

We evaluate the possible models, showing that each process contributes in a unique way to LiBeB evolution, and that the different behaviors of the proposed mechanisms allow only a restricted set of possible combinations of them that still fit the data. In particular, we will show that, if the LEN component produces Be and B in the early Galaxy as observed in Pop II stars, then this mechanism remains the dominant source of LiBeB today, contrary to what has been previously thought. Also, as a continuation of the work of Olive et al. (1994), we determine the maximum contribution of the neutrino process to the LiBeB production in the new context in which LEN are considered.

Two important assumptions should be made explicit here. (1) We take the LEN component, observed to exist in Orion, to be ubiquitous in all star-forming regions throughout the Galaxy's history. Also, (2) we determine the LEN irradiation time such that the particle bombardment in these regions gives the LiBeB abundances observed in extreme Pop II stars. As we will argue, the required exposure times ($\lesssim 10^5$ yr) are reasonable.

A word about the chemical evolution models is in order. We adopt the same standard Galactic evolutionary model as in Olive et al. (1994) and Vangioni-Flam, Cassé, & Ramaty (1996). Our analysis is restricted to a simple closed box model, including the production of light elements by GCRs, LEN, and neutrinos and their destruction in stars, as in Olive et al. (1994). We take into account the new neutrino yields released by Woosley & Weaver (1996) and the recent work on low-energy nuclei being injected into active star-forming regions by Cassé et al. (1995), Vangioni-Flam et al. (1996) and Ramaty et al. (1995, 1996a, 1996b), analyzing in finer detail the supernovae (SNs) of different masses.

2. ROLE OF DIFFERENT COMPONENTS

2.1. *LEN*

The nuclear lines observed in Orion (Bloemen et al. 1994) must be excited via low-energy nuclear interactions; the γ-ray emission thus provides the first direct evidence of a LEN component. Since the astrophysical source of LEN is uncertain, we will try three different models (§§ 3.1–3.3). The first of these models to have been considered is the one most studied in the literature, and the one that does the best job of giving LiBeB evolution; we will thus focus on this model for the moment. In this scenario, the production rates of the LiBeB isotopes have been determined by adopting a simple source spectrum of the kind $N(E) = \text{const}$ up to $E = E_c$, and $N(E) \propto E^{-n}$ above E_c. We follow Cassé et al. (1995) and Ramaty et al. (1995, 1996a) in assuming that all nuclear species have the same source spectrum, which we propagate down to thermalization in the cloud. We assume that Orion is representative of all the active star-forming regions in the Galaxy at all times; consequently, the production rates need to be multiplied by the irradiation or exposure time τ to get the corresponding yields. The LEN mechanism is thus determined by a source composition (or, if one assumes the sources to come from a variety of supernovae, the lower limit m_{inf} of this spectrum), the exposure time τ, and the spectral parameters n and E_c. (A summary of the production mechanisms, the free parameters in each, and how these are fit is found in Tables 1 and 2.)

The LEN component is uniquely capable of naturally producing significant Be in the early Galaxy, and, moreover, it naturally gives the observed approximately linear relation between Be (as well as B) and Fe/H. We will thus *require* that LEN reproduces the early Galactic Be; having done so, the yields of Li and B will depend on the particular LEN particle spectrum chosen. Thus, the details of the LEN contribution (and thus the details of the GCR and ν-process contributions) to LiBeB analysis depend upon the spectrum assumed, and so some investigation of spectral dependence is in order.

For the present work, however, rather than examining the full parameter space of possible LEN spectra, i.e., of (n, E_c) pairs, we will instead focus on two interesting limiting cases. The first is the case emphasized in the literature so far, in which one searches for spectra that give LEN nucleosynthesis yields consistent with all the constraints discussed above. This will have the effect of minimizing the need for contributions from the other sources, in particular, from the ν-process. The LEN spectrum for this case was first sought by Cassé et al. (1995), who favored an $E_c \sim 10$ MeV. Since

TABLE 1

LiBeB Production Sites by Isotope

Source	Isotope				
	^{6}Li	^{7}Li	^{9}Be	^{10}B	^{11}B
LEN	Yes	Yes	Yes	Yes	Yes
GCR	Yes	Yes	Yes	Yes	Yes
ν-process.....	No	Yes	No	No	Yes

TABLE 2

THE INTERPLAY OF SOURCE PARAMETERS AND OBSERVABLES

Source	Parameter	Fixed by
LEN:		
Steady state	Irradiation time τ	Be/H at [Fe/H] ≤ -1
Direct ejecta	None	N/A
Reaccelerated ejecta	Lower mass limit m_{inf}	Varies
GCR	Total flux F	Solar Be/H
ν-process	Yield normalization f	Solar $^{11}B/^{10}B$

then, it has been pointed out (Ramaty et al. 1995, 1996a) that energetic considerations favor $E_c \sim 30$ MeV. We will examine this more recent model, which has an index $n = 9$.

Second, we will consider the case of the spectrum that has the *lowest* possible contribution of ^{11}B given the Be production (i.e., the lowest $^{11}B/Be$ ratio), corresponding to $E_c = 20$ MeV nucleon^{-1} (also with $n = 9$). This gives the maximal room for a ν-process contribution. Thus, this will set an upper limit to the needed ν-process yields for LEN-dominated LiBeB evolution.

For a given spectrum, the remaining parameters for the LEN component are the composition and the irradiation time τ. We will try different compositions of particular kinds of supernovae (i.e., those with Wolf-Rayet progenitors) and of ensembles of supernovae of different masses. In our analysis, we will adjust τ to fit the observed rise of Be/H at low [Fe/H]. Note that B/H in this metallicity regime is thus fixed and becomes a prediction of the model. The contribution of LEN at higher metallicity is judged by comparison with the observed solar ratios.

2.2. *Galactic Cosmic Rays*

The GCRs are treated classically (i.e., without the overconfinement used in Prantzos et al. 1993). The relative production of the different isotopes is taken from the rates given by Read & Viola (1984); their intensity is taken proportional to the supernova rate and as a free parameter. Since the ν-process does not produce Be for a given LEN production rate, the GCR component must add whatever extra Be is necessary to obtain the solar abundance. Thus, the GCR intensity is fixed to obtain the right Be/H ratio at solar birth, adding their contribution to the LEN contribution. (Fitting the intensity is equivalent to determining the present effective cosmic-ray flux F; the implications of this point are further discussed in Lemoine, Vangioni-Flam, & Cassé 1996.) Having fixed the GCR contribution to give the correct solar Be abundance, the abundances of ^{10}B and ^{11}B become predictions of the model.

2.3. *Neutrinos*

Neutrino spallation is a source of ^7Li and ^{11}B via the interactions of neutrinos (predominantly ν_μ and ν_τ) on nuclei and, particularly important here, on ^4He and ^{12}C (Woosley et al. 1990; Woosley & Weaver 1996, hereafter WW). The lithium and boron yields are quite sensitive to the temperature of the μ and τ neutrinos, in which there is a fair amount of uncertainty (e.g., Janka & Muller 1996). As a result, the overall yields of ^7Li and ^{11}B have considerable

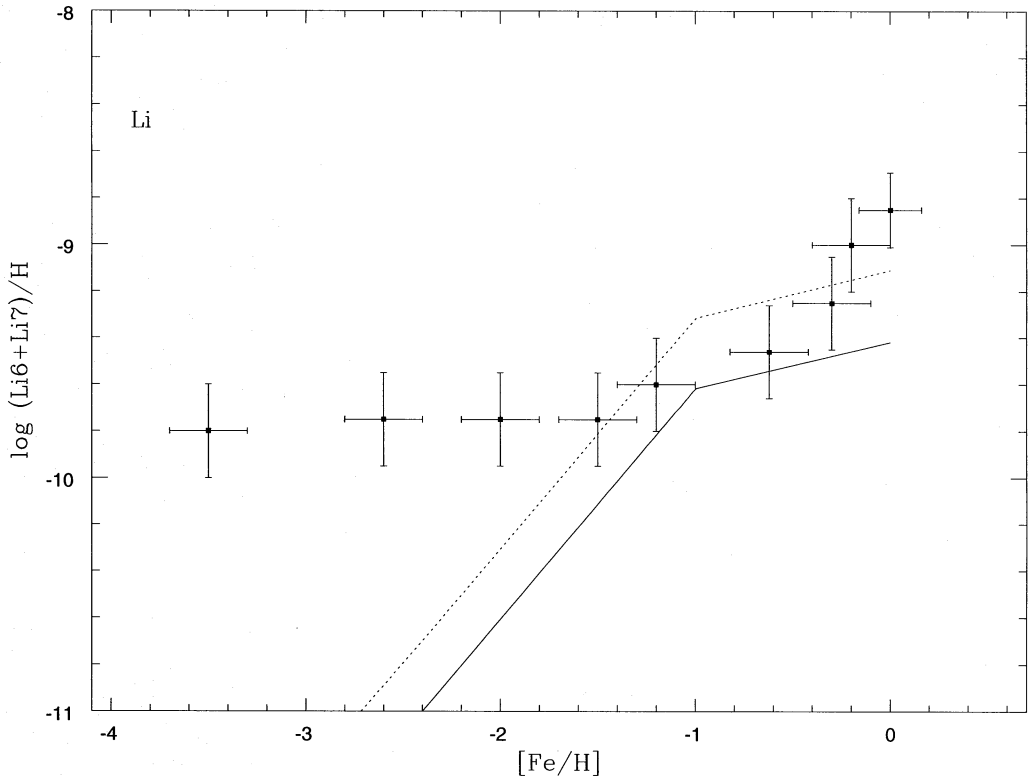

FIG. 1.—Evolution of $^7Li/H$ from neutrino spallation only. The metallicity-dependent yields from Woosley & Weaver (1996) are multiplied by factors $f = 1$ (*dotted line*) and $f = 0.5$ (*solid line*). Data points are from Spite & Spite (1993) and Rebolo, Molaro, & Beckman (1988).

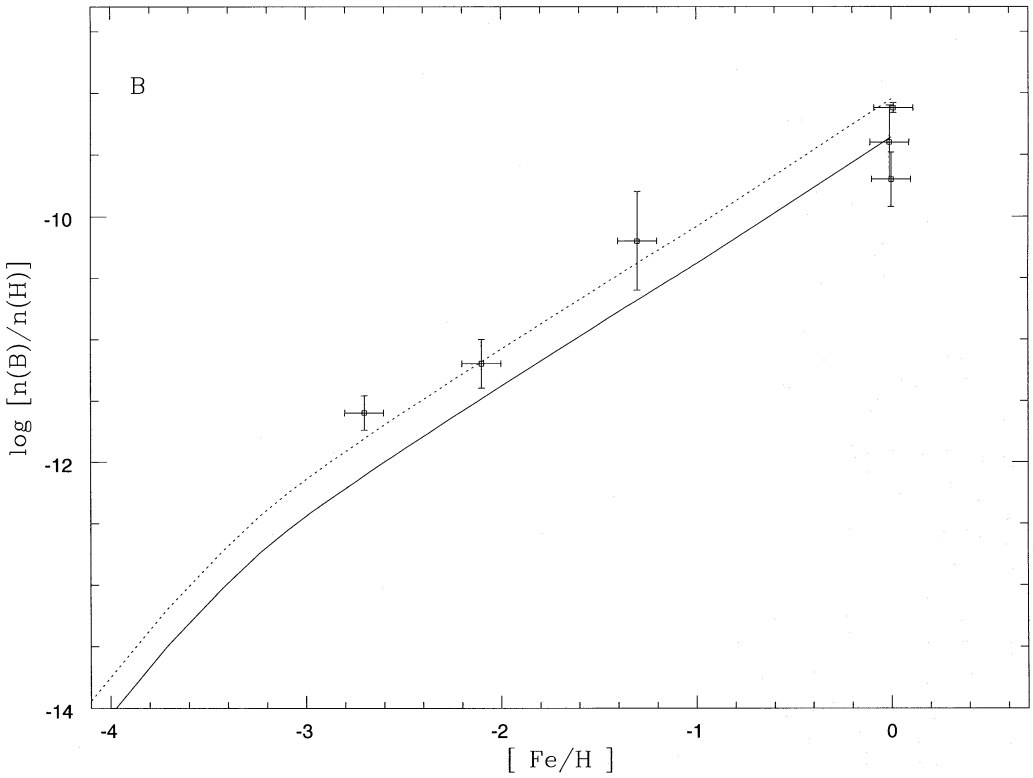

FIG. 2.—Evolution of B/H from neutrino spallation only. The metallicity-dependent yields are the same as in Fig. 1. Data points are from Duncan, Lambert, & Lemke (1992) and Kiselman & Carlsson (1994). From bottom to top, the three values at solar [Fe/H] correspond to solar photospheric (Khol et al. 1977), present Galactic average (Boesgaard & Heacox 1978), and meteoritic (Anders & Grevesse 1989).

uncertainties, and we will consider variations in the overall production level. In Olive et al. (1994), ν-process nucleosynthesis was incorporated into a model of Galactic chemical evolution, with the primary purpose of augmenting the low value for $^{11}B/^{10}B$ produced by standard GCR nucleosynthesis. To correctly fit the observed ratio of 4, it was found that the yields of Woosley et al. (1990) had to be tuned down by a factor of about 2 to avoid the overproduction of ^{11}B. Tuning down the ν-process yields ensured as well that the production of ^{7}Li was insignificant and did not affect the Spite plateau. However, the resulting ratio of B/Be was predicted not only to be high but also to be metallicity dependent, with B/Be increasing at low metallicity. The recently non-LTE–corrected (Kiselman 1994; Kiselman & Carlsson 1994) B/Be ratio at low metallicity may lend support to the enhanced production of boron at early times (Fields, Olive, & Schramm 1995).

Recently, the ν-process yields have been updated and now include a metallicity dependence (WW). We employ these new yields, but, recognizing the uncertainties in the input physics (see § 3.4.), we allow the magnitude of the yields to be a relatively free parameter, scaling them by a factor f. Figures 1 and 2 show that the full yields ($f = 1$) lead to a marginal overproduction of ^{7}Li around [Fe/H] $= -1$, while ^{11}B production by neutrinos is so efficient that no room is left for other mechanisms. This case is excluded since other processes are necessary to produce ^{9}Be that consequently introduce their own ^{11}B contribution. If we reduce the yields by a factor of 2 ($f = 0.5$) (solid lines in Figs. 1 and 2), we can allow other mechanisms to contribute to the observed ^{11}B abundance. Indeed, when the LEN processes are included to account for Population II ^{9}Be, we will see that a further reduction in the ν-process yields are necessary. Incidentally, note that, at solar metallicity, the new yields are about twice the old ones. Olive et al. (1994) divided the old yields by 2, which corresponds to a division by 4 of the new yields. In the discussion below, f is adjusted to give the right $^{11}B/^{10}B$ ratio; once the LEN and GCR contributions have been fixed to fit the Be evolution, the B evolution in these models becomes a prediction. As we will see in the next section, when all the components are taken into account, the needed reduction in ^{11}B yields will depend on the LEN spectrum adopted.

3. EVOLUTION DRIVEN BY TYPICAL LEN PROGENITORS

The calculation includes the three components sequentially: LEN to adjust the Be/H evolution, GCRs to fit the solar abundance of ^{9}Be, and possibly neutrinos to explain the meteoritic $^{11}B/^{10}B$ ratio. This procedure will be applied in turn to the different LEN sources proposed: massive stars (typically 60 $M_{\odot}$; Ramaty et al. 1995, 1996a; Vangioni-Flam et al. 1996), the external layers of Type Ic supernovae (Fields et al. 1996), and the ejecta of supernovae between 15 and 100 $M_{\odot}$, given the high velocities in the explosion and then the further reacceleration in the local medium.

3.1. *Most Massive Stars*

The WC model adopted by Ramaty et al. (1995, 1996a, 1996b) is one of the best LEN candidates. Moreover, including pre- and post-WC stages of evolution (O, Of, WN, and explosion), or considering the explosion of a massive star of 60 $M_{\odot}$ not affected by mass loss, as in the early Galaxy (Maeder 1992), we get results similar to the WC case (Vangioni-Flam et al. 1996). So the WC case will serve as a

reference for all stars of $\sim 60\ M_\odot$ on the main sequence, independent of their metallicity and related mass loss.

As stated in § 2.1., we tried two limiting spectra. For the $E_c = 30$ MeV nucleon^{-1} spectrum, the required irradiation time is $\tau = 5 \times 10^4$ yr. A modest GCR contribution (35%, 30%, and 20% for ^{9}Be, ^{10}B, and ^{11}B, respectively) is sufficient to bring the calculated ^{11}B/^{10}B ratio at solar age to its observed value of 4.05 ± 0.05, leaving virtually no room for neutrino spallation. The ^{11}B/^{10}B ratio evolves from 4.8 (the LEN value) at the beginning of Galactic evolution to 4 at solar birth (Fig. 3, *solid line*). The derived B/Be ratio, evolving from 26 and 20, also agrees with observations at all metallicities (Fig. 4, *solid line*). Accordingly, in this case, the WW ^{11}B neutrino yields are constrained to be reduced by a factor of at least 10 ($f = 0.1$) to avoid overproduction of this isotope.

The proposed solution, based on a WC composition and $E_c = 30$ MeV nucleon^{-1}, seems satisfactory since it explains, at the same time, the general ^{9}Be and B evolution, without overproducing ^{7}Li in the early Galaxy, and the ^{11}B/^{10}B ratio in the solar system. However, a more involved solution, combining GCRs, LEN, and neutrinos, cannot be a priori excluded.

To explore the strength of the constraints on the ν-process in our LEN-dominated scenario, we employed an LEN spectrum tuned to minimize ^{11}B production, and thus leave maximal room for a ν-process contribution, while still explaining the Population II ^{9}Be evolution. Indeed, the ^{11}B/^{10}B production ratio versus E_c for a WC composition (Ramaty et al. 1996b) presents a minimum of about 3 at 20 MeV nucleon^{-1} (compared with about 5 at $E_c = 30$ MeV nucleon^{-1} at zero metallicity). Higher values of E_c are excluded since they lead to line widths inconsistent with the COMPTEL data (Ramaty et al. 1995, 1996a; Tatischeff et al. 1996). While this apparently excludes an E_c as high as 100 MeV nucleon^{-1} (for which the ν-process contribution can be somewhat larger), it should be recalled that the line width data of Bloemen et al. (1994) are subject to some uncertainty.

Taking spectra with $E_c = 20$ MeV nucleon^{-1}, fitting the lower bound of the early Be evolution, and adjusting the cosmic-ray flux to get the solar value of ^{9}Be, we find an irradiation time of 5×10^4 yr (this is equivalent to minimizing the Orion contribution; see Fig. 5). In this case, with $f = 0.5$, we get a reasonable Be and B evolution; however, we also get ^{11}B/^{10}B = 7 at the solar epoch, which is far too large.

Therefore, we adopt $f = 0.2$, which gives ^{11}B/^{10}B = 4.5 (Fig. 3), which is close to the observed value. Any further reduction would lead us to the first case where neutrinos are negligible. For ^{11}B, the neutrino contribution in this case is 40%, the GCR contribution is 25%, and the Orion contribution is 35%. Concerning ^{9}Be, the respective contributions are 60% for GCRs and 40% for Orion. Finally, for ^{10}B, we get 55% for GCRs and 45% for Orion.

However, as shown in Figure 4, the neutrino addition alters maximally the B/Be ratio at [Fe/H] about -2. Below this value, the Orion component dominates since it is produced by massive (fast evolving) stars that eject their C and O very rapidly, whereas the neutrino component is delayed since it arises from all stars more massive than 11 $M_\odot$. Above [Fe/H] = -2, the B/Be ratio decreases due to the growing importance of GCRs. This bump in the B/Be versus [Fe/H] curve provides a clear test for the operation of the neutrino mechanism in conjunction with the LEN process.

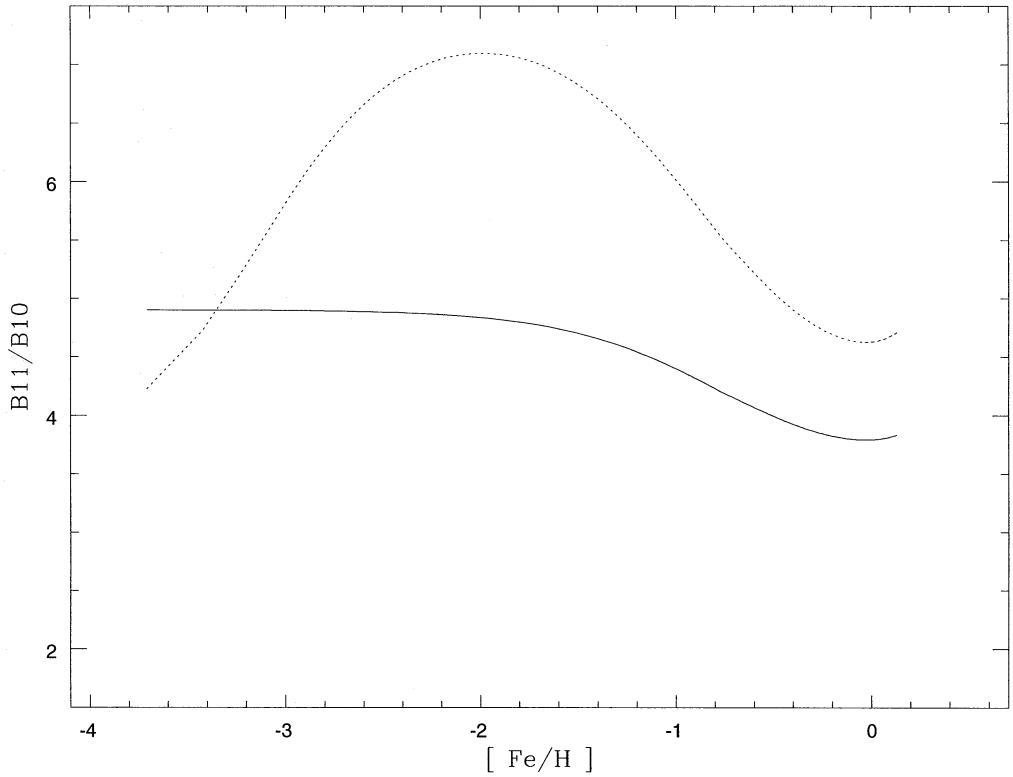

FIG. 3.—Evolution of ^{11}B/^{10}B. *Solid line*: LEN ($E_c = 30$ MeV nucleon^{-1}) + GCR; *dotted line*: LEN ($E_c = 20$ MeV nucleon^{-1}) + GCRs + neutrinos ($f = 0.2$).

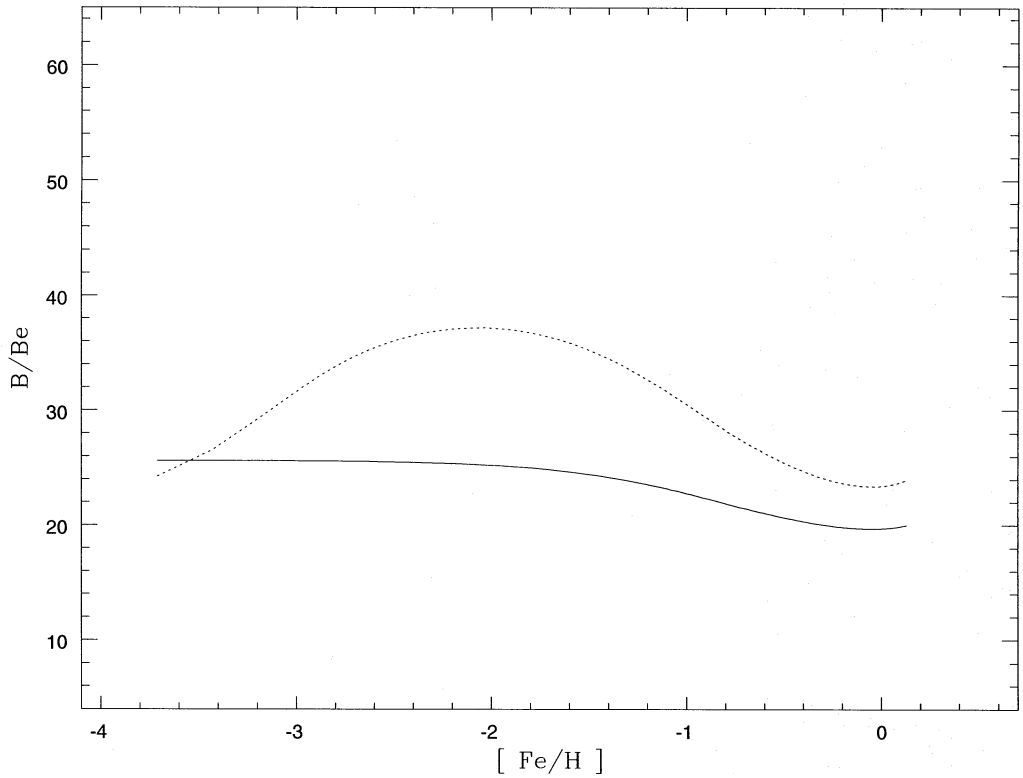

FIG. 4.—Same as Fig. 3, but for evolution of B/Be

The recent data of Duncan et al. (1996) lead to a B/Be ratio of about 10, irrespective of [Fe/H]. Non-LTE corrections could enhance this ratio at low metallicity (Kiselman 1994; Kiselman & Carlsson 1994; Thevenin et al. 1996). This correction, which is dependent on stellar parameters such as surface temperature and gravity, may be as large as a factor of 5 at [Fe/H] = −2. However, as shown in Figure 4, there is a bump in the B/Be evolution, and the non-LTE correction decreases continuously with increasing metallicity. Thus, the non-LTE correction at [Fe/H] = −2

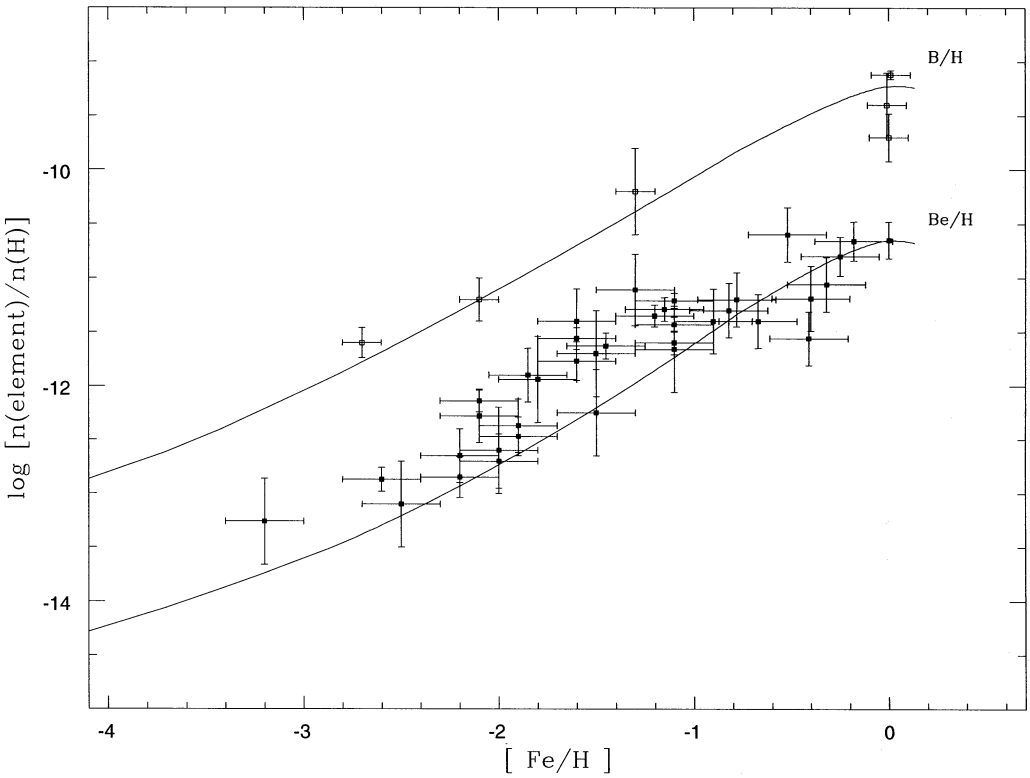

FIG. 5.—Evolution of Be and B. LEN (E_c = 20 MeV nucleon^{-1}) + GCRs + neutrinos (f = 0.2). Data points are from Ryan et al. (1990), Gilmore et al. (1992), Ryan et al. (1994), and Boesgaard & King (1993) for Be, and from Duncan et al. (1992) and Kiselman & Carlsson (1994) for B.

should not be greater than the correction at [Fe/H] = −3. This may be indicative of an intrinsic inconsistency between the neutrino and LEN processes. A measurement of $^{11}B/^{10}B$ in stars at this metallicity (which is not out of reach of the *Hubble Space Telescope*; Duncan 1995, private communication) would be of considerable interest since the predicted ratio is twice solar in this metallicity range (Fig. 3).

The WC case posits that only very massive stars contribute to the LEN component, i.e., the lower limit m_{inf} to the LEN sources is $m_{inf} = 60\ M_\odot$. Can other supernovae contribute to the LEN component? Since the source of these particles remains unclear, this question remains an open one, but we can get an important hint by noting the Li/Be ratio produced by lower mass supernovae. For $m_{inf} < 60\ M_\odot$, one has Li/Be $\gtrsim 100$; thus, an attempt to fit the Be abundance at low metallicities will lead to a conflict with the Spite plateau. The high Li/Be production ratio can be understood physically as being due to the composition of the ejecta of lower mass supernovae. Yields from these stars have large amounts of H and, more importantly, He, which is very effective, via the $\alpha + \alpha$ reaction, in producing Li. Thus, it is clear that, in order to have an acceptable Li production, such stars must be avoided, and so m_{inf} must be fairly large; in fact, we find that the lowest acceptable level is $m_{inf} \geq 35\ M_\odot$. This conclusion holds for both of the proposed spectra.

3.2. *External Layers of a Type Ic SN*

If a supernova progenitor has been subject to heavy mass loss, then its outermost ejecta are propelled to high velocity corresponding to several MeV nucleon^{-1} (Nomoto, Iwamoto, & Suzuki 1995; Woosley, Langer, & Weaver 1993). The direct impact of the fastest particles on the surrounding medium should produce a copious amount of γ-ray lines of C and O, as observed in Orion (Fields et al. 1996). This case is particularly clean since there is no free parameter in the problem. The energy spectrum, composition, and number of fast nuclei are derived directly from the calculated velocity and composition profiles of the external part of the supernova. The spectrum is close to a power law with index 4 and a maximum energy ~ 10 MeV nucleon^{-1}. Here the irradiation time τ is not a free parameter but is identified with the stopping time of the ejected nuclei, which is imposed by ionization losses in the cloud medium (i.e., a few 10^3 yr). Since the exposure time is fixed, we may not adjust it, as was done in the previous section, to ensure that the light-element yields make a significant contribution to LiBeB evolution; instead, the yields are fixed. Unfortunately, due to the shorter irradiation time compared with the WC case, the LiBeB yields that were obtained are of order $10^{-9}\ M_\odot$ (compared with typical ν-process yields of $\sim 10^{-7}\ M_\odot$) and fall short of explaining the observations.

On the other hand, this kind of process could serve as excellent injector to subsequent acceleration. In such a scenario, shock acceleration of the material ejected by SNs (as well as stellar winds) is required to get efficient production of light elements by C- and O-rich ejecta (see the following section). If further acceleration of SNs and wind material does not take place at all (which is unlikely, see, e.g., Nath & Biermann 1994; Biermann 1996; Bykov & Bloemen 1994), then fitting B in the early Galaxy demands the full contribution of neutrino production ($f = 1$). But in this case, ^{9}Be is underproduced in the early Galactic times. With the overconfinement scenario (Prantzos et al. 1993) being excluded because it leads to a slope of 2, a complementary process of primary nature is required (see, e.g., Tayler 1995), which would probably bring its own boron contribution. Consequently, once again, the neutrino contribution would have to be reduced.

3.3. *Production by Reaccelerated Supernova Ejecta*

We now consider the contribution of all supernovae (15–100 $M_\odot$; Weaver & Woosley 1993; Woosley et al. 1993) when assuming (re)acceleration in their ejecta with the same spectrum as in the case of the direct ejecta ($n = 4$), but pushing the maximum energy up to 30 MeV nucleon^{-1} instead of 10 MeV nucleon^{-1}. This choice of spectrum parameters does not contradict any observational constraint. As with the WC case (§ 3.1.), the composition and irradiation (reacceleration) time remain free parameters.

Adopting these spectral characteristics, we have varied the lower mass limit of the contributing supernovae from $m_{inf} = 15$ to $60\ M_\odot$. As expected, the lower the m_{inf}, the higher are the average yields, and the shorter τ. Further, τ varies between 500 yr ($M > 15\ M_\odot$) and 50,000 yr ($M > 60\ M_\odot$). The supernovae of lower mass ($M < 25\ M_\odot$) are so efficient that they leave no room for the ν-process or GCR contributions, which is quite unrealistic; thus, we are again driven to favor the massive stars alone as sources (M above $35\ M_\odot$). For the mass spectrum chosen in § 3.1 ($M > 60\ M_\odot$), the $^{11}B/^{10}B$ ratio is about 3 instead of 4, and a slight neutrino contribution is allowed as in the previous case ($f = 0.2$). In this specific situation, an important part of the solar system lithium, if not all of it, can be produced by LEN in the disk, due to the operation of the $\alpha + \alpha$ reaction. Indeed, more ^{6}Li and ^{7}Li are produced than in the case of the most massive stars ($M > 60\ M_\odot$), since supernovae between 35 and $60\ M_\odot$ are more helium rich than above this mass (Weaver & Woosley 1993).

3.4. *Implications for the* ν*-Process*

If the LEN contribution is a significant source of Be in the early Galaxy, then it necessarily produces copious B as well. Thus, in order to avoid B overproduction in early and solar epochs, the ν-process yields are required to be reduced from their calculated values. Is such a reduction plausible? To be sure, supernovae are known to create a huge neutrino flux, as observed in SN 1987A. However, the details of the neutrino spectrum are more model dependent. The largest uncertainties lie in the neutrino temperature (which controls the neutrino flux) and the neutrino spallation cross section. Both sources carry at least a factor of 2 uncertainty (Woosley 1995, private communication). The LEN spectrum, with $E_c = 20$ MeV and a reduction in the ν-process yields by a factor of 5, is probably at the limit of compatibility between these two mechanisms. Note that, if the ν-process yields can be verified (e.g., via ^{19}F observations [Timmes et al. 1996] or through a confirmation of the details of the model parameters used to get the Li and B yields), then there is a potential conflict with the LEN hypothesis. In this case, a new source of primary ^{9}Be would be required.

4. CONCLUSION

We have estimated the contribution of the different spallation processes (nuclei at high and low energies and neutrinos at low energy) to the production and evolution of the

LiBeB isotopes. Low-energy nuclei are required to explain the Orion γ-ray observations and must have a composition that is overabundant in C and O. Examining specific sources, we find that nuclei reflecting the composition of C- and O-rich stellar ejecta (WC stars and/or massive undressed SNs), moderately accelerated in the source vicinity by shock waves or turbulence, would play a significant role in the story of Be and B.

Depending on the spectrum chosen, there is a varying amount of room for the GCR and neutrino processes. Fortunately, different combinations of these processes give different evolution histories for the LiBeB isotopes, and so with good enough data, one may determine the actual combination. In particular, the presence of a significant ν-process component causes an enhancement of the $^{11}B/^{10}B$ ratio, leading to values approaching 8 at [Fe/H] $\simeq -2$ (Fig. 3); this is about twice the solar ratio and the expected ratio in the absence of a ν-process contribution. A less pronounced but still measurable enhancement of the B/Be ratio also occurs [Fe/H] $\simeq -2$, with the ν-process raising B/Be to about 30 (Fig. 4).

In any event, the low-energy nuclei contribution is important regardless of its spectrum. This unique process is able to explain consistently the Be and B evolution and solar system abundances (using the meteoritic B/H ratio), and the meteoritic $^{11}B/^{10}B$ ratio, with the GCRs playing a secondary role, especially at low metallicity. A more detailed work, involving updated GCR production rates and a more refined analysis of the different components, will be presented in a forthcoming paper (Lemoine et al. 1996).

While WC-type sources provide particle compositions that are good candidates for Orion and that also give good LiBeB evolution, direct ejecta seem to do only the former; their LiBeB production is negligible due to the short particle lifetime (ionization stopping time). With reaccelerated ejecta, the LEN component can again provide a key component in a good fit to LiBeB evolution, but only for source compositions like those of massive supernovae. Thus, we see that, at least for the cases we have studied, massive progenitors for LEN particles are needed to provide a good LiBeB evolution. The details of such a selection effect remain to be shown; our results provide a hint to model builders.

Since we have to reduce the neutrino yields by a factor 5 even in the best case ($E_c = 20$ MeV nucleon^{-1}), we fall short in explaining Li in Population I stars. In this case, stellar sources are required as asymptotic giant branch stars (Abia, Isern, & Canal 1993). They should be rather long living (small masses), otherwise the Spite plateau would be violated. Similarly, even if ν-process nucleosynthesis is the dominant mechanism in the production of ^{11}B, the $^{11}B/^{10}B$ ratio necessitates a reduction in the neutrino spallation yields and would also preclude the ν-process from explaining the Population I Li abundances (Olive et al. 1994).

In closing, it is worth noting that the solar B/H ratio is still uncertain, varying from 2×10^{-10} (within a factor of 2 for Pop I stars; Boesgaard & Heacox 1978) and $(7.5 \pm 0.6) \times 10^{-10}$ in carbonaceous chondrites (Anders & Grevesse 1989) to the photospheric value of 4×10^{-10} (Khol, Parkinson, & Withbroe 1977). As a by-product of this work, we remark that, in all the fits, the meteoritic B/H value is favored. The progress in this field is now linked to better abundance determination.

We are grateful to Tom Weaver, Stan Woosley, and Frank Timmes for access to the neutrino yields, and the latter two for helpful conversations. We thank Yvette Oberto and Roland Lehoucq for permanent help. This material was based on work supported by the North Atlantic Treaty Organization under a grant awarded in 1994. This work was supported in part by PICS 114, "origin and evolution of the light elements," CNRS. This work was also supported in part by DOE grant DE-FG02-94ER-40823.

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