Proceedings of ICRC 2001: 1667 © Copernicus Gesellschaft 2001

ICRC 2001

Measurements of the isotopes of lithium, beryllium, and boron from ACE/CRIS

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Abstract. The cosmic-ray isotopes of lithium, beryllium, and boron (LiBeB) are generally believed to originate from interactions within the interstellar medium, primarily through CNO spallation. Other sources are known to contribute to the abundance of ^{7}Li and ^{11}B, most notably the production of ^{7}Li from big bang nucleosynthesis. Thus, identifying the abundances of the galactic cosmic-ray LiBeB places important constraints on the interpretations of early epoch nucleosynthesis. The Cosmic Ray Isotope Spectrometer (CRIS) on ACE has been measuring isotopic composition from helium through zinc in the energy range ∼70-500 MeV/nucleon since 1997 with high statistical accuracy. We present measurements of the isotopic abundances of LiBeB from CRIS and discuss these observations in the context of previous cosmic-ray measurements and predictions from cosmic-ray transport models.

1 Introduction

Lithium, beryllium, and boron (LiBeB) are rare in nature as is indicated by solar-system abundance measurements from photospheric and meteoritic data (Anders and Grevesse 1989). Galactic cosmic-ray (GCR) LiBeB abundances, however, are found in significant excess of solar-system abundances (LiBeB/CNO ∼0.25 for GCRs compared with $\sim 10^{-6}$ for solar-system values). This excess is attributed to the spallation of CNO GCRs on the interstellar medium (ISM) (Reeves et al. 1970). Observations from meteorites as well as from the local interstellar medium (ISM) of ^{7}Li/^{6}Li and ^{11}B/^{10}B are not consistent with spallation production, suggesting the need for other sources of the lithium and boron isotopes, such as stellar nucleosynthesis (Reeves et al. 1994) and neutrino spallation (Woosley and Weaver 1995), in addition to the expected contributions to ^{7}Li from primordial nucleosynthesis (Schramm 1993).

The Cosmic Ray Isotope Spectrometer (CRIS) on ACE has been measuring the isotopic composition of $2 \lesssim Z \lesssim 30$ in the energy range ∼30-500 MeV/nucleon since 1997, including the abundances of LiBeB between ∼30-200 MeV/nucleon. The LiBeB nuclei observed by CRIS are produced predominantly as spallation products from the interaction of CNO GCRs with the ISM, resulting in energies between 200-500 MeV/nucleon. The GCR LiBeB is a result of the competing processes of production from spallation and escape from the Galaxy. Indeed, most of the LiBeB nuclei at energies covered by CRIS escape from the Galaxy. Fortunately, the escape rate is essentially the same for all LiBeB species of equal energy per nucleon (Garcia-Munoz et al. 1987), permitting a direct measure of the relative production rates by measuring the relative abundances such as ^{6}Li/^{7}Li, ^{7}Be/^{9}Be, ^{11}B/^{10}B.

Another source of LiBeB via spallation complicates the issue. LiBeB nuclei may also be produced from GCR protons and helium nuclei interacting with the ISM. Typical energies for these cosmic rays are ∼1 GeV/nucleon. In order to draw conclusions concerning the abundance of LiBeB nuclei in the ISM from CRIS observations, the cross-sections for generating LiBeB nuclei from several GeV proton and helium nuclei need to be similar to the cross-sections governing the spallation of ISM from CNO at energies covered by CRIS. A recent survey of the available cross-section data by Yanasak et al. (these proceedings), suggests that the differences between the cross-sections for producing LiBeB nuclei between 200-500 MeV/nucleon and 500-2000 MeV/nucleon are less than 20 %. Predictions of the ^{6}Li/^{7}Li ratio is further complicated since the cross-section for $\alpha + \alpha$ fusion to A=6,7 increases by more than 2 orders of magnitude between 10 and 100 MeV/nucleon, implying that a large fraction of ISM lithium may be produced at very low energies.

The history of LiBeB nuclei over the last 10 Gyr is being uncovered through observations of low-metallicity halo stars (Ryan et al. 1994; Duncan et al. 1997). The elemental ratios of Be/H or B/H and Fe/H (where Fe/H indicates the metallicity of the star) are observed to follow an

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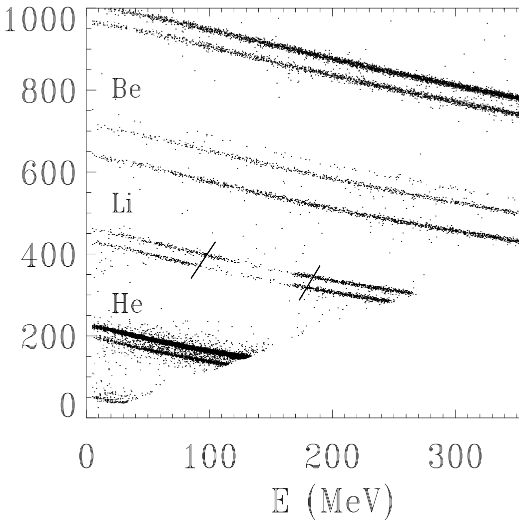

Fig. 1. Energy loss (ΔE) versus the energy (E) deposited in a detector element midway through the stack for He, Li, Be, and B events. ΔE and E have been corrected for incidence angle. The solid lines indicate the region exempted from the analysis to exclude events within the low duty-cycle helium event buffer.

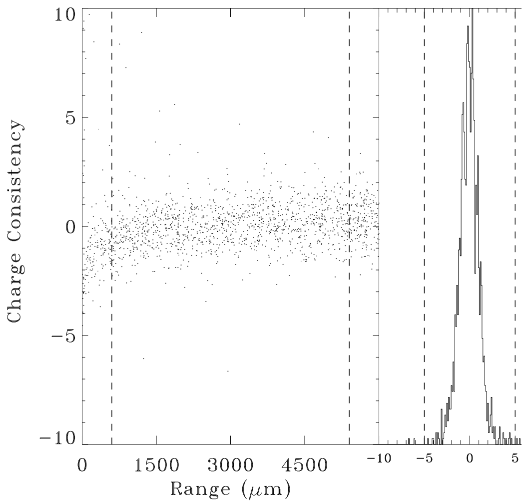

Fig. 2. The charge consistency parameter versus range for boron events. The area outside of the dashed lines excludes data near the detector faces. The figure to the right is the charge consistency parameter histogrammed. Here the dashed lines refer a 5-sigma charge consistency cut applied to ensure a clean sample of data.

approximately linear correlation which is unexpected if the dominant source of LiBeB nuclei is GCR spallation. This follows from the simple argument that both GCRs and the ISM experience an increase in metallicity with time due to the contributions of evolving stars, resulting in a quadratic dependence of Be/H or B/H on Fe/H. A linear correlation, on the other hand, suggests a primary origin of LiBeB nuclei not coupled to the ISM metallicity, such as the fragmentation products of freshly synthesized supernova ejecta. Scenarios have been postulated to explain the observed correlation, including the origin of LiBeB species from within superbubble regions (Bykov 1999; Parizot et al. 1997; Higdon et al. 1999), and models in which Be and B nuclei originate from GCRs accelerated as debris from grains formed in SN II ejecta (Ramaty et al. 1997; Vangioni-Flam et al. 1996). The recent observations of cosmic-ray ^{59}Co and ^{59}Ni from ACE/CRIS (Wiedenbeck et al. 2000) suggesting a delay of greater than 10^5 yrs between nucleosynthesis and cosmic-ray acceleration places further constraints on these theories and appears to favor cosmic-ray acceleration from within the ISM or within superbubble regions, rather than from freshly synthesized supernova ejecta.

Observations of GCR LiBeB, over a wide range in energy, help to constrain cosmic-ray propagation as well as elucidate the dominant sources of LiBeB over time. In this paper, we present the isotopic ratios of GCR LiBeB nuclei measured from CRIS between December 1997 and April 2000 and compare these observations with previously published results.

2 Data Analysis

CRIS identifies the charge and mass of incident particles using dE/dx and the residual energy technique (Stone et al. 1998). The mass resolution is refined with the measurement of particle trajectory via a scintillating optical fiber hodoscope (SOFT) (Stone et al. 1998). In the present study, CRIS observations of LiBeB are separated into two separate time intervals, corresponding to differing levels of solar modulation. The first time period ranges from December 20, 1997 to January 23, 1999 and the second period ranges from January 24, 1999 to April 18, 2000. Both intervals exclude periods of intense solar activity. The amount of solar modulation experienced during these two time intervals is determined using a spherically symmetric model described by Fisk (1971). The solar modulation parameter, ϕ, is chosen by matching the predictions of a propagation model to the elemental spectra from CRIS at low energies and from HEAO-3 at high energies (Davis et al. 2000). The first and second intervals correspond to $\phi \sim 400$ MV and $\phi \sim 590$ MV, respectively.

Figure 1 shows an example of the energy loss versus the energy deposited in two detectors midway through the CRIS stack for helium through oxygen events. As can be seen from Figure 1, the isotopes exhibit excellent mass resolution. In Figure 1, lithium events between the solid lines have been classified into one of the many event buffers established to regulate particle rates (Stone et al. 1998). In particular, these lithium events have been classified into a helium event buffer which is sampled at a lower rate, resulting in a reduced duty-cycle and a lower density region in the track. For the present analysis, events located within the solid lines are excluded.

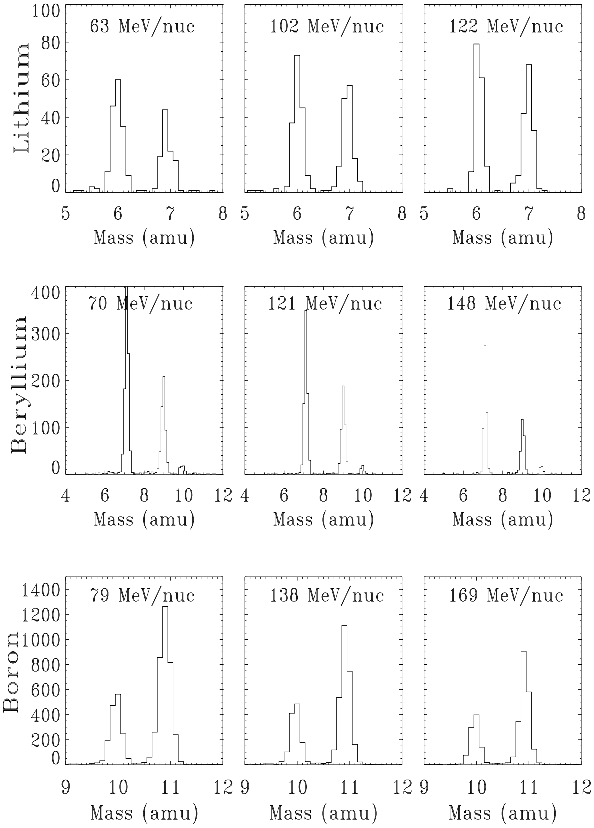

Fig. 3. Mass histograms for the isotopes of LiBeB in three of the six energy ranges covered in this study. Labels refer to the median energy for each energy bin.

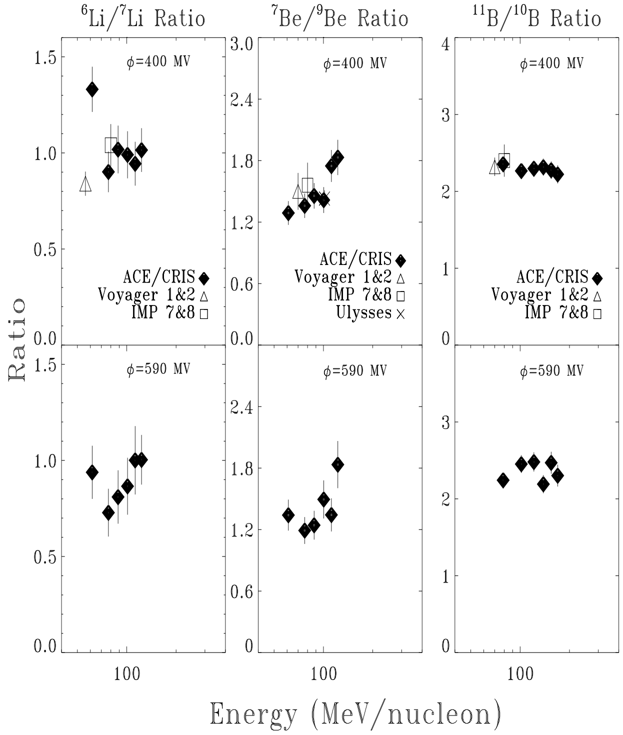

Fig. 4. The ratios of ^{6}Li/^{7}Li, ^{7}Be/^{9}Be, and ^{11}B/^{10}B obtained from CRIS during both time intervals compared with previous measurements. The observations of Voyager 1 & 2 and IMP 7 & 8 were obtained during comparable periods of solar modulation to that experienced by CRIS during the first time period.

Valid events are required to trigger all three SOFT hodoscope planes. Furthermore, events that stop near the faces of the detector elements are rejected from the analysis. Additional background events are removed by demanding consistency between the measures of charge and mass from various combinations of the stack detector pulse heights (Stone et al. 1998). Figure 2 shows the charge consistency parameter plotted against particle range (i.e. distance traversed before stopping in the detector stack) for boron events stopping midway through the stack. The charge consistency parameter is a measure of the correspondence between the charge determined using the first detector in the stack as ΔE and the charge determined using the sum of the first detector through the detectors preceeding the detector in which the particle stops, as ΔE. A similar consistency parameter can be formed using the last detector penetrated as ΔE. The actual parameter is formed by taking the ratio of the charge determined from two separate methods as described above, subtracting from the ratio the mean of this distribution and dividing the difference by the sigma of the distribution. Figure 2 also shows the histogram of the charge consistency parameter and a gaussian fit to this distribution results in a σ of $\sim$1. For this study, we chose to accept events within 5σ of the peak (delineated in Figure 2 by dashed lines) in both charge consistency parameters (using the first and last detector as ΔE in the charge determination).

The resulting mass histograms for LiBeB events in the first time period are shown in Figure 3 for three of the six energy bins analyzed in this study, ranging from $\sim$30 MeV/nucleon to $\sim$200 MeV/nucleon. The isotopes of LiBeB are clearly separated and the number of events for each isotope is simply determined by adding the number of events under each peak. The present analysis is limited to events with an opening angle from the detector zenith of less than 25 degrees. Corrections are applied to account for the probability of a particle surviving fragmentation within the instrument and for the charge dependent tracking efficiency with the SOFT hodoscope. The spallation correction accounts for the number of interaction lengths penetrated and is based on the cross-section formula of Westfall et al. (1979).

3 Results and Discussion

Figure 4 shows the isotopic ratios of ^{6}Li/^{7}Li, ^{7}Be/^{9}Be, and ^{11}B/^{10}B for both time periods along with previous measurements of these ratios from Voyager 1 & 2 (Lukasiak et al.

1999), IMP 7 & 8 (Garcia-Munoz et al. 1981), and Ulysses (Connell 1998). Observations from Voyager 1 & 2 were made over 19 years at an average solar modulation level of $\phi \sim$ 450 MV and IMP 7 & 8 observations were made at a solar modulation level of $\phi \sim$ 430 MV. These measurements were obtained during periods of comparable solar modulation to that experienced by CRIS during the first time interval. CRIS observations of ^{6}Li/^{7}Li, ^{7}Be/^{9}Be, and ^{11}B/^{10}B are in agreement with both Voyager, IMP and Ulysses, to within the statistical accuracy of the measurements. Though the solar modulation is different between the two time periods covered by CRIS, the observations are in agreement between both time intervals suggesting that solar modulation does not significantly effect the original ISM abundances. The large aperture of CRIS permits a unique measurement of the LiBeB isotopes, with sufficient numbers to measure the isotopic ratios as a function of energy, providing further constraints on cosmic-ray propagation models.

As cross sections show less than 20% variation between 200-2000 MeV/nucleon, we can consider the CRIS data to be a fair representation of LiBeB created not only by CNO GCRs colliding with the ISM, but created from all GCR-ISM interactions. GCR abundances represent a relatively young ($\sim 1.5 \times 10^7$ years; Yanasak et al. 1999) population, especially in comparison with presolar isotopic abundances, such as those found in meteoritic data. We can follow the different stages of LiBeB evolution by comparing measurements of the LiBeB isotopes from a variety of sources depicting distinct periods of LiBeB formation. The GCR ratio of ^{7}Li/^{6}Li is well below the solar-system value of ∼12 determined from meteorites (Anders and Grevesse 1989) and the ISM value of 12.5 ±4.0 (Lemoine et al. 1993). The ^{11}B/^{10}B ratio is also well below the ratios determined from meteorites (4.05 ±0.2) (Chaussidon et al. 1995) and from present abundance measurements of the ISM (3.4 ± 0.7) (Lambert et al. 1998). The ISM measurements of Lemoine et al. (1993) should reflect the contribution from stars, and, indeed, are found to be consistent with measurements of Population I stars (see compilation from (Lemoine et al. 1998) and (Hobbs 2000)). The discrepancy between the GCR ^{7}Li/^{6}Li and the ^{11}B/^{10}B ratios and the solar-system values is attributed to an excess of ^{7}Li and ^{11}B, postulated to originate in part from neutrino spallation in core collapse supernovae (Vangioni-Flam et al. 1996). Furthermore, observations of very old stars (low metallicity), indicate an additional source of the isotope ^{7}Li from primordial nucleosynthesis (∼1/10 solar) (Spite and Spite 1993).

4 Summary

The isotopic ratios of LiBeB are in agreement with previous measurements of GCRs. The observed ratios during both time periods are also in agreement suggesting that the effects of solar modulation are not significant, though this will be tested further with future observations from CRIS and the Solar Isotope Experiment (SIS) on-board ACE during periods of extreme solar modulation. CRIS observations over an extended energy range will provide additional constraints on propagation models as will be discussed in a companion paper in these proceedings (Yanasak et al. 2001). Futhermore, we plan to determine the absolute energy spectra of LiBeB GCRs upon completion of a thorough study of the SOFT detection efficiencies of the light elements. The absolute energy spectra will further constrain current propagation models and delineate possible sources of LiBeB nuclei.

Acknowledgements. This work was supported by NASA at NASA Goddard Space Flight Center, the Jet Propulsion Laboratory, Washington University and the California Institute of Technology (under grant NAG5-6912).

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