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Voyager Measurements of the Charge and Isotopic Composition of Cosmic Ray Li, Be and B Nuclei and Implications for Their Production in the Galaxy

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Abstract

Determining the isotopic composition of Li, Be and B in cosmic rays is important for understanding the propagation of these particles in the Galaxy. In this paper we report analysis of 21 years of Voyager 1 and 2 data. A total ~600 Be nuclei are measured along with corresponding numbers of Li and B. Our results are compared with propagation calculations using the latest cross sections. The agreement is excellent including even the $^{7}Be/^{9}Be$ ratio which has not been well predicted using earlier cross sections. The abundance of the isotopes ^{6}Li, ^{7}Li, ^{7}Be and ^{10}B is important for studies of early epoch nucleosynthesis in our Galaxy and the ^{7}Li abundance has cosmological implications. We present a calculation of the production of these isotopes in the Galaxy from the cosmic ray data using a Monte Carlo diffusion propagation model.

1. Introduction

The isotopes of Li, Be and B are pure spallation products of primary cosmic rays, mainly C, N and O, when they interact with interstellar matter during their propagation in the Galaxy. The determination of the various isotopic ratios to ^{12}C, for example, is important to constrain propagation models of galactic cosmic rays. The Voyager 1 and 2 data on these isotopes provides these ratios at a low level of solar modulation which allows them to be used with the latest cross section measurements to better determine the production of these isotopes in the Galaxy. Cosmic rays are an important producer of ^{6}Li, ^{7}Li, ^{7}Be, ^{9}Be and ^{10}B throughout the lifetime of the Galaxy and the production of ^{7}Li in particular has important cosmological implications. New production calculations of these isotopes in the Galaxy are carried out using a Monte Carlo diffusion program and improved cross sections. Some of these production ratios differ significantly with earlier calculations.

2. Data Analysis and Results

The data presented here is an update of earlier results described in Lukasiak, McDonald and Webber, 1997. The separation of the different elements and isotopes is achieved using the multiple dE/dx versus E technique on the Voyager (V) HET telescopes. Figure 1 shows the mass histograms of Li, Be and B from the combined V1 and V2 spacecraft. The mass resolution of the HET telescope is σ=0.18 AMU for all 3 elements. The energy interval for each isotope is mass dependent and the energy limits for the various isotopes are given in Table 1. The isotopic ratios shown in Table 1 were corrected for these differences in energy intervals using a spectral index equal to 1.0. The weighted average solar modulation level for the 21 years covered by this study, is 450 MV as determined from the 150-450 MeV/nuc He intensity as described by Ferrando et al., 1991. This is lower than the average solar modulation level observed at the Earth at sunspot minimum.

Table 1. Elemental Ratios and Isotopic Composition (Voyager 1 and 2, 1977-1998, ϕ=450 MV)

Element/Isotope	Number of events	Energy Range (MeV/n)	Measured Ratio [%]	Propagation calculations [%]
Li/C	870, 17064	33-85	12.28±0.43	12.20
Be/C	672, 18661	41-106	5.53±0.22	5.55
B/C	3412, 18661	44-114	24.17±0.45	23.72
^{6}Li/Li	312	34-89	45.7±3.2	42.1
^{7}Li/Li	312	31-81	54.3±3.8	57.9
^{7}Be/Be	284	43-113	57.4±4.3	55.8
^{9}Be/Be	142	37-98	38.3±3.7	39.1
^{10}Be/Be	14	35-92	4.2±1.1	4.9
^{10}B/B	776	45-119	30.5±1.3	28.6
^{11}B/B	1583	43-112	69.5±2.2	71.4

3. Interpretation of the Results

We compare the results in Table 1 with propagation calculations using a Leaky-Box Model (LBM). This model is described earlier in Webber et al., 1996, and Lukasiak et al., 1997, however, in this latest calculation we use the new cross sections into Li, Be and B reported by Webber et al., 1998. For the interstellar path length we used $\lambda=25.2\beta R^{-0.50}$ for rigidities R>3.3 GV and 13.9β for R<3.3 GV. For the solar modulation we use a force field calculation, event weighted according to the average modulation, ϕ, for each year of the study. A comparison of these predictions with the measurements is shown in both Table 1 and Figure 2 where the various isotopic ratios are shown with respect to Carbon. Also shown in Figure 2 are the interstellar (IS) ratios at 100 MeV/nuc calculated from the propagation model . The calculated and measured isotope ratios to C agree in all cases to within the $\pm$ 1σ data errors. This includes the ^{9}Be abundance and in particular the ^{7}Be/^{9}Be ratio which is observed to be 1.50±0.12 by Voyager and calculated to be 1.43. Earlier propagation calculations (e.g., Connell and Simpson, 1998) gave a ^{7}Be/^{9}Be ratio (1.00) that is more than 4σ different than the actual ratio of 1.43±0.10 measured by Ulysses.

The ability of the propagation calculations to reproduce the new measurements of these isotopic abundances from Voyager means that the production of these isotopes in the Galaxy by cosmic rays can now be calculated more accurately than previously. The results of these new calculations are shown in Table 2 and in several cases differ significantly with earlier ones as summarized by Reeves, 1994.

Note first that the calculated IS ratios in Table 2, column 4 are different than the measured ones in column 3 because of the effects of solar modulation on the isotopes of different charge to mass ratio. The calculated stopping ratios, the actual numbers of particles that come to rest and contribute to the galactic abundance, are different again. The calculation of the stopping fractions is performed for each isotope using a Monte Carlo diffusion program (Webber and Rockstroh, 1997) which keeps track of all particles falling below a threshold energy ~10 MeV/nuc. The fraction of particles in the interstellar spectrum that eventually fall below this threshold is a function of the particles rate of ionization loss which is ~Z^2/A and the shape of the interstellar spectrum. Note that for the production of ^{7}Li we include the decay of ^{7}Be by electron-capture at these low energies.

When one compares these new calculations with earlier ones summarized in Reeves, 1994, one notes that the isotopic ratios within an individual charge, e.g., Li, Be or B are in reasonably good agreement, but that the ratios between charges agree less well with differences of a factor of 1.5 or more in the cases involving ^{9}Be. This could be important for comparing the production of these elements during the history of the Galaxy since in several cases cosmic ray production is believed to be an important source.

Table 2. Relative Abundance of Li, Be and B Isotopes

Element/Isotope	Reeves (1994)	Measurements (~80 MeV/nuc)	Calculated IS (100 MeV/nuc)	Calculated Stopping
$^{7}Li/^{6}Li$	1.4	1.19±0.09 (1.77)*	1.22 (1.86)*	1.26 (1.95)*
$^{6}Li/^{9}Be$	5.0	2.43±0.20	2.51	2.78
$^{7}Li/^{9}Be$	7.0	2.90±0.24 (4.30)*	3.05 (4.67)*	3.50 (5.42)*
$^{11}B/^{10}B$	2.5	2.28±0.10	2.38	2.52
$^{11}B/^{9}Be$	12.0	7.98±0.57	7.90	7.56
$^{10}B/^{9}Be$	5.0	3.51±0.28	3.44	3.00
Li/Be	12.0	5.34±0.41 (6.83)*	5.56 (7.18)*	6.73 (8.20)*
B/Be	17.0	11.50±0.82	11.34	10.50
B/Li	1.42	2.07±0.09 (1.75)*	2.06 (1.55)*	1.56 (1.25)*

* $^{7}Be \rightarrow {}^{7}Li$ (K-cap)

4. Summary and Conclusions

New data from the Voyager spacecraft covering the individual isotopes of all three nuclei, Li, Be and B are reported. All of the various isotopic ratios are consistent with galactic propagation calculations using the latest 1998 cross section measurements. New calculations of the stopping particles as a measure of the galactic production of these isotopes show large difference with earlier calculations particularly for the charge ratios Li/Be, Li/B and Be/B.

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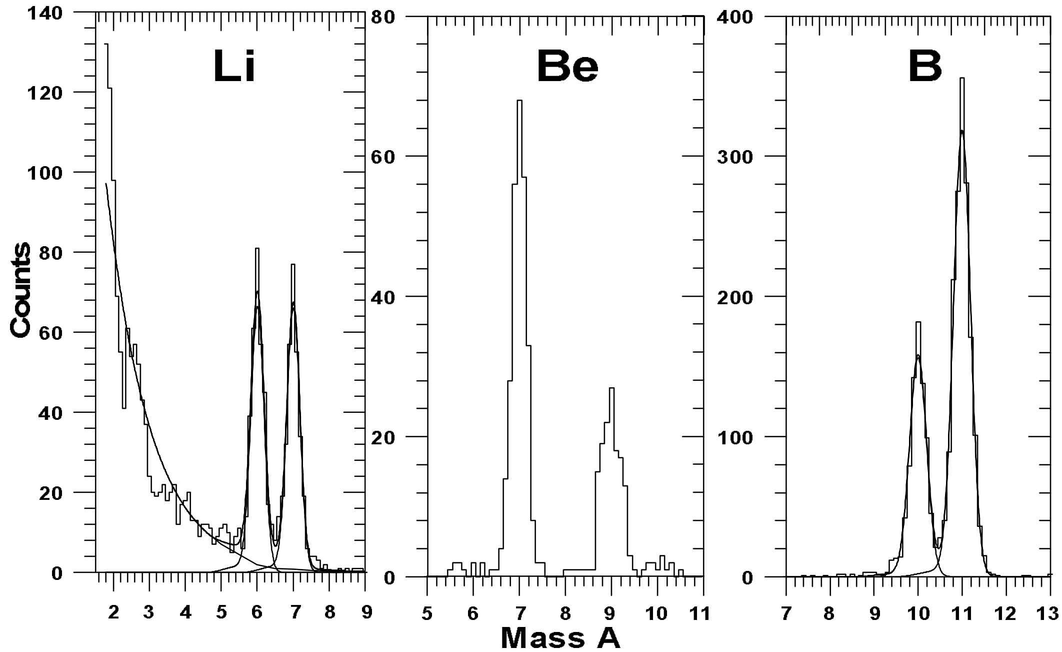

Figure 1. Mass histograms for cosmic ray Li, Be, B nuclei from summed Voyager 1 and 2, 21 year average. Solid curves are a result from the multiparameter χ^2 fitted to the histograms.

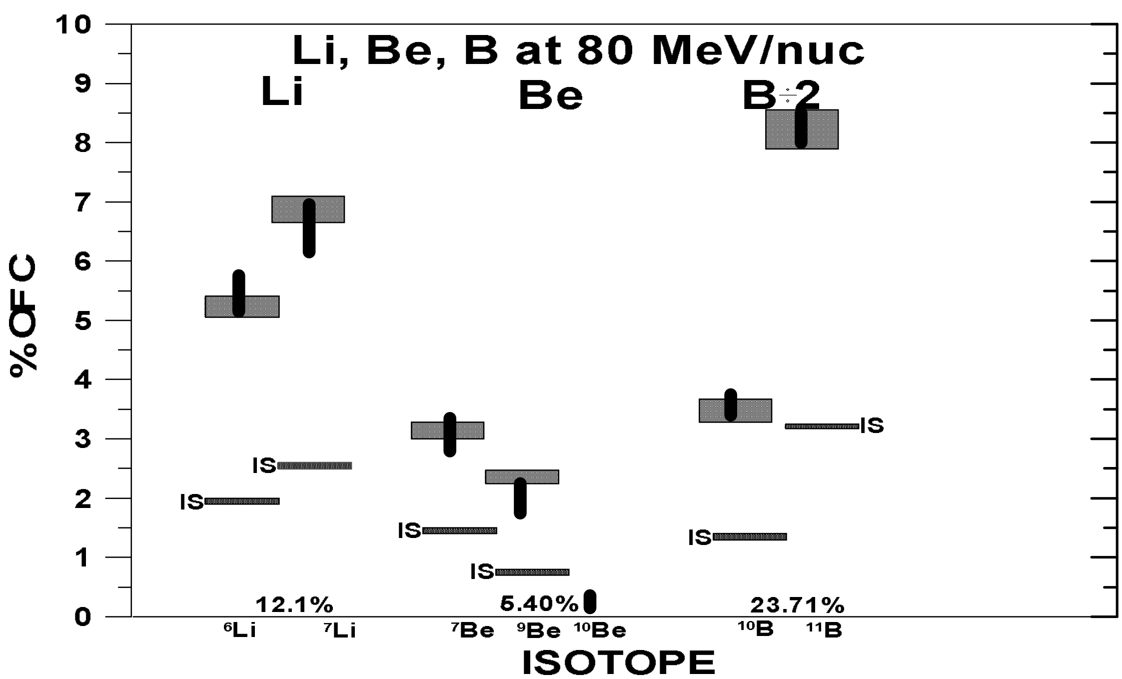

Figure 2. Ratios of abundance of Li, Be and B isotopes to C; 1) As measured by Voyager, showing also propagation calculations with errors as shaded bands, and 2) interstellar ratios as calculated using propagation program.