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THE RELATIVE ABUNDANCE OF THE ISOTOPES OF Li, Be AND B AND THE AGE OF COSMIC RAYS

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Abstract. Using a balloon borne double dE/dx x total energy telescope we have determined the isotopic composition of cosmic ray Li, Be and B nuclei in the energy range 100–250 MeV nuc.$^{-1}$. The measured mass resolution, σ for these nuclei is ~ 0.3 AMU. The observed isotopic composition is in agreement with that predicted on the basis of interstellar fragmentation with the exception of a deficiency of Be^{10}. If the low abundance of Be^{10} is attributed to the decay of this radioactive isotope we obtain a mean cosmic ray lifetime of $(3.4^{+3.4}_{-1.3}) \times 10^6$ yr.

1. Introduction

In a previous paper (Webber *et al.*, 1971) we presented data on the abundance of Li, Be and B nuclei in cosmic radiation as a function of energy. From a study of the Be/B ratio, assuming that these nuclei are produced as secondaries at approximately the same energy we observe them at Earth by heavier cosmic ray nuclei interacting with interstellar hydrogen enroute to the Earth; we were able to make some estimates of the amount of decay of the radioactive isotope Be^{10} into B^{10} (half life $= (2.7 \pm 0.4) \times 10^6$ yr)** and so argued that the lifetime of the cosmic rays producing Be was most likely ~10^7 yr or longer. In addition in this experiment we could resolve the Be^7 isotopes from B^{9+10}, and from the measured Be^7/Be^{7+9+10} ratio also came to a similar conclusion for the cosmic ray lifetime; subject, of course, to the combined uncertainties in the data, in the fragmentation parameters that were used to determine the expected abundance of the Be isotopes produced by cosmic ray fragmentation in interstellar space, and in the models for the origin and propagation of this radiation through the galaxy to the Earth.

In the summer of 1972 we carried out a further balloon flight with a new instrument, similar in design to the previous instrument but with a larger geometrical factor (540 st cm^2) and improved resolution. The improvements in the resolution of the individual dE/dx detectors allowed us to separate all of the isotopes of the L nuclei, and in particular Be^9 and Be^{10} which had not been separated previously. We wish to present this new data and discuss some of the implications with respect to the lifetime of cosmic rays.

2. Instrumentation

This data was obtained with the instrument shown in Figure 1. In the most recent

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[**] A recent measurement which we have used in this paper gives this lifetime to be $(1.5 \pm 0.3) \times 10^6$ yr (Yiou and Raisbeck, 1972).

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version of this instrument the thickness of the two d*E*/d*x* elements was increased from 0.45 g cm^{-2} to 1.0 g cm^{-2}. The resulting mass resolution was improved by ~30% which was sufficient to permit resolution of the isotopes of the light nuclei. At the time of the balloon flight on July 4, 1972, solar modulation effects were much less than during the earlier flights.

3. The Data

The data to be discussed here are obtained in the double d*E*/d*x*·*E* mode for particles

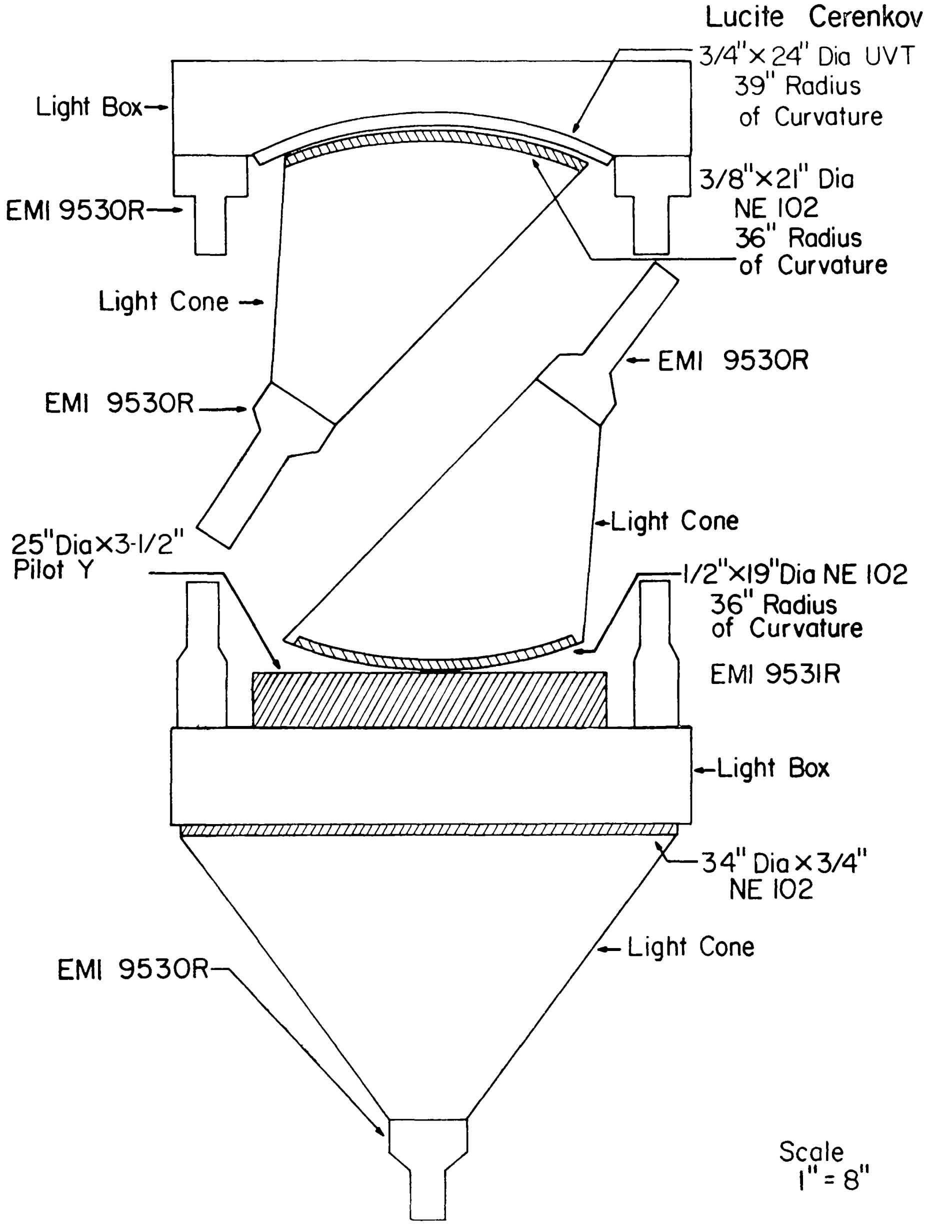

Fig. 1. Outline drawing of cosmic ray telescope.

that stop in the 9 g cm^{-2} thick total E detector. A two dimensional pulse height matrix of the pulse heights $(S_1+S_2)/2$ vs. E is shown in Figure 2 for events that satisfy the selection criteria $2|S_2-S_1|)/(S_1+S_2)\leqslant 0.2$. A careful comparison of events on sets of matrices with different selection criteria and a comparison with the percentage of particles expected to interact in the telescope verifies that these criteria remove >90% of all of the interacting particles while at the same time removing a negligible fraction (<3%) of the non-interacting particles. The remaining background events are a negligible fraction of the true Li, Be, and B events as can be observed by the general lack of events at locations on the matrix removed from the expected charge lines.

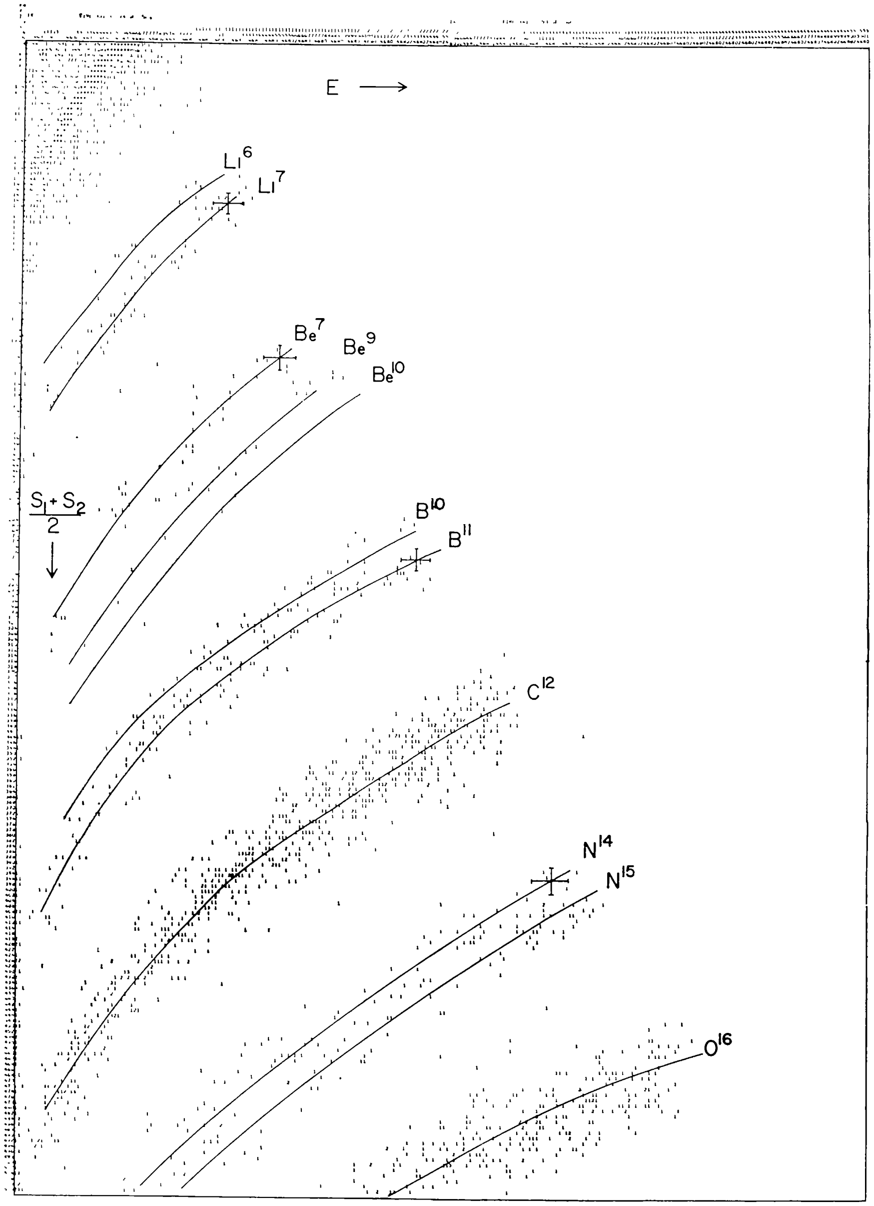

Fig. 2. Two-dimensional pulse height matrix $(S_1+S_2)/2$ vs. E for stopping particles.

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Without a selection criterion the background events form a level ~20–30% of the true Li and Be tracks. The use of a selection or redundancy technique in cosmic ray telescopes reduces the background considerably below levels in previous systems using anticoincidence counters. The detailed procedures for this technique, which is now being used by many balloon and satellite groups but as yet has not discussed thoroughly in the literature are presented in a separate instrumental publication.

From several matrices of the types shown in Figure 2 we are able to construct a mass histogram for the entire 1972 flight data by summing events parallel to each of the mass lines. This mass histogram is shown in Figure 3 and the data are also tabulated in Table I. Three distinct clumps of events for Be nuclei are evident in the figure as well as separate distributions for Li^6 and Li^7 and for B^{10} and B^{11}.

4. Resolution of the Instrument and Uncertainties of the Mass Assignment

There are two main sources of error in the determination of the isotopic mass in this experiment and because of the seminal nature of this measurement it is useful to discuss them in some detail. One source of error is related to the location of the mass

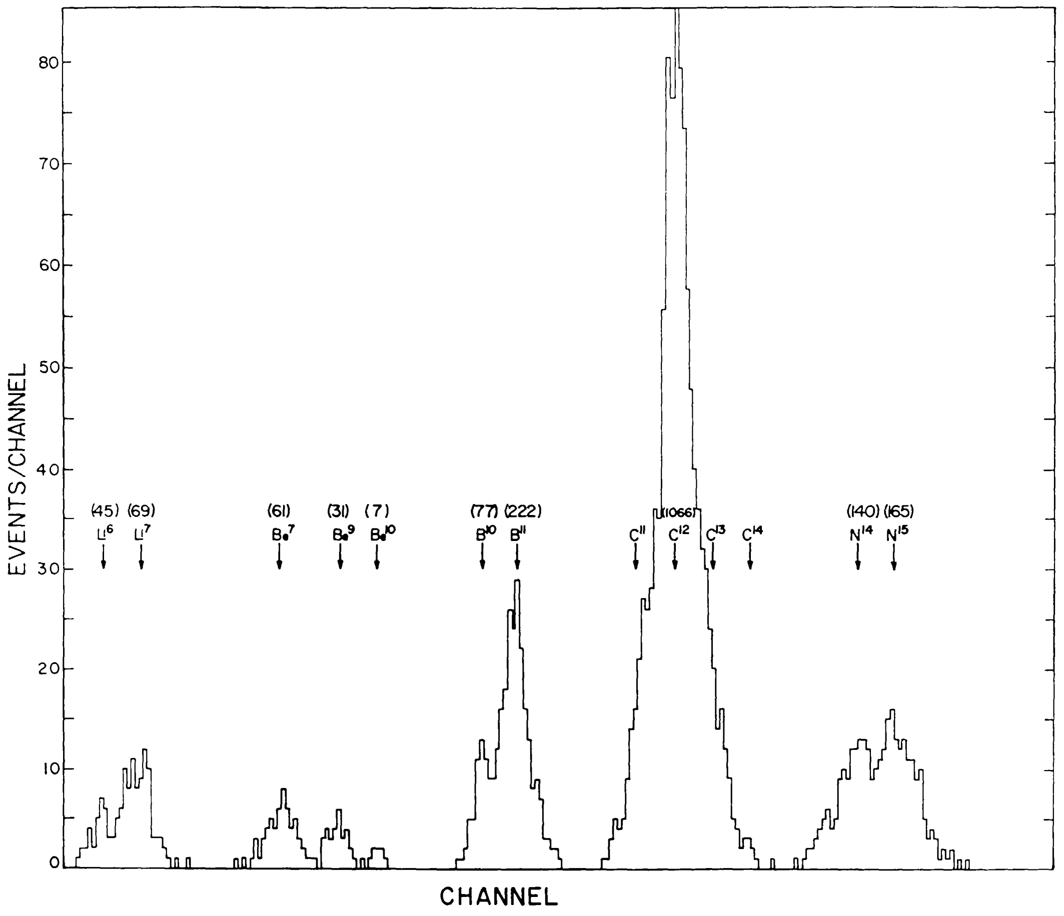

Fig. 3. Observed mass distribution of stopping nuclei ($Z = 3$–7).

TABLE I

Isotope	Energy interval (MeV nuc.$^{-1}$)	Mean rigidity (6V)	Observed number of events	A[a]	B[a]	Total factor[a]	Corrected relative number of observed events		Predicted number of of events[b]
Li^6	122–195	1.13	45	1.03	1.08	1.12	134	51	62 ± 10
Li^7	112–178	1.25	69	1.14	1.06	1.21		83	60 ± 10
Be^7	156–249	1.12	62	0.75	1.02	0.77	81	45	42 ± 7
Be^9	134–216	1.34	31	0.89	1.01	0.91		29	22 ± 4
Be^{10}	127–202	1.44	7	1.00—	1.00	1.00		7	18 ± 3
B^{10}	162–258	1.32	77	0.73	1.01	0.74	224	57	58 ± 10
B^{11}	154–248	1.41	225	0.75	0.98	0.74		167	167

[a] All factors normalized to Be^{10} correction factor.
[b] Normalized to observed number of B^{11}.

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lines themselves for the various isotopes. We have separately identified He^4 in this experiment and we have assumed that the principal isotopes of carbon and oxygen are C^{12} and O^{16}. Best fit response lines are then fitted to the pulse height distributions for He^4, C^{12}, and O^{16}. These lines serve to determine the response of the individual dE/dx and E counters at levels of energy loss, dE/dx, which bracket those to be expected for Li, Be B nuclei. It should then be a trivial matter to determine the response lines for the Li, Be and B isotopes if the output of the individual counters, dL/dx, is linear with dE/dx. There is, however, a dependence between dL/dx and dE/dx in plastic scintillators which is a function of both energy and charge (e.g. Webber and Kish, 1972). It is therefore necessary to extrapolate the response functions determined for He^4, C^{12} and O^{16} to the intermediate charges. This extrapolation is facilitated by the fact that there are at least 4 points of direct calibration of the response for the Li, Be, and B nuclei as a function of energy corresponding to: (1) The energy at which the Cerenkov output becomes zero; (2 and 3) the maximum and minimum energies that stop in the total energy counter; (4) the maximum energy that stops in the S_2 scintillator. It should be kept in mind that these non-linearities vary in a systematic way with energy and charge (Webber *et al.* 1973) and that the calibration of the response for Li, Be and B nuclei is already rather well defined by the He, C and O data. Utilizing all of this information it is possible to locate each mass line for these nuclei to an accuracy $\lesssim 0.2$ AMU at the 95% confidence level. These errors on the location of the mass lines are shown in Figure 2.

Once the mass lines have been accurately located, one has then to consider the intrinsic fluctuations in output which distribute the events about each line. In our telescope the major source of these fluctuations for low Z nuclei is due to Landau fluctuations in the dE/dx elements. (For $Z \leqslant 8$ nuclei systematic effects such as path-length differences (<3.5% FWHM) and non-uniformities in the counters (<1% FWHM in the counters used in this flight) are not as important.) We have dealt with the question of resolution at some length in recent articles (Webber and Kish, 1972; Webber *et al.*, 1973).

The Landau fluctuations may be evaluated by studying the *observed* mass distributions themselves for various nuclei. For example, we clearly resolve the isotope pair He^3–He^4, achieving a resolution ~6% FWHM or ~0.2 AMU which is sufficient to produce a He^3 peak to He^3–He^4 valley ratio of ~3:1 in the He mass histograms (see Figure 4). This is of interest since He^3–He^4 have about the same percentage separation as the Be^7–Be^9 pair. As the charge increases the resolution will improve, however, and for carbon nuclei we obtain a FWHM resolution in the double dE/dx dimension of 4.6%. This corresponds to a mass resolution σ of 0.33 ± 0.04 AMU. The effective mass resolution in AMU we obtain for other nuclei is shown in Figure 5. Note that the generally accepted criteria to resolve adjacent identical Gaussian distributions requires that σ be <0.43 times the separation of the distributions – in this case 1 AMU. On this basis we should be just capable of resolving the isotopes of nitrogen, and indeed nitrogen does appear to be composed of two isotopes, N^{14} and N^{15} with about equal abundance. The observed mass histograms for Li, Be, B

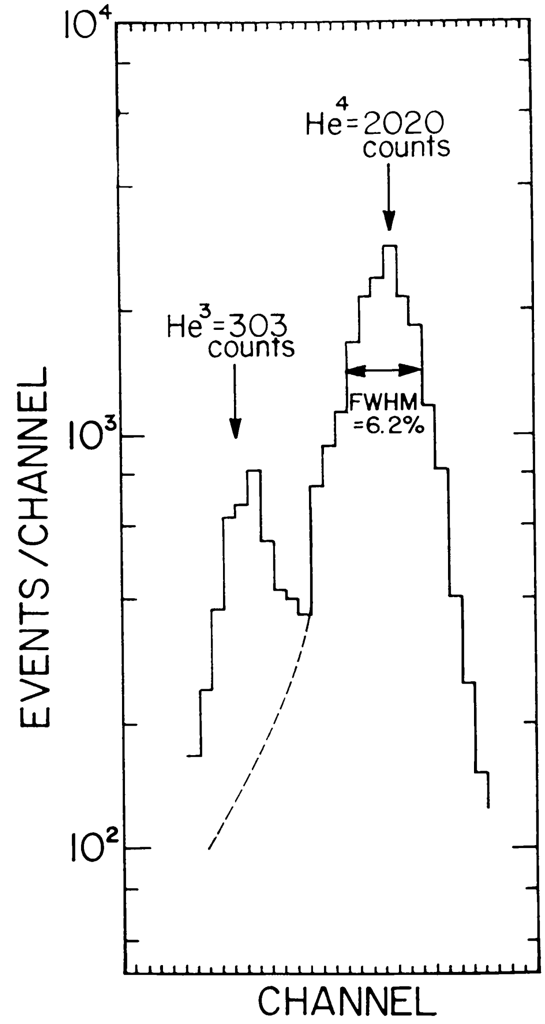

Fig. 4. Observed mass distribution for stopping He nuclei. Energy range 128-136.5 MeV nuc.$^{-1}$ for He^4, 156.5–169 MeV nuc.$^{-1}$ for He^3.

nuclei are consistent with those expected on the basis of the resolution data given in Figure 5. To illustrate this we have constructed idealized distributions for Li, Be and B nuclei on the basis of the accurate instrumental resolution data from He^3, He^4, C and O nuclei. These distributions, normalized to the actual numbers of the different isotopes observed are shown in Figure 6.

A more complete discussion of this instrument and its capabilities is in press (Webber *et al.*, 1973). Some idea of the possible improvements in resolution that can be obtained by improving the systematic non-uniformities $(\delta S)/S$ of the individual counters, from the value ~0.015 appropriate to our particular telescope is also shown in Figure 5.

5. Corrections of the Raw Data

The observed number of events as given in column four of Table I cannot be used

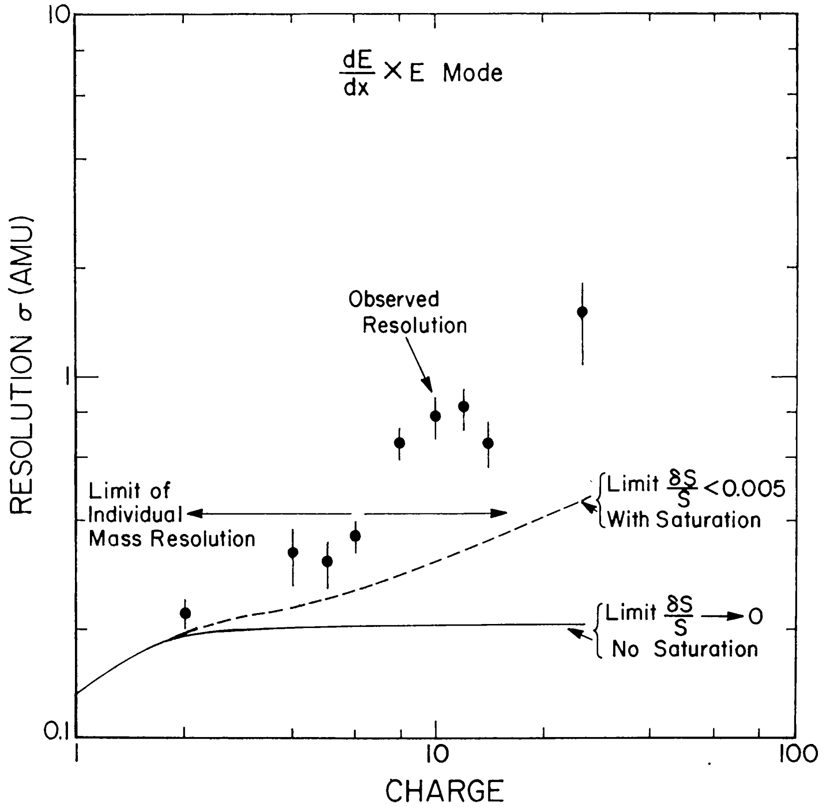

Fig. 5. Measured mass resolution of $dE/dx \times E$ telescope as a function of charge. Attainable limits with specific improvements are also indicated in the figure.

immediately to determine the ratios of the various isotopes in interstellar space. The following effects must be considered:

(1) The energy intervals must be adjusted to equal energy intervals with respect to Be^{10}. We assume that all isotopes have the same energy spectrum and that this spectrum is identical to that for He or C nuclei measured on the same flight. This correction term is given in Table I, column A.

(2) The effects of solar modulation must be accounted for. Since the energy and rigidity intervals for the different isotopes are slightly different we recognize that the solar modulation of each isotope will also be slightly different. Furthermore, since the leading term in the modulation is $\sim p$ (rigidity) there will be a further adjustment related to the mass to charge ratio of each isotope. We have used our measurements of the proton and helium modulation over the solar cycle (Lezniak and Webber, 1971) to correct the abundances to those to be expected in 1965 at a time of sunspot minimum. To further correct these values to interstellar space we have assumed that the residual modulation at the sunspot minimum in 1965 is given (Lezniak and Webber, 1971) in the currently accepted theoretical picture by $\phi = 140$ MV (ϕ = energy loss parameter). These two corrections are combined in column B of Table I. It is difficult to evaluate the errors in this correction; however, we have the advantage that the modulation is small in 1972 corresponding to near sunspot minimum conditions.

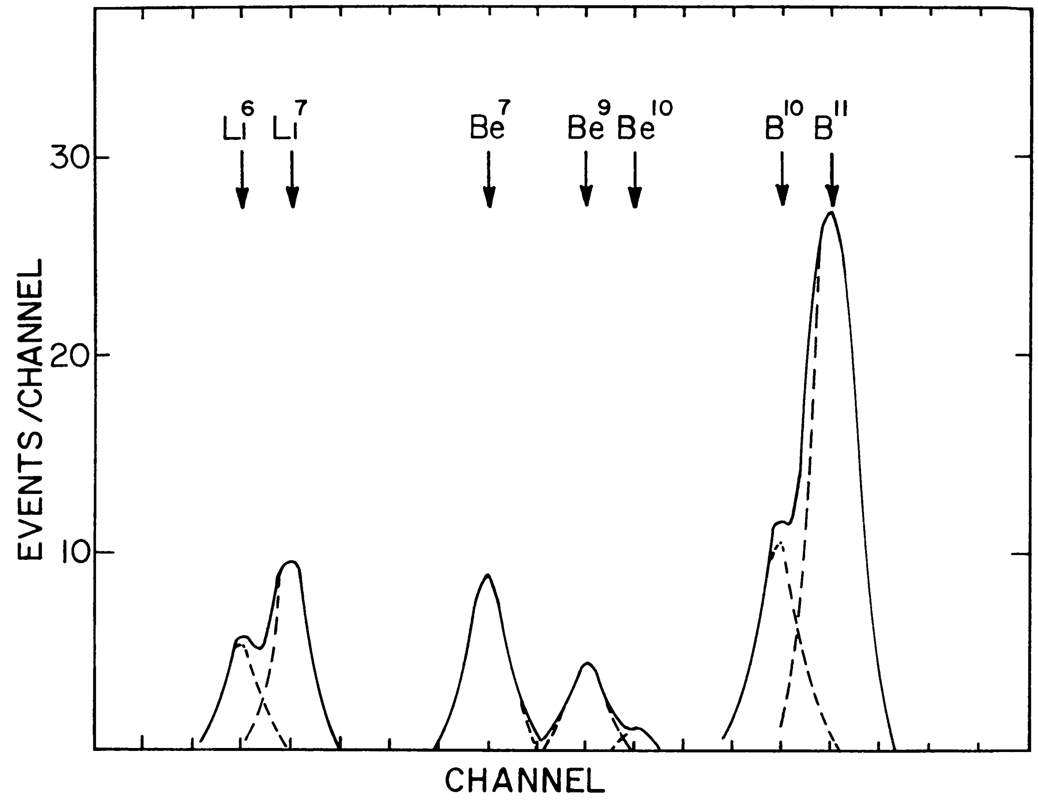

Fig. 6. Synthesized expected mass distribution for Li, Be and B nuclei, based on He^3, He^4, C and O resolution data. These distributions should be compared with those actually observed as shown in Figure 3.

(3) The final correction is related to the production of secondary nuclei in the atmosphere above the detector. From the growth curve of (Be + B) nuclei obtained in the atmosphere on this and other flights we estimate that only ~7% of these nuclei are produced in the atmosphere above the depth of 2.9 g cm^{-2} at which our detector was located. Data on the fragmentation parameters important in the production of the various isotopes of the light nuclei in air is almost non-existent and suitably accurate theoretical predictions are not available. We have therefore *not* made a correction for any possible differences in the interstellar and atmospheric fragmentation parameters on the relative isotopic abundances *except* for a 5% adjustment in the relative B^{11} abundance due to the fact that the C^{11} ($\tau \sim 20$ min) produced in the atmosphere does not decay.

Results and Interpretation

The next to last column in Table I gives the corrected relative number of observed events – the number that would be expected in interstellar space near the Earth in a common energy/nucleon interval. In the final column we show the predicted number of events of the isotopes normalized to the production of B^{11}. This prediction is based on the fragmentation cross sections for particles of 400 MeV/nuc presented

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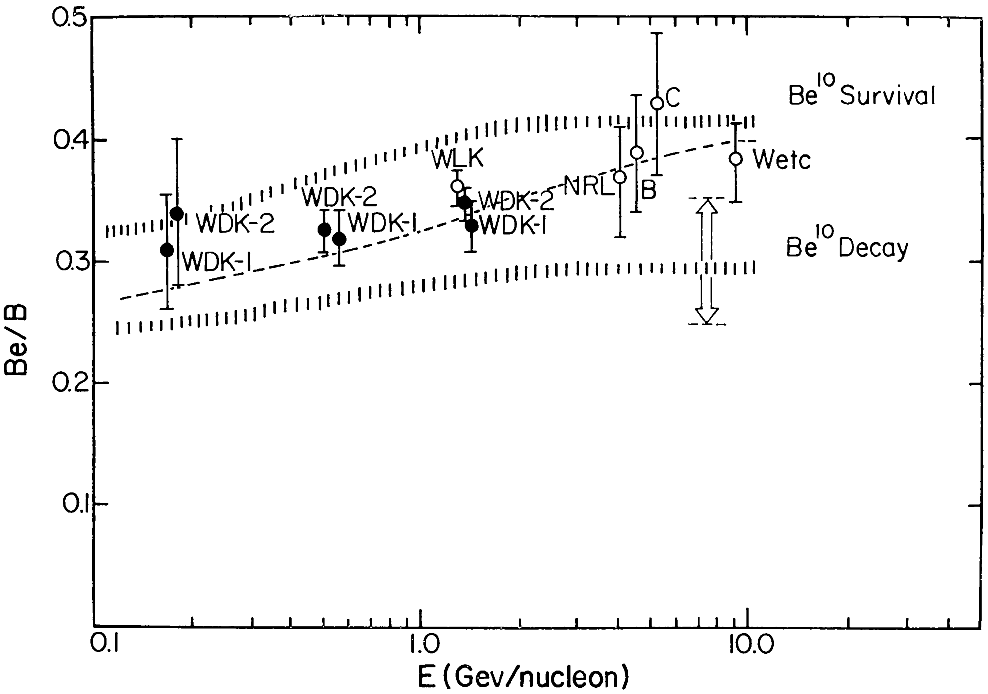

Fig. 7. Measurements and predictions of Be/B ratio as a function of energy. The symbol NRL refer to O'Dell *et al.* (1972), B refers to Smith *et al.* (1973), and C refers to Casse *et al.* (1972). Other symbols are discussed in text.

by Shapiro and Silberberg (1970) and updated with recent measurments (Raisbeck *et al.*, 1972) and includes the production of Be from B. Our predicted relative abundances agree very closely with those given at a similar energy in a recent paper by Meneguzzi *et al.* (1972), and are consistent with our present understanding of the fragmentation cross sections and the propagation of cosmic rays in the galaxy. That is to say propagation models in which the particles are assumed to have an exponential pathlength distribution with a characteristic length $X_0 = 5$ g cm^{-2}, and each species has a similar total energy spectra and the effects of ionization energy loss and secondary and tertiary production are included.

If one recognizes and includes an average uncertainty of $\pm 15\%$ in the fragmentation parameters (O'Dell *et al.*, 1972; Raisbeck *et al.*, 1972), the observed and predicted abundances of all the isotopes agree within $\pm 1\sigma$ with the exception of Be^{10} and possibly Li^7. The measured Li^7/Li^6 ratio of 1.6 ± 0.33 as compared with the predicted value of 0.98 is indicative of a possible excess of Li^7. The calculated abundance of the Li isotopes is obtained by considering fragmentation from all $A/Z = 2$ isotopes of heavier nuclei plus the contribution from B^{11}. Production of Li from Be and from neutron rich heavier isotopes such as N^{15} which may be present in appreciable numbers in the cosmic radiation is not considered, and this production would enhance the predicted Li^7 abundance relative to Li^6. The decay of appreciable amounts of Be^7 to Li^7 by electron capture (Yiou and Raisbeck, 1970; Raisbeck and Yiou, 1971) is not a likely possibility since the observed and predicted abundances of Be^7 agree

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closely. The cause of the enhanced Li^7/Li^6 ratio is unknown, however, if we include a $\pm 15\%$ uncertainty in the fragmentation parameters the differences between the observed and predicted Li^7/Li^6 ratio are only of marginal significance.

In the case of Be^{10}, 7 events are observed whereas 18 are predicted. The observed abundance of the other Be isotopes is in good agreement with predictions – in addition the Be^{10} cross sections are among the most extensively measured and calculated. Production from heavier isotopes with $(A/Z)>2$, which we have not considered, would tend to enhance the predicted Be^{10} abundance. Even allowing for $\pm 15\%$ errors in the fragmentation parameters the measurement and prediction differ by $\sim 3\sigma$ and must be considered significant. A most reasonable explanation of this difference is that some of the Be^{10} has decayed enroute to the Earth, and this difference can be used to determine the age of cosmic rays. If this is the correct explanation, the observed abundance of B^{10} should be slightly larger than that predicted when Be^{10} decay is not included. Actually, the observed abundance of B^{10} is very nearly the same as predicted if Be^{10} decay did not occur and the presence of ~ 11 decay Be^{10} events is not observable at the present level of accuracy of either the data or the fragmentation parameters.

We shall proceed on the basis that the low Be^{10} abundance is due to radioactive decay of this isotope with a half life $\tau = 1.5 \times 10^6$ yr. Then assuming that: (1) Cosmic rays are in stable equilibrium e.g., $dN_i/dt = 0$; (2) That the sources of Be^{10} are spread homogeneously through space and are producing Be^{10} at a total rate P_{10}, and (3) The loss rate (fragmentation break up and leakage) is independent of energy and determines a lifetime T; we may write

$$\frac{dN_{10}}{dt} = 0 = P_{10} - N_{10}\left(\frac{1}{T} + \frac{\ln 2}{\gamma\tau}\right),$$

where γ is $= 1/\sqrt{(1-\beta^2)} \simeq 1$ for the nuclei in question and we define a mean life for $Be^{10} \equiv T_R = \tau/ln 2 = 2.2 \times 10^6$ yr. Then for the ratio of Be^{10} to an identical species that does not decay $(N_{10})_0$ we have

$$\frac{N_{10}}{(N_{10})_0} = \frac{1}{1 + T/\gamma T_R}.$$

From the observed numbers for Be^{10} we find that the mean cosmic ray lifetime $T = (3.4 \pm^{3.4}_{1.4}) \times 10^6$ yr where the errors quoted are due to the statistics of the Be^{10} measurement only and do not include fragmentation errors. Alternatively we may state that the lifetime has a 95% probability of being between 1×10^6 and 1×10^7 yr. A more sophisticated calculation, using a specific distribution of cosmic ray lifetimes, would lead to a slightly different mean life but is not warranted by the accuracy of the data.

This current data is consistent within $\sim 2\sigma$ with our earlier data (Webber *et al.*, 1971). Previously we observed a Be^7/(All Be) ratio $= 0.76 \pm 0.09$, based on 45 Be events, now we find this ratio to be 0.55 ± 0.06 based on 100 Be events. The somewhat shorter lifetime we now deduce is due in part to the shorter Be^{10} lifetime used, and in part to the data itself.

It should be pointed out that essentially similar information on the age of cosmic rays can be obtained by studying the energy dependence of the Be^{10} abundance e.g. the Be^{10}/Be^{9} ratio, which should be expected to vary because of time dilation effects on the Be^{10} lifetime. So far, it has not been possible to determine the Be^{10} abundance as a function of energy and instead a considerable effort has been made (e.g., Shapiro, 1972; Webber *et al.*, 1971) to study the energy dependence of the Be/B ratio which embodies the same information on Be^{10} decay but in diluted form. In Figure 7 we show a compilation of recent data on this ratio. This compilation includes several previously unpublished results from our group. The points labelled WDK-2 are from a balloon flight at Ft. Churchill in 1971 with the same detector used to make the measurements labelled WDK-1 which were previously published (Webber *et al.*, 1971). The point labelled WLK is from a measurement with this same basic detector above a rigidity cutoff of 2.9 GV and the point labelled W, etc., is above a rigidity cutoff of 11.3 GV. The ratios have been plotted at the energies measured at Earth. We recognize that to account for energy loss effects which are believed to be a part of the interplanetary modulation, these points, particularly the low energy ones, should be moved to the right by $\sim$100–200 MeV nuc.$^{-1}$ in Figure 7, in order to obtain the interstellar ratio. The bands labelled Be^{10} decay and survival are values taken directly from a recent review by Shapiro (1972) as are the error bars on these values which represent the uncertainties in the fragmentation parameters (O'Dell *et al.*, 1972). We have not adjusted our measured ratios above a given rigidity cutoff to correspond to the equivalent values above a fixed energy/nucleon as the above authors have done because our measurements indicate that the average A/Z of these two charges is only slightly different and therefore, such a correction is not necessary (Webber *et al.*, to be published). The dashed line in this figure represents the expected variation of the Be/B ratio with energy in interstellar space if the lifetime of 3.4×10^{6} yr given earlier is assumed. The data points are seen to be consistent with this possibility although it should be evident from the figure that the Be/B ratio is not known accurately enough to determine this lifetime by itself.

A significant aspect of our measurement is the detailed agreement between the observed and predicted isotopic abundances of Li, Be and B as indicated in the last two columns of Table I. The complete model of the origin and propagation of cosmic rays is implicit in the predicted isotopic abundances. These measurements confirm the accuracy of the assumptions that nuclear fragmentation reactions in interstellar space are the main source of Li, Be and B in cosmic rays. For example, models in which the cosmic rays pass through most of the matter in the sources while being accelerated at quite different (lower) energies than we observe them at Earth can immediately be ruled out because of the large differences to be expected in the isotopic abundances resulting from energy dependent differences in the fragmentation parameters.

Obvious major problems still remain in our understanding of the role of Be^{10} in determining the age of cosmic rays, problems related to the need for improved statistical accuracy of the data, and improved values for the fragmentation parameters, as well as to adequately account for the effect of solar modulation. We believe that our measurements indicate for the first time that it will indeed be possible to use Be^{10} to make precise determinations of the cosmic ray residence time in the galaxy as suggested many years ago (Hayakawa *et al.*, 1958; Peters, 1963).

Acknowledgements

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