MEASUREMENTS OF COSMIC-RAY Li, Be AND B NUCLEI IN THE ENERGY RANGE 100 MeV/NUC TO >22 BeV/NUC

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Abstract. We report on new measurements of the spectra of Li, Be and B nuclei in the primary cosmic radiation in the energy range 100 MeV/nuc to > 22 BeV/nuc. The differential spectrum of these light nuclei is found to have a maximum at ~ 400 MeV/nuc in 1966. The L/M ratio is found to be equal to 0.25 ± 0.01, constant over the entire energy range of the measurement. Atmospheric and solar modulation effects on the L nuclei and the L/M ratio are discussed. It is concluded that this ratio is representative of conditions in interstellar space. Using the most recently available fragmentation parameters gives a material path length of 3.6 g/cm^2 of hydrogen for the particles producing the L nuclei. The absence of any variation of the L/M ratio with energy places severe constraints on models for the propagation of cosmic rays. Models in which the material path length is a strong function of energy – or that exhibit an exponential path-length distribution for a fixed energy are incompatible with these results. An examination of the abundance ratios of the individual L nuclei separately reveals major discrepancies with the predictions of interstellar diffusion theory based on presently accepted fragmentation parameters. The constancy of the measured Li/M and B/M ratios with energy is not in accord with the large energy dependence of these ratios expected from the energy dependence of the fragmentation cross-sections. The low Li/M ratio and high B/M ratio to be expected if these nuclei are created at a much lower energy than we observe are also not found. This presents difficulties for theories which suggest that the passage through matter has occurred at low energies subsequently followed by considerable acceleration.

The Be/M ratio in cosmic rays is anomalous in that it is ~ 40% larger than expected on the basis of the fragmentation cross-sections. Evidence presented here on the isotopic composition of Be nuclei suggests that this discrepancy is due to an enhanced abundance of Be^9 or Be^{10} in cosmic rays. This discrepancy complicates the determination of a cosmic-ray 'age' using the decay of Be^{10} into B.

Nevertheless the Be/B ratio is observed to remain constant at 0.42 ± 0.03 over the energy range from 100 MeV/nuc to over 10 BeV/nuc. Unless the fragmentation parameters into the various isotopes of Be and B are such that e.g. $\Delta(\mathrm{Be/B}) < 0.05$ as a result of this decay, then the age of cosmic rays is either $> 3 \times 10^8$ years or $< 10^6$ years. The further observation that the mass to charge ratio of all Be nuclei of energy ~ 1 BeV/nuc is $= 2.05 \pm 0.1$ suggests that Be^{10} is present at these energies. This supports the idea of a short lifetime.

1. Introduction

Perhaps the most accurately accomplished set of measurements at the present time that provides information on the origin and propagation of cosmic rays is that of the abundance of the Li, Be, B nuclei. In order to properly interpret these measurements we must construct a model in which these nuclei are created as secondaries by heavier cosmic rays. This secondary production may occur at the locale of acceleration or it may proceed as the cosmic rays move through the magnetic fields and hydrogen in the galaxy. In any case, these measurements and others relating to the production of secondary (fragmentation) nuclei such as He^3 or H^2, can most directly be understood in

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terms of the passage of the cosmic rays through a certain amount of material (in g/cm^2). To interpret this distribution of material at a fixed energy and as a function of energy requires not only a model for the diffusion of cosmic rays to be taken, but also an assumption regarding the distribution of sources to be made.

A method exists for the direct determination of the age, T, of cosmic rays using the time-dilated decay of the relativistic Be^{10} nuclei as the measuring device. This isotope which has a half life $\tau_0 = 4 \times 10^6$ years is suitable for the measurement of ages in the range 10^6–10^8 years. A direct method of estimating T would be to measure the flux of Be^{10} as a function of energy. Such a measurement is not feasible with present-day techniques and instead it is necessary to measure the ratio of Be/B, since $Be^{10} \rightarrow \rightarrow B^{10} + e + \bar{\nu}$. This measurement requires a high degree of precision, particularly at high energies. The details of this interpretation depend critically on the value of the many cross-sections, σ_{ij} for the breakup of heavier nuclei into the various isotopes of Li, Be, and B. Daniel and Durgaprasad (1966) have examined this question using data available in 1965. Recently, several new cross-section measurements have become available, particularly from the Orsay group of Bernas *et al.* (1967), Gradsztajn *et al.* (1967), and Yiou *et al.* (1968).

We have just completed a study of cosmic-ray charge composition in the energy range from ~100 MeV/nuc to >22 BeV/nuc at balloon altitudes. In the course of these measurements made with new high-resolution instruments, we have catalogued some 3000 Li, Be and B nuclei.

In this paper we propose to examine the characteristics of the spectrum of these light nuclei, with particular emphasis on Be and B. The type of atmospheric effects that can modify the results will be discussed. The 'extrapolated' data will be presented and compared with the expected charge distribution based on recent cross-section measurements. The astrophysical implications of the results will also be discussed.

2. Instrumentation and Balloon Flights

The data to be discussed here were obtained on balloon flights using three similar, but quite distinct, instruments. The details of the balloon flights are given in Table I. The operation of instruments is as follows:

A. INSTRUMENT I

This is basically a Čerenkov-scintillation counter telescope. It contains two thin scintillators which form the telescope coincidence, followed by a 15-cm dia. UVT lucite Čerenkov detector, subsequently followed by another (range) scintillator. The first three telescope elements are all pulse-height analysed using separate 2048 channel analysers. This instrument, its response to charged particles and the method of unfolding the differential spectrum from the measured pulse-height distribution have been described in detail in a previous publication (Ormes and Webber, 1968). It is used to obtain the differential energy spectra of Li, Be, B, and C as well as other nuclei from ~140 MeV/nuc to 1 BeV/nuc. The Čerenkov threshold of 300 MeV/nuc for

TABLE I

Balloon-flight details

Date	Location	Instrument	Cut-off Rigidity[a] (BV)	Altitude (g/cm^2)	Collection Factor (ster m^2 sec)	Mt. Wash., N.M.
13 July, 1966	Ft. Churchill, Canada	I	0.2	2.1	159	2337
25 July, 1966	Ft. Churchill, Canada	I	0.2	2.8	196	2367
16 May, 1967	Palestine, Texas	III	4.35	5.0	521	2332
3 June, 1967	Palestine, Texas	III	4.95	5.0	854	2255
15 Sept., 1967	Queensland, Australia	II	11.2	6.2	756	2262

Cut-offs determined using latest $2° \times 2°$ world grid of Shea and Smart (private communication).

lucite and the energies corresponding to ranges of 2.1 and 8.8 g/cm^2 provide calibration points for the low-energy nuclei. This four-element system provides a substantial improvement in background suppression and charge resolution over the earlier two-element system upon which the results of Paper 1 (Webber and Ormes, 1967) were based. The larger area and longer flight times provided more than 2 times the total area-time factor than in the entire earlier series of measurements.

B. INSTRUMENT II

This is a large-area double scintillation counter telescope (diameter of individual elements $=61$ cm). This system is used to obtain the integral intensity of nuclei at geomagnetic latitudes $\gtrsim 40°$, where only relativistic nuclei of each charge are present. The scintillators are optically compensated to obtain uniformity in light collection to within $\pm 2\%$. The technique for compensation, and the details of the charge resolution etc. are being reported in a separate publication (Von Rosenvinge and Webber, 1968). The analysis of flight data using this instrument is particularly simple. Because of the good charge resolution and low background, each charge stands out as an individual clump of particles in the two dimensional matrix of scintillator outputs.

C. INSTRUMENT III

This instrument is identical to II except that a 1.7-m long gas Čerenkov detector is inserted between the scintillation counter-telescope elements. Thus in addition to the integral intensity of particles above the rigidity threshold determined by the geomagnetic field at the location of the flight, the integral intensity of events above the gas

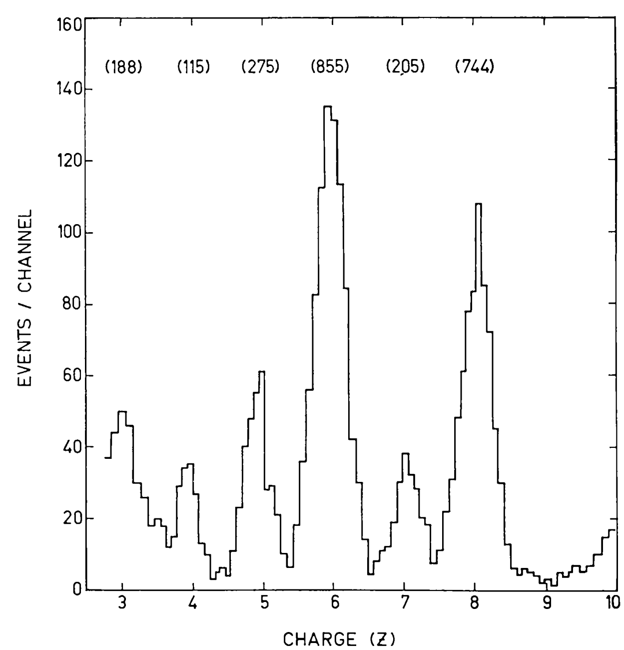

Fig. 1. Charge histogram in the range $Z=3$–10 obtained from a flight on 16 May, 1967, at Palestine, Texas. Numbers refer to the actual numbers of nuclei assigned to each charge.

Čerenkov threshold is obtained. In the two measurements with this instrument reported here, Freon gas was used at 2 atm and 1 atm pressure giving effective thresholds of 15 and 22 BeV/nuc respectively. A paper describing the operation of this system and a more complete discussion of the results obtained is now in preparation. For these studies it is relevant to note that the gas threshold energy is quite sharp and rather clearly defined, particularly for heavy nuclei.

In the last analysis the ability to study the charge spectra, particularly of the light nuclei, Li, Be, and B, depends on the degree of resolution of the different charges and on the statistical accuracy of the results. This in turn depends on the amount of 'background' present in the pulse-height matrix and the intrinsic resolution of the detector for adjacent charges. A pulse-height histogram for the charge range $Z=3$–10 for the flight on 16 May, 1967 with Instrument III is shown in Figure 1. Similar resolution is obtained for the other flights including the flights at Fort Churchill with Instrument I.

3. Corrections for Atmospheric Effects

Before one can interpret the measurements of light nuclei at balloon altitudes in terms of the extraterrestrial abundance of these nuclei, corrections must be made for production in the residual atmosphere.

We shall consider two separate aspects of this problem. First, there is the simple correction of the overall intensity of light nuclei to the top of the atmosphere. This is most conveniently carried out in terms of obtaining the L/M ratio as a function of atmospheric depth. The second aspect concerns the relative abundance of the individual nuclei themselves. Of particular interest here is the Be/B ratio as a function of atmospheric depth. Both of these corrections require either a complete knowledge of the fragmentation probabilities into the various isotopes of the light nuclei or direct measurements of the absorption of the different cosmic-ray nuclei in the upper atmosphere.

Consider the simple correction of the overall intensity of light nuclei and the L/M ratio to the top of the atmosphere. In Figure 2 we show the expected variation of the L/M ratio with atmospheric depth, based on the compilation of fragmentation parameters by WEBBER (1967) and an assumed L/M ratio $=0.25$ at the top of the atmosphere. In the first 10 g/cm^2 of atmosphere the expected increase in this ratio is almost linear at a value of $+0.008$/g/cm^2. Direct measurements of the L/M ratio with atmospheric depth have been carried out in Paper 1 to within ~ 2 g/cm^2 of the top of the atmosphere and lead to an almost identical value for this rate of growth. At a depth of 5 g/cm^2 the correction to the top amounts to a reduction of 0.04 in the measured L/M ratio. An extreme error of 25% in this correction will introduce an uncertainty of 0.01 in the L/M ratio at the top of the atmosphere. This uncertainty is comparable to the statistical uncertainty of the measurements we are about to discuss.

The correction of the intensities of the individual light nuclei to the top of the atmosphere is a somewhat more difficult and uncertain matter.

The most straightforward way of making this correction would be to observe the variation of the intensities of the various nuclei as a function of atmospheric depth and extrapolate to the top of the atmosphere. This procedure has already been utilized for certain individual nuclei in Paper 1. These earlier data have been combined with that from the present study. The relevant results may be summarized by noting that no change in the abundance ratios Be/B, Be/Li or Li/B in the upper 20–30 g/cm^2 of atmosphere is observed. In the upper 10 g/cm^2 this statement can be made with an accuracy of $\pm 20\%$ in the individual ratios for various energy intervals.

Using the fragmentation approach, the situation is very complicated indeed and is best illustrated by Table II, which shows the ratios of the various light nuclei to be expected in the atmosphere and in interstellar space as derived by SHAPIRO and SILBERBERG (1967) from a study of all of the available fragmentation parameters, including the recent measurements of the Orsay group.

The interstellar ratios reflect the possible decay or survival of Be^{10}. The difference between the interstellar (Be^{10} survive) and the atmospheric ratios is mainly due to the decay $C^{11} \rightarrow B^{11} + e^+ + \nu\,(\tau_0 \sim 20$ min), which provides an appreciable fraction ($\geqslant 35\%$) of the interstellar B^{11}, but is inoperative in the atmosphere. As a result of the fact that

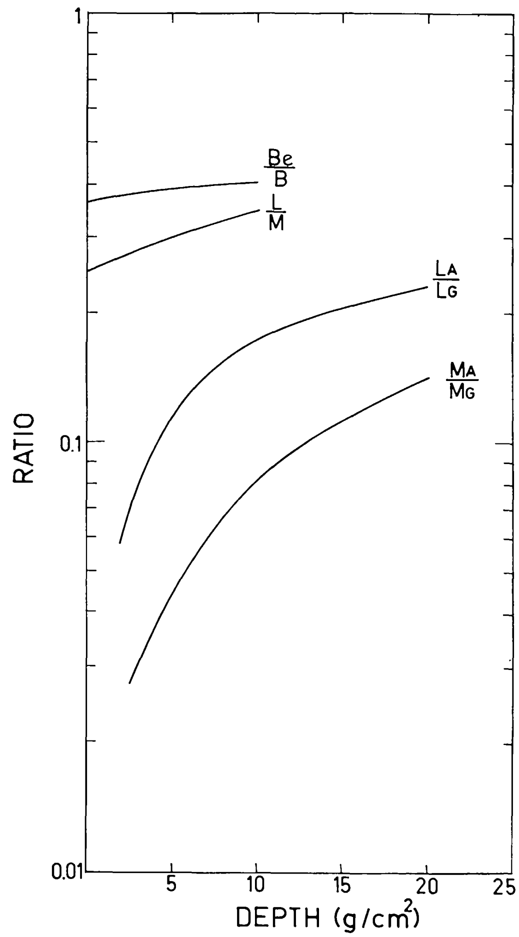

Fig. 2. Calculated variations of L/M and Be/B ratios as a function of atmospheric depth. Also shown are the ratios of atmospheric secondary to incident galactic light and medium nuclei.

TABLE II

Production of various light nuclei in the atmosphere and in interstellar space

Ratio	Interstellar Space				Atmospheric[a]	Observed (2–6 g/cm^2)
	200 MeV/nuc		> 1.5 BeV/nuc		> 1.5 BeV/nuc	(100 MeV/nuc – 4 BeV/nuc)
	Be^{10} Decay	Survive	Be^{10} Decay	Survive		
Be/B	0.18	0.20–0.24	0.28–0.29	0.31–0.37	0.57 ± 0.14	0.44 ± 0.02
Be/Li	0.43	0.47–0.55	0.47	0.50–0.57	0.54 ± 0.13	0.73 ± 0.04
Li/B	0.42	0.44	0.61	0.62–0.65	1.06 ± 0.21	0.60 ± 0.04

[a] Interactions in Emulsion with $N_h \leqslant 7$.

TABLE III

Number of events and intensities of different charges observed in selected energy intervals

Energy or Rigidity	Li	Be	B	L nuclei		M nuclei		L/M ratio
				(Intensity in particles/m^2 ster sec)				
150–210 MeV/nuc	30	18	40	88	0.23 ± 0.02	438	1.09 ± 0.06	0.21 ± 0.03
210–340 MeV/nuc	–	–	90	200[a]	0.52 ± 0.04	752	1.95 ± 0.08	0.27 ± 0.02
340–450 MeV/nuc	–	54	131	267[b]	0.70 ± 0.04	961	2.42 ± 0.08	0.27 ± 0.02
	(–)	(–)	(74)	(160)[a]		(410)		(0.38 ± 0.04)
450–600 MeV/nuc	–	62	134	292[b]	0.74 ± 0.04	997	2.48 ± 0.08	0.29 ± 0.02
	(–)	(–)	(87)	(192)[a]		(482)		(0.39 ± 0.04)
600–1000 MeV/nuc	110	72	173	355	0.88 ± 0.04	1470	3.67 ± 0.10	0.24 ± 0.02
	(–)	(39)	(101)	(210)[b]		(692)		(0.30 ± 0.03)
$>$1000 MeV/nuc	199	150	332	681	1.80 ± 0.08	2533	6.46 ± 0.16	0.27 ± 0.01
	(–)	(81)	(215)	(446)[b]		(1387)		(0.31 ± 0.02)
$>$15 BeV/nuc	10	8	15	34	0.058 ± 0.010	139	0.23 ± 0.02	0.24 ± 0.05
$>$22 BeV/nuc	8	7	12	28	0.031 ± 0.006	102	0.116 ± 0.012	0.28 ± 0.006
$>$ 4.35 BV	245	160	378	783	1.53 ± 0.06	2959	5.84 ± 0.15	0.26 ± 0.01
$>$ 5.00 BV	277	185	450	912	1.18 ± 0.04	3790	4.36 ± 0.12	0.24 ± 0.01
$>$11.1 BV	102	65	129	296	0.38 ± 0.02	1252	1.56 ± 0.05	0.24 ± 0.015

[a] Data on Li and Be lacking – intensity of Li and Be nuclei estimated from (Li + Be) = 1.2B as determined from data at other energies.
[b] Data on Li lacking – intensity of Li nuclei estimated from Li = $\frac{1}{2}$(Be + B) as determined from data at other energies.

C^{11} does not decay to B^{11} in the atmosphere, the Be/B and Li/B ratios would be expected to increase slightly with increasing atmospheric depth. The manner in which the Be/B ratio increases with depth using the values summarized by SHAPIRO and SILBERBERG (1967) is shown in Figure 2. The expected increase of 0.03 in the first 5 g/cm^2 is well within the uncertainties of the experimental intensity-depth measurements discussed earlier and comparable in fact, to the accuracy with which we can measure the Be/B ratio itself. We therefore argue that the atmospheric corrections to the various light nuclei ratios and particularly to the Be/B ratio are not large enough to seriously modify measurements made within 5 g/cm^2 of the top of the atmosphere.

Finally, with regard to the atmospheric corrections we should point out that no allowance has explicitly been made for the energy-dependence of the fragmentation parameters in air. In view of the uncertainty in our knowledge of the energy-dependence of these parameters, and the relative smallness of the corrections themselves, we believe that this omission is justified in the present analysis.

4. The Results

The principal results of this study are summarized in Table III. All data here are corrected to the top of the atmosphere using the fragmentation corrections as discussed earlier. The actual number of observed events attributable to each charge or charge group are shown in order to give an idea of the statistical errors. The numbers from our previous survey are shown in parenthesis. It is to be noted that two groups of measurements appear in this table. In one instance the energy intervals are derived by the instrumental calibration. In the other instance rigidity intervals are defined by the geomagnetic cut-off at the location of measurement. A comparison of intensities and spectra determined by these two methods provides a means for determining the mass to charge ($A/Z \equiv \Lambda$) ratio of the various nuclear species, as will be discussed shortly. For the purposes of plotting this data and converting from energy to rigidity, we have assumed the following A/Z ratios. Lithium = 2.17 corresponding to a mixture of Li^6 and Li^7; beryllium = 2.00, corresponding to a mixture of Be^7 and Be^9; boron = 2.20 corresponding to B^{11}; carbon, nitrogen and oxygen = 2.00, corresponding to C^{12}, N^{14}, and O^{16}, respectively. The reasons for this selection will be discussed and justified as the data are further presented.

The differential energy spectra of light and medium nuclei at the top of the atmosphere over the range 100 MeV/nuc to 22 BeV/nuc are shown in Figure 3. The data on these charge groups obtained in Paper 1 are also shown in this figure as are selected satellite and rocket measurements at lower energies made during 1965. The effects of solar modulation should not greatly influence a direct comparison of these separate observations since the change in neutron monitor rates between the sunspot minimum year of 1965 and the time of our low-energy measurements in 1966 is only 3%. Indeed, the slightly higher intensities of L and M nuclei obtained at low energies by the Chicago group (FAN *et al.*, 1968) may be evidence of this effect.

In Figure 4, we show the ratio of L to M nuclei as a function of energy. In order to

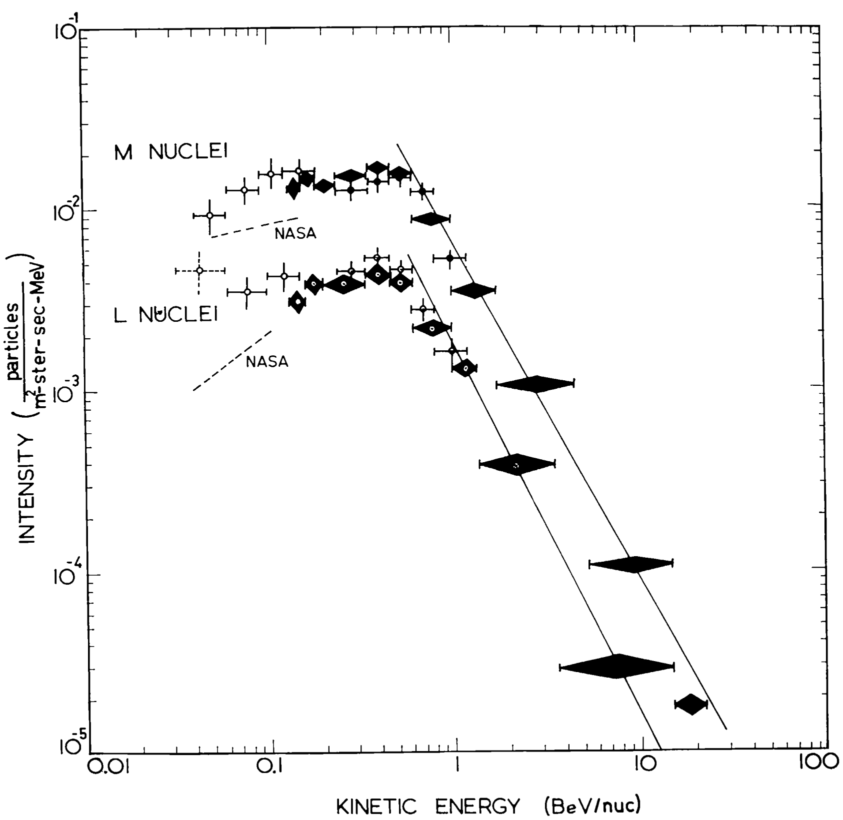

Fig. 3. Differential energy spectra of L and M nuclei. This data is shown as solid diamonds, Paper 1 as solid circles. The open circles refer to the low-energy data of Fan *et al.* (1968). (The data from Balasubrahmanyan *et al.* (1966) are almost identical and are not shown here.) The dashed line labelled NASA is from Reames and Fichtel (1967).

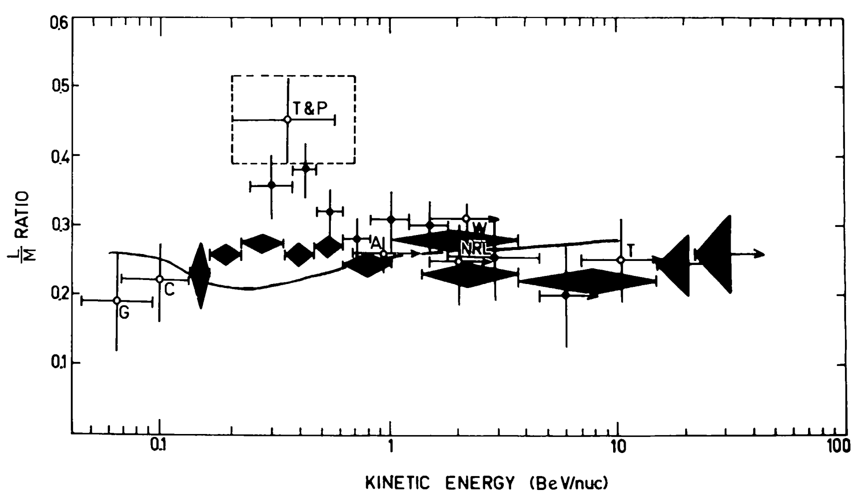

Fig. 4. The L/M ratio as a function of energy. This data are shown as solid diamonds; Paper 1, as solid circles. NRL refers to O'Dell *et al.* (1962), W to Webber (1967), T to Durgaprasad (1965), A to Aizu *et al.* (1960), T and P to Anand *et al.* (1966), C to Fan *et al.* (1968), and G to average of measurements of Reames and Fichtel (1967) and Balasubrahmanyan *et al.* (1966). The dotted square represents an average of a number of earlier measurements in the 200–700 MeV/nuc range (see Reames and Fichtel (1967) for a compilation of these measurements). The solid line is described in the text.

simplify this presentation we have been selective in our choice of experimental results to show in this figure. However, all of the most recent definitive measurements are shown. It is evident that our results are consistent with a value of 0.25 ± 0.02 for this ratio, constant as a function of energy from ~ 100 MeV/nuc to over 22 BeV/nuc. Our earlier results (Paper 1) gave some evidence for a maximum in this ratio in the energy range 200–450 MeV/nuc. However, the experimental points in this energy range are the most uncertain, and it should be noted that the remainder of the earlier results are in agreement with the much more precise recent results. A large body of measurements exists, however, as typified by the recent work of ANAND *et al.* (1966), and shown by the rectangular area in Figure 4, which indicates an L/M ratio between 0.4 and 0.5 in the energy range 200–600 MeV/nuc. An examination of the original results suggests that this high value is due, in most cases, to a much more prominent peak in the differential spectrum of L nuclei than we observe, rather than any differences in the spectra of M nuclei. Since we use both range-energy and dE/dx vs. Čerenkov techniques in overlapping fashion in this range in our new instrument, we feel this is probably the most accurately known energy range of our new spectra.

Figure 5 shows the differential spectra of Be, B and C nuclei that we have obtained in our recent study. Satellite observations at low energies made in 1965 are also shown.

We have not presented other types of spectra for these nuclei; however, they can be

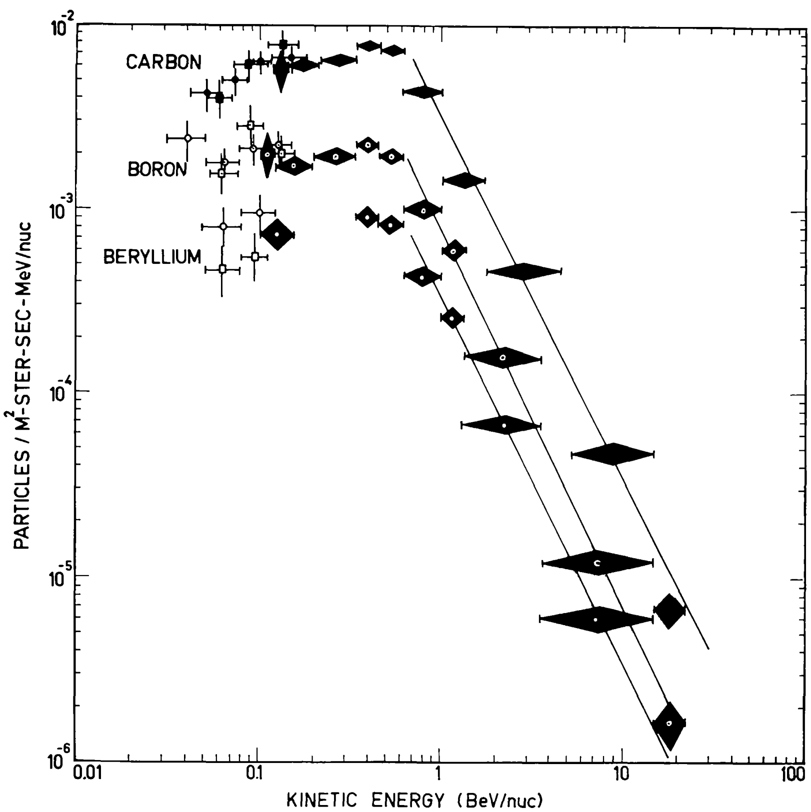

Fig. 5. Differential energy spectra of Be, B and C nuclei measured in this work. The low-energy data of FAN *et al.* (1968) is shown as circles, that of BALASUBRAHMANYAN *et al.* (1966) as squares.

derived from the data presented in Table III. For completeness here we give the exponents of the integral rigidity spectra in the range 5–50 BV as follows:

L nuclei = 1.56 ± 0.05; M nuclei = 1.60 ± 0.03; Li nuclei = 1.49 ± 0.08; Be nuclei = = 1.51 ± 0.08; B nuclei = 1.57 ± 0.06; and C nuclei = 1.60 ± 0.05.

In order to compare the spectra of the separate L nuclei and examine any possible differences it is most convenient to plot the Li/M, Be/M and B/M ratios. These are shown as a function of energy/nuc in Figures 6 and 7. Figure 8 shows the corresponding Be/B ratio. Only a few measurements of these ratios at high energies are currently

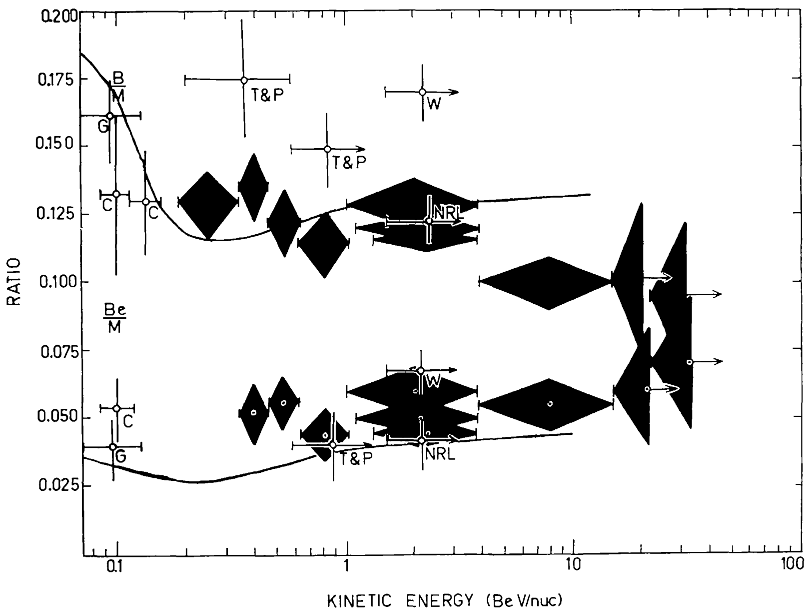

Fig. 6. The Be/M and B/M ratios as a function of energy. This work is shown as diamonds. The letters refer to the same references as in Figure 4.

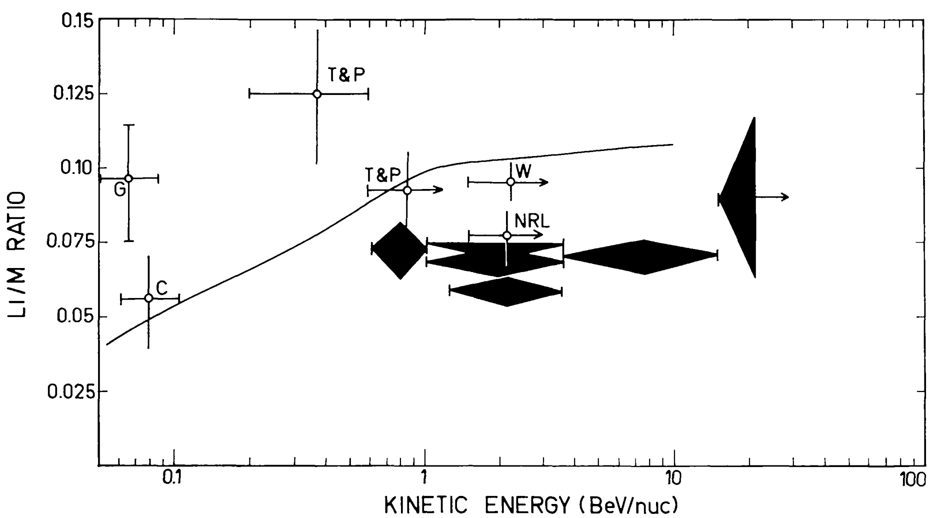

Fig. 7. The Li/M ratio as a function of energy. This work shown as diamonds. The letters refer to the same references as in Figure 4.

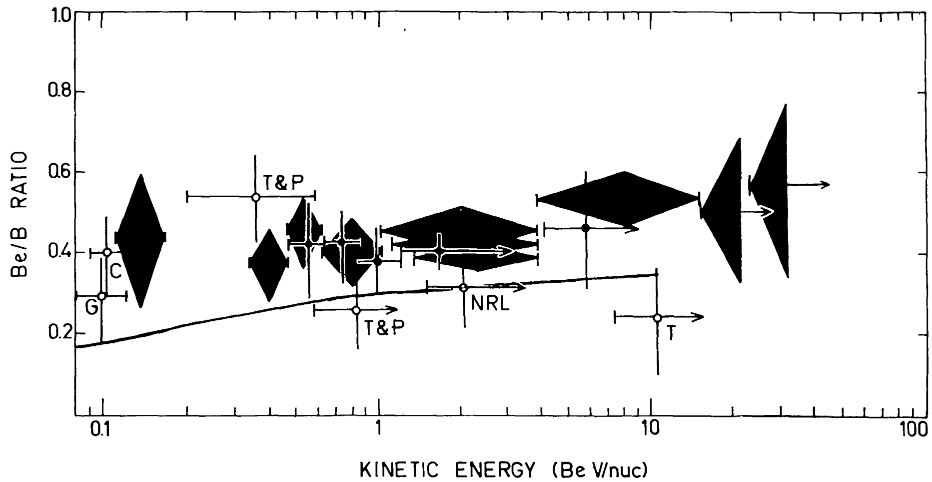

Fig. 8. The Be/B ratio as a function of energy. This work shown as diamonds, Paper 1 as solid circles. The letters refer to the same references as in Figure 4.

available. These are shown in the figures along with the satellite measurements of the Chicago and NASA groups at low energies. The most striking aspect of these data is the relative constancy of these individual charge ratios, with the possible exception of the B/C ratio. It is true that large uncertainties exist, particularly in the earlier measurements and our most recent ones at very high energies. The ratios measured at low energies on satellites are in very close agreement with our most recent ones, however, and together open up a completely new aspect of the study of light nuclei in the cosmic radiation – a study of the spectra of the individual charges themselves. We shall discuss the implications of these measurements in a later section.

A. ISOTOPIC COMPOSITION

Implicit in the previous discussion are important assumptions regarding the isotopic composition of the various species of light nuclei. These assumptions affect our interpretation of the relative influence of solar modulation on these nuclei and indeed the precise isotopic composition is of fundamental importance in our understanding of their origin and propagation. Because of the very formidable experimental difficulties involved in identifying the separate isotopes of these cosmic ray nuclei we cannot, at present, do better than to make the set of assumptions leading to the mass to charge ratios as presented earlier.

However, because of the fact that we measure the individual spectra separately in energy intervals (<1 BeV/nuc) and rigidity intervals (>4.3 BV) we have a possibility of making a rough estimate of the mass-to-charge ratio of each charge. The manner in which this is accomplished is best illustrated by referring to Figure 9. Here the integral energy/nuc and rigidity spectra of various nuclear species are shown separately. In deriving these spectra we have first assumed that all charges have a mass-to-charge ratio $=2$. The energy to rigidity conversion is then determined accordingly. If this is, in fact, the correct ratio then the high-energy part of the spectrum should fit smoothly

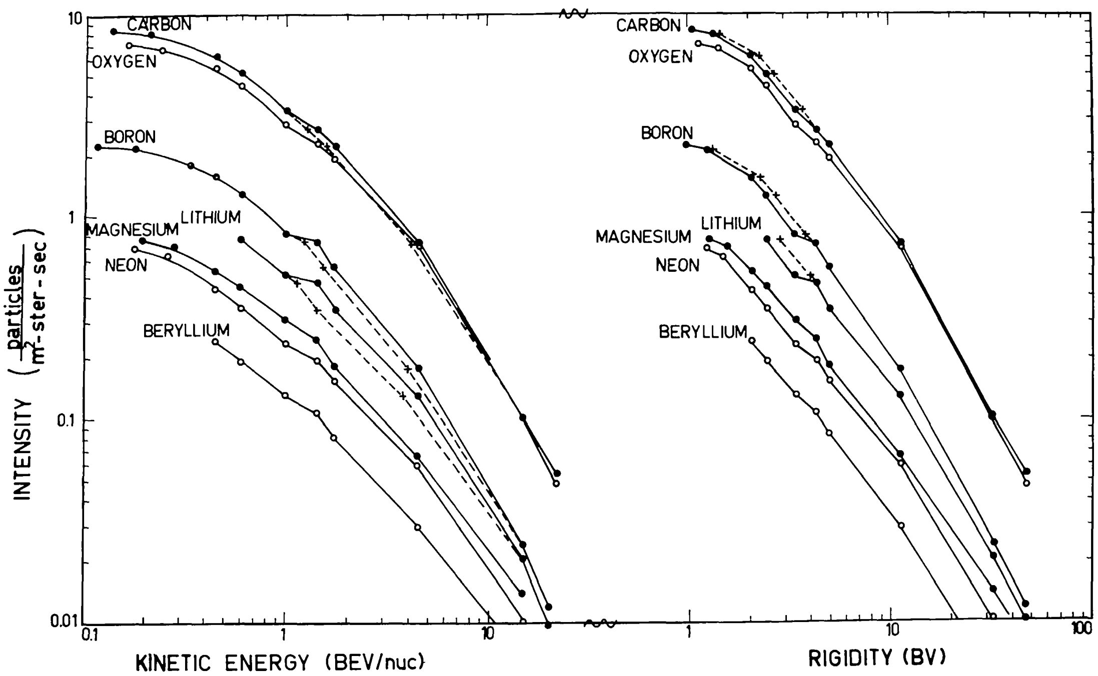

Fig. 9. Integral rigidity and kinetic energy/nucleon spectra of various charges from Li to Mg. Solid lines are spectra derived assuming $A/Z = 2.0$ for all charges. Dashed lines are spectra obtained using other values for A/Z as described in the text.

onto the low-energy part. If 2.0 is not the correct mass-to-charge ratio, the two parts of the spectrum will be displaced relative to one another by an amount which is dependent on the value for the correct mass-to-charge ratio. The spectra will be smooth and continuous only when the correct mass-to-charge ratio is used in converting from energy/nuc to rigidity. As we have noted earlier, substantial differences in the energy to rigidity conversion occur for the mass-to-charge ratios expected for L nuclei.

Consider first the kinetic energy/nuc spectra in Figure 9. Some charges in the cosmic radiation are believed to have mass-to-charge ratios = 2.0, e.g., O^{16}, Ne^{20}, Mg^{24}. The low-energy parts of the spectra for these charges (determined by the instrumental energy limits) are seen to fit smoothly on to the high-energy parts (determined by rigidity limits). Hence our use of a A/Z ratio = 2.0 seems to be the correct one for these charges and to confirm expectations based on cosmic abundance and theories of nucleogenesis.

The carbon spectrum is also seen to be smooth. However, it is thought possible that an appreciable fraction of cosmic-ray carbon could be C^{13} (Webber, 1967), thus altering the A/Z ratio. The dotted curve shows the alterations necessary for the assumption that all carbon is C^{13} with an A/Z ratio = 2.17. It is seen that the spectra obtained using this assumption are also smooth. However, the carbon abundance now becomes less than the oxygen abundance above 2 BeV/nuc. This transition, appearing just at the switchover point for the two types of measurements, is unrealistic and would seem to argue against the presence of a large fraction of C^{13} in the cosmic radiation. The measurement is certainly not definitive as to the C^{13}/C^{12} ratio but gives a measure of the uncertainties in determining the A/Z ratio using this approach. Allowing for the errors in the measurements we find (A/Z) C $=2.05 \pm 0.10$. The values of the A/Z ratio for O, Ne, and Mg are 2.0 ± 0.10.

Consider now the various light nuclei. Both the rigidity and energy/nuc spectra of Li and B nuclei have a very noticeable 'kink' in them if we assume the mass-to-charge ratio of these nuclei is $=2.0$. Clearly, then, this assumption is incorrect. The fragmentation cross-section measurements summarized by SHAPIRO and SILBERBERG (1967) suggest that for Li we may expect comparable abundances of the isotopes Li^6 and Li^7; in the case of B, B^{11} will predominate with a possible 10% admixture of B^{10} depending upon the fraction of Be^{10} that has decayed. Thus the expected A/Z ratios of these nuclei are expected to be very nearly 2.17 and 2.20 respectively. The dotted curves in Figure 9 show the spectra derived using values of 2.25 and 2.20 respectively for the A/Z ratio. The spectra obtained are more satisfactory – not only do they join smoothly at 1 BeV/nuc, but the shape is now similar to the known $A/Z = 2.0$ nuclei spectral shapes. From this we conclude that the A/Z ratio $= 2.25 \pm 0.10$ for Li and 2.20 ± 0.10 for B.

The Be spectrum is most interesting. This spectrum is completely in accordance with the assumption of an A/Z value $= 2.0$, and in fact, considering the errors on the individual measurements we conclude $A/Z = 2.05 \pm 0.10$ for Be. The fragmentation cross-section measurements summarized by SHAPIRO and SILBERBERG (1967) indicate that 80% of all Be should be Be^7. The remaining fraction will be Be^9 plus Be^{10}, again depending on the possible decay of Be^{10}. If Be^{10} has not decayed the expected A/Z value for Be nuclei is 1.90. On the other hand, if Be^{10} has decayed we expect $A/Z = 1.82$. These measurements indicate that there may be more Be^9 or Be^{10} than is suggested by the cross-section measurements. We will see later that Be on the whole appears to be 'overabundant' in cosmic rays as compared with expectations based on presently known fragmentation cross-sections. We believe that these features are not unrelated and suggest that the cross-section values used for the production of Be^9 or Be^{10} may be too low.

It should be pointed out that the errors involved in our determination of the mass-to-charge ratio of various nuclei using this approach embrace both uncertainties in the energy and rigidity intervals as well as the experimental uncertainties of the various intensity measurements. Systematic distortions of the energy and rigidity calibrations will effect the A/Z ratios deduced, however the fact that we observe the 'correct' A/Z ratios for a wide variety of charges strongly suggests that such distortions must be minor.

It should also be noted that these observations apply only to the energy range 1–2 BeV/nuc. Different mass-to-charge ratios may exist in other energy ranges.

B. SOLAR MODULATION EFFECTS

It is generally accepted that solar modulation will modify the spectra of nuclear species with equal mass-to-charge ratios in an identical manner. When evaluating solar modulation effects it is usually considered that all charges with $Z>3$ have a mass-to-charge ratio $=2$, and therefore changes in the ratios of heavier nuclei brought about by solar modulation are negligible. In general this is a reasonable argument; however, as we have seen, the L nuclei in particular, deviate markedly from this value. Indeed, the ratio $\varLambda_{\mathrm{Be}}/\varLambda_{\mathrm{Li}}=0.78$ is not much different than the value of 0.75 for this ratio, which applies to He^3/H^2! The solar modulation effects on the He^3/H^2 ratio are considered to be very important (Ramaty and Lingenfelter, 1968). Consequently, before we can attempt to make astrophysical deductions from the measurements and indeed to compare charge ratios measured at different times in the solar cycle, we must attempt to correct for the effects of modulation in the solar environment.

In the discussion to follow two aspects of the solar modulation are of importance. These are: (1) the functional (energy or rigidity) dependence of the modulation, and (2) the magnitude of the residual modulation existing at sunspot minimum.

The current state of our experimental understanding of these aspects has been reviewed most recently by Webber (1968) and we shall follow the conclusions reached therein.

M_A is taken to be the ln of the ratio of the intensity of species A at time t_1 to that at time t_2 both at the same energy/nucleon. The modulation M of a given species is usually described by the form

$$M=\frac{K(t_2)-K(t_1)}{D(\beta_1 P)}=\frac{\Delta K}{D(\beta_1 P)},$$

where $K(t)$ is a quantity depending on the level of solar modulation (sometimes called the modulation parameter), D is the diffusion coefficient, and P is the particle rigidity (see discussion in Webber, 1968). The functional dependence of the modulation is contained in the diffusion coefficient. Current measurements indicate that over the energy range in question D ranges from being $\sim\beta$ at low energies to $\sim\beta P$ at higher energies. Let us call $R_{AB}(t)$ the ratio of the differential intensities of species A and B at time t and at the same energy/nuc. Then the percentage change in R_{AB} with time is given by

$$\Delta=\frac{\Delta K}{\beta}\,\frac{(P_B-P_A)}{P_A\cdot P_B}\times 100\%$$

if $D\sim\beta P$ (provided $\Delta\leqslant 25\%$), where P_A and P_B are the rigidities of species A and B at the same velocity and are determined by the respective mass-to-charge ratios. R_{AB} thus depends on the solar modulation parameter and the difference in mass-to-charge ratios of the species in question. If $D\sim\beta$, then the ratio R_{AB} at the same energy/nuc will be unchanged by solar modulation and consequently $\Delta=0$.

In Figure 10 we show the variation of some of the L nuclei ratios with the level of solar modulation for the assumption that $D\sim\beta P$. Typical sunspot-minimum conditions are believed to correspond to values of $K(t)=0.5$ BV, sunspot-maximum conditions to $K(t)=1.5$ BV. The assumption that $D\sim\beta P$ is probably valid for the curves for 300 and 600 MeV/nuc, but results in an overestimate of the variation at 100 MeV/nuc, where the effective diffusion coefficient is more like β. Nevertheless, the variation of

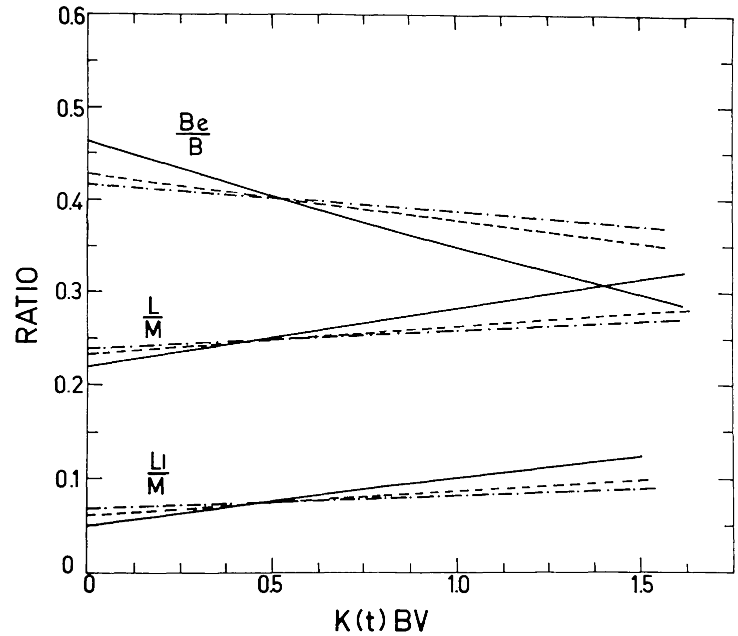

Fig. 10. Changes in the L/M, Be/B and Li/M ratios caused by solar modulation. Solid line refers to 100 MeV/nuc particles, the dashed line to 300 MeV/nuc particles, and the dot-dash line to 600 MeV/nuc particles. Modulation $\sim 1/\beta P$ is assumed which may result in an overestimate of the changes for 100 MeV/nuc particles.

certain ratios is indeed substantial at low energies, and in view of the increased precision of the measurements must be considered in comparing measurements made at different times in the solar cycle.

The 'demodulation' of the ratios observed at the earth to those representative of interstellar space is obtained by considering the solar radial dependence to be of the same form as the time dependence, and taking $\Delta K = 0.5$ BV, 0.5 BV being, as noted earlier, the best current estimate of the residual modulation parameter at sunspot minimum (Gloeckler and Jokipii, 1967). The resultant changes in the L/M and Be/B ratios at 300 MeV/nuc produced by demodulation effects are probably just below the present level of detectability. However, changes in the Be/Li ratio must be taken into account.

5. Interpretation of Measured Spectra and Ratios

A. The L/M Ratio

The most significant aspect of these measurements is the constancy of the L/M ratio from 120 MeV/nuc out to the highest energy we have measured, >22 BeV/nuc. The satellite measurements shown in Figure 4 indicate that this constancy probably extends down to 50 MeV/nuc. Above 2–3 BeV/nuc our measurements represent a new standard of accuracy and a considerable extension of the spectra to higher energies. At lower energies, particularly the 200–600 MeV/nuc range, a clear difference exists between our latest values for the L/M ratio and most earlier measurements. According to our previous discussion, this magnitude of difference cannot arise because of solar modulation effects. As we noted earlier, those reporting a high L/M ratio in this energy range generally obtain a sharply peaked spectrum of L nuclei. Although we do not feel competent to evaluate the emulsion measurements, we can state quite emphatically that our most recent counter-measurements represent a substantial improvement in accuracy over previous one (WEBBER and ORMES, 1967; MCDONALD and WEBBER, 1962) in this crucial energy range.

It is clear that our interpretation of the L/M ratio dependence on energy must be substantially different from those who report a peak in this ratio between 200–600 MeV/nuc. Calculations based on compilations of the relevant fragmentation parameters for the passage of heavier cosmic-ray nuclei through hydrogen (SHAPIRO and SILBERBERG, 1967; REAMES and FICHTEL, 1968) suggest that the L/M ratio should remain almost constant with energy if the material path length after acceleration is also constant with energy. The L/M ratio as a function of energy calculated by Reames and Fichtel is shown as a solid line in Figure 4, normalized to the data at 1 BeV/nuc. A number of important new laboratory measurements of fragmentation parameters are involved in these most recent calculations which considerably modify the previously calculated L/M dependence with energy. The amount of matter required to produce a L/M ratio$=0.25$ at 1 BeV/nuc is 3.6 ± 0.5 g/cm^2 of hydrogen. Although the calculated and measured variation of the L/M ratio with energy are not precisely the same, we do not believe the differences are significant at the present level of accuracy of the measurements and of the fragmentation parameters.

A number of suggestions have been made, principally on the basis of the earlier measurements of a high L/M ratio in the 200–700 MeV/nuc range, that the material path length of cosmic rays after acceleration is a function of energy* – possibly even being given by a function of the form $X = \beta X_0$, X_0 being the path length in g/cm^2 at high energies (DURGAPRASAD, 1967; BISWAS *et al.*, 1967). The L/M ratio we measure is incompatible with these suggestions. Indeed, taking our measurements of the L/M ratio, and the calculations which predict the essential constancy of this ratio with energy, at face value, and taking a simple path length as results from a one-dimensional diffusion for the propagation of the particles, we would say that this path length must be constant with energy to within $\pm 15\%$.

More complicated distributions of path length at a fixed energy have been invoked to explain a variation of L/M ratio with energy. These range from a Gaussian path-length (matter) distribution typical of three-dimensional diffusion (BALASUBRAHMANYAN *et al.*, 1965) to the exponential distribution suggested by COWSIK *et al.* (1967). The exponential distribution used by Cowsik *et al.* produces a marked variation in the L/M ratio with energy and is not in agreement with our results. A Gaussian distribution of path lengths with a value of the variance $\sigma \ll 1$, and a mean path length $\bar{X}$ constant with energy is compatible with our results.

* These arguments are based in part on the variation of the He^3/He^4 ratio with energy at low energies. A recent publication (RAMATY and LINGENFELTER, 1968) utilizing new calculations and cross-sections for the production of He^3 with energy concludes that the present experimental data on this ratio are also consistent with a path length constant with energy.

The above models presuppose that the passage through matter and the secondary production of the L nuclei takes place after the cosmic rays are accelerated and that the L nuclei we observe at a particular energy have been created at approximately this energy. It is possible that the passage through matter occurs simultaneously with acceleration as in an interstellar Fermi process. Or that acceleration occurs after passage through matter at much lower energies, possibly characteristic of localized source regions. In these circumstances the expectations based on interstellar fragmentation may be greatly modified.

The effects of a small amount of Fermi acceleration in interstellar space on the L/M ratio have been examined by REAMES and FICHTEL (1968). They find that the L/M ratio is decreased slightly at energies <200 MeV/nuc if the interstellar Fermi acceleration constant is taken to be a 'realistic' value of $\leqslant 10^{-15}$/sec. This might explain the decrease in the measured L/M ratio to 0.2 at ~ 60 MeV/nuc, although the errors in this measurement hardly warrant such a definitive conclusion at present.

KRISTIANSSON (1966) seems to be the first person to present arguments of substance which suggest that the passage of cosmic rays through matter might have occurred at a very low energy, possibly <100 MeV/nuc. His argument is based on the supposition that above a charge of 20 only iron nuclei are present in the source region. The charge distribution in the range $21 \leqslant Z \leqslant 25$ that is observed at the earth is then a result of fragmentation of these iron nuclei as they pass through 4 g/cm^2 of hydrogen, not at the energy at which we observe them but at a much lower energy. The strong energy-dependence of the appropriate fragmentation parameters enables Kristiansson to obtain a unique fit to the measured charge distribution obtained at energies >1 BeV/nuc only if the actual production has occurred at much lower energies. His argument assumes the complete lack of nuclei in this charge range initially in the source.

It would be reasonable to argue that this material is traversed in a localized source region, possibly during or before the acceleration process. In this case, the energy-dependence of the L/M ratio might no longer be directly related to the energy-dependence of the fragmentation parameters but to the details of the acceleration process as well. The relationship between the L/M ratio and the amount of matter traversed would depend on the fragmentation cross-sections at a much lower energy. Thus, while it would be possible to reproduce the observed L/M ratio it would not be possible to produce at the same time the observed relative abundances of Li, Be or B nuclei separately. This is because the fragmentation parameters for these nuclei change markedly with energy, whereas we have seen in Figure 4 this is not the case for the L nuclei as a whole.

B. THE Li/M, Be/M, B/M AND Be/B RATIOS

The L/M ratio just discussed cannot provide us with the type of information necessary to determine the energy at which matter traversal takes place. However, an examination of the separate ratios of the individual L nuclei to M nuclei presented in Figures 6 and 7 contains much more definitive information in this regard. To interpret this data we must determine the ratios to be expected on the basis of the presently known fragmentation parameters as compiled by REAMES and FICHTEL (1968) and SHAPIRO and SILBERBERG (1967). Using these parameters we have calculated the approximate expected ratios as a function of energy. This calculation is shown in Figures 6, 7, and 8, where the matter passage has been taken in the one-dimensional approximation and normalized to the value of 3.6 g/cm^2 obtained from the measured L/M ratio of 0.25.

It is seen from the figures that while there is general agreement between the predicted and measured ratios, important differences exist. These are most apparent in the measured Be abundance which appears to be significantly larger than expected from the fragmentation parameters. Also the abundance of Li seems to be lower at high energies than is predicted. These differences complicate the interpretation of the measured ratios.

Let us, however, examine the measured ratios individually and consider first B/M. Here the agreement is best between measurements and prediction between 100 MeV/nuc and 4 BeV/nuc. Above 4 BeV/nuc our measured boron abundance is lower than predicted. However, the experimental errors on these points are quite large. A test to determine whether the B nuclei have been produced at approximately the same energy we observe them would be to observe the expected increase in the B/M ratio at low energies. At present the cosmic-ray data are not precise enough to see this increase. However, if all B nuclei were produced at low energies and then accelerated, the B/M ratio at all energies should be close to the low-energy value of 0.18. This is not the case.

The most conspicuous feature of the Be/M ratio is the fact that in all cases the observed ratio is larger than that to be expected using the current fragmentation parameters. This discrepancy cannot be reconciled by assuming the matter traversal occurs at a low energy since the expected Be/M ratio varies only slightly with energy and is never larger than 0.04, whereas the mean of the data points is 0.042. The cross-sections for the production of Be^7, the dominant Be species, are presumably reasonably well known. However, the cross-sections for Be^9 and Be^{10} are neither well known nor large. As we have noted earlier, it is possible that these latter cross-sections are underestimated. In any case we believe that this difference between the measured and predicted Be abundance is significant and its resolution may provide a valuable insight into the cosmic-ray propagation problem.

Because of this problem regarding the Be abundance it is difficult to use our measured values of the Be/B ratio with energy to make definitive statements regarding the age of the cosmic rays. It is obvious from Figure 8 that this ratio is sensibly constant at a value 0.42 ± 0.03 from 100 MeV/nuc to at least 10 BeV/nuc. The expected Be/B ratio (no Be^{10} decay) should increase slowly with increasing energy from 0.2 to 0.3 as a result of the energy-dependence of the fragmentation cross-sections. In addition the decay of Be^{10} should make the high-energy value of this ratio 0.03–0.08 higher than that observed at lower energies (see Table II). A 'kink' of this magnitude is not evident in the data. It would be just at the limit of detection if it occurred at less than 10 BeV/nuc. The age of cosmic rays implied by these data is thus $>10^8$ years if the kink occurs at energies >10 BeV/nuc, or $<1 \times 10^6$ years if the kink occurs at <100 MeV/nuc. Of course, the smallness of this effect and the fact that it is superimposed on a Be/B ratio slowly increasing with energy due to the energy-dependent cross-sections could render it unobservable altogether and make the limits presented above meaningless. Until the reasons for the anomalous abundance of Be in the cosmic-ray beam are determined it is best to leave this method for evaluating the age of cosmic rays in abeyance.

Turning to the Li/M ratio we note, as in the case of B, a strong energy-dependence in the predicted ratio and therefore the possibility of determining whether or not Li is created at the energy at which we see it or possibly at a much lower energy. Here the measured Li/M ratio is best interpreted as being constant at a value $= 0.07 \pm 0.01$ between 100 MeV/nuc and 10 BeV/nuc. This is clearly less than the expected ratio at high energies. It is therefore not possible to observe the expected decrease at lower energies. The measured value for this ratio is certainly larger than the value of 0.04 to be expected if all Li were created at energies $\leqslant 100$ MeV, however.

To sum up, we would claim that on the basis of the measurements of the energy-dependence of the Li/M, Be/M and B/M ratios we see no evidence that these nuclei are created at much lower energies than we observe them at earth. On the other hand, the constancy of these ratios is not entirely in accord with the idea that these nuclei are fragmented at approximately the same energy at which we observe them. The strong energy-dependence of the Li/M and B/M ratios to be expected in this case is not observed.

Further, more accurate measurements of these light nuclei in cosmic rays and of the relevant fragmentation cross-sections are needed before these difficulties can be resolved.

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