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A COMPARISON OF THE ENERGY SPECTRA OF COSMIC RAY HELIUM AND HEAVY NUCLEI

T. T. VON ROSENVINGE and W. R. WEBBER
Physics Dept., University of Minnesota, Minneapolis, Minn., U.S.A.

and

J. F. ORMES*
Goddard Space Flight Center, Greenbelt, Md., U.S.A.

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Abstract. Recent observations of the spectra of cosmic ray helium, M, LH and VH nuclei in the energy range from $\lesssim 200$ MeV/nuc to > 22 GeV/nuc are reported. The differential spectra of all of these groups of nuclei are found to have a maximum at 300–400 MeV/nuc at sunspot minimum. The average exponents on the integral rigidity spectra in the range 5 to 50 GV are 1.54 ± 0.03 for He nuclei, 1.50 ± 0.04 for M nuclei, 1.47 ± 0.06 for LH nuclei and 1.40 ± 0.08 for VH nuclei. The spectra of these groups of nuclei are compared and it is found that the average He/M, He/LH and He/VH ratios are 16 ± 1, 70 ± 3 and 200 ± 15 respectively. These values are reasonably constant from the highest down to the lowest energies measured although some evidence for a 'dip' is present in the 500–1000 MeV/nuc range for both the He/LH and He/VH ratios. Solar modulation effects on these ratios are discussed and it is concluded that the ratios measured at earth are representative of those existing in interstellar space only if energy loss processes in interplanetary space are unimportant. The influence of interstellar propagation on the spectra and charge ratios at low energies arising from ionization energy loss and nuclear spallation during matter traversal is examined. It is found that propagation models that contain a large number of relatively short path lengths significantly modify the expected effects of ionization energy loss at low energies. Specifically it is suggested that the presently measured charge ratios are consistent with the passage of the average cosmic radiation through enough matter to reproduce the abundances of the so-called fragmentation nuclei, Li, Be, B and He^3. Two component models are not required to explain our data. Rather we feel that a better representation of the situation results from considering a continuous spatial distribution of sources which, along with the actual interstellar propagation conditions, leads to a particular distribution of matter path lengths. It is pointed out that large differences exist in the approaches used in the literature to calculate the effects of matter traversal in interstellar space at low energies. These differences play an important role in the interpretation of the experimental results. Significant modifications of the charge ratios at low energies can also be obtained by requiring that some of the matter traversal occur in the cosmic ray sources themselves during the cosmic ray acceleration process. This may be sufficient to produce charge ratios that are essentially flat at low energies even in the presence of interstellar ionization loss.

1. Introduction

Because of their high charge M$(6 \leqslant Z \leqslant 9)$ nuclei, LH$(10 \leqslant Z \leqslant 14)$ nuclei and especially VH$(Z \geqslant 20)$ nuclei should be sensitive indicators of the effects of ionization energy losses occurring during the passage of cosmic ray nuclei through matter. A study of the energy spectra of these nuclei and a comparison with the spectrum of nuclei of lower charge but similar charge to mass ratio, such as helium, is capable of providing

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* NASA-NAS post-doctoral fellow.

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unique information on the propagation and possibly the acceleration of the cosmic radiation.

Until recently the observed numbers of cosmic ray nuclei with $Z \geqslant 20$ have not been sufficient to permit a detailed study of their energy spectrum.

This situation has been remedied by contemporary counter (Webber and Ormes, 1967, Paper I) and emulsion (Freier and Waddington, 1968) studies of the VH spectrum. The agreement between these separate measurements is, in general, satisfactory, although both suffer from a paucity of measurements of the intensity of VH nuclei above 1.5 GeV/nuc. In the papers of Freier and Waddington where their impressive results on the VH spectrum were compared with other workers' measurements of the helium spectrum, the accuracy of the comparison is probably as much limited by the accuracy of the deduced helium spectrum as by uncertainties in the VH spectrum.

Observations of VH nuclei at still lower energies than could be reached in these balloon experiments ($\leqslant 200$ MeV/nuc) have also been reported from a satellite by Comstock *et al.* (1966, 1969) and a rocket (Reames and Fichtel, 1967). The rocket measurements give intensities that appear to be a reasonable extension of the higher energy balloon results, however the satellite observations give differential intensity values which are less than both of the balloon measurements by a factor of approximately 2 above 300 MeV/nuc. As a consequence, the satellite point at ~ 200 MeV/nuc must be treated with reserve. This is unfortunate, since the lowest energy VH nuclei measurements are most sensitive to the possible propagation and acceleration effects.

Although VH nuclei are the most sensitive indicators of the effects of ionization energy loss these effects should nevertheless be readily observable for M and LH nuclei as well. Measurements on these latter groups of nuclei can be made more accurately and to lower energies than for VH nuclei. Therefore they provide a useful confirmation of the VH data as well as enabling the systematics of any variations with charge to be examined.

We have recently extended our M, LH and VH nuclei measurements reported in Paper I, and have obtained 5 new integral intensity values above 1 GeV/nuc and extending out to >22 GeV/nuc. In addition the low energy parts of the M, LH and VH spectra have been measured more accurately than in Paper I. In this paper we shall compare these new measurements on M, LH and VH nuclei with our recent measurements of the helium spectrum covering the range from ~ 100 MeV/nuc to >24 GeV/nuc (Ormes and Webber, 1968). Much of this helium data has not been published previously. In most instances the helium, M, LH and VH nuclei spectra have been measured simultaneously thus eliminating the need to correct for the sometimes considerable effects of solar modulation.

2. Instrumentation and Balloon Flights

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

TABLE I

Balloon flight details

Date	Location	Instrument	Cut-off rigidity[a] (GV)	Altitude (g/cm^3)	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	195	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
1 Aug. 1964	Tucuman, Argentina	A[c]	12.1	6.9	57	2407
8 Aug. 1964	Tucuman, Argentina	A[c] (Rotating)	9.9[b] 14.3[b] 18.2[b]	5.8	96	2410

[a] Cut-offs determined using latest 2° × 2° world grid of Shea and Smart (private communication).

[b] Applies for measurements in the West, North-South and East pointing directions respectively. Average zenith angle = 40°.

[c] This instrument is described in Paper I.

Instrument I. This is basically a Cerenkov-scintillation counter telescope. It contains two thin scintillators which form the telescope coincidence, followed by a 15 cm dia. UVT lucite Cerenkov detector, subsequently followed by another (range) scintillator. The first three telescope elements are all pulse height analyzed using separate 2048 channel analyzers. 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 helium, M, LH and VH nuclei from ~100 MeV/nuc to 2 GeV/nuc. The Cerenkov threshold of 300 MeV/nuc for lucite, and the energy corresponding to a range of 8.8 g/cm^2 provide calibration points for the low energy nuclei. This 4-element system provided a substantial improvement in background supression and charge resolution over the earlier two element system upon which the results of Paper I 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.

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 $<40°$ 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 2-dimensional matrix of scintillator outputs.

Instrument III. This instrument is identical to II except that a 1.7 m long gas Cerenkov 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 Cerenkov threshold is obtained. In the two measurements with this instrument reported here, Freon gas was used at two atmospheres and one atmosphere pressure, giving effective thresholds of 15 and 22 GeV/nucleon respectively: (for helium these thresholds are 16 and 24 GeV/nucleon). 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, since the output of the gas Cerenkov detector is pulse height analyzed, the gas threshold energy can be rather clearly defined, particularly for heavy nuclei.

In the last analysis the ability to study the relative spectra of individual charges 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 of all events above the Texas cut-off for the charge range $Z = 10$–28 for the two Texas flights with instrument III is shown in Figure 1.

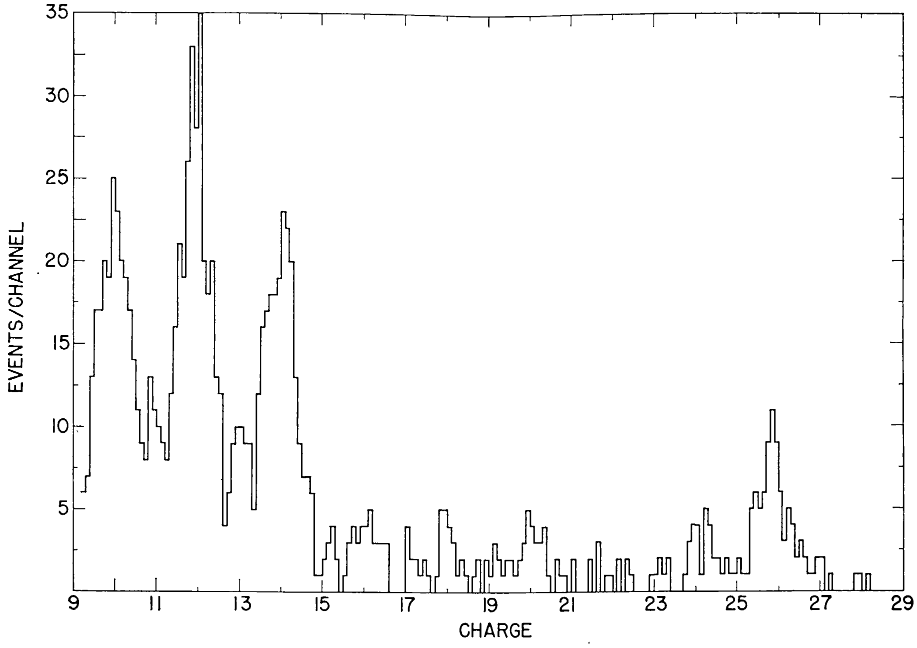

Fig. 1. Charge distribution of nuclei from $Z=10$ to 28 observed in Texas in May–June, 1967.

Similar charge resolution is obtained for the other flights including those at Ft. Churchill using instrument I.

3. Atmospheric Corrections

The observed intensities at balloon altitudes have been extrapolated to the top of the atmosphere using absorption mean free paths of 50 g/cm^2, 33 g/cm^2, 30 g/cm^2 and 16.5 g/cm^2 respectively for Helium, M, LH and VH nuclei as directly measured in air (Paper I). It is assumed that these mean free paths are energy independent following the work of Cleghorn (1967). The correction for ionization energy loss in the atmosphere has been applied separately. It should be noted that the mean depths of overlying matter were between 2.5 and 6 g/cm^2 for the various flights so that atmospheric corrections are not believed to be unduly serious.

4. Results

The helium and VH nuclei results are summarized in Table II. The total numbers of VH nuclei actually observed are also listed so that one may evaluate the statistical errors.

The differential energy spectra for these two nuclei are shown in Figure 2. The dashed curves represent the smoothed spectra (measured or deduced) used in the analysis of Freier and Waddington (1968). The published results of Comstock *et al.* (1966, 1969), and Reames and Fichtel (1967) on VH nuclei at low energies are also shown. In addition, there are measurements on VH nuclei by Bhatia *et al.* (1968) and Durgaprasad and Reames (1968) which provide valuable indications of the behaviour

TABLE II

Intensity of helium and VH nuclei (Epoch 1966)[a]

Energy or rigidity	He nuclei		VH nuclei
	(particles/m^2-ster-sec)		
190– 240 MeV/nuc	12.5 ±1[b]		–
240– 280 MeV/nuc	10.5 ±1[b]	(9)	0.050 ±0.018
280– 440 MeV/nuc	44.5 ±3[b]	(52)	0.195 ±0.03
440– 560 MeV/nuc	29 ±1.5[b]	(30)	0.146 ±0.03
560– 700 MeV/nuc	26 ±1.5[b]	(33)	0.155 ±0.03
700–1000 MeV/nuc	40 ±2.5[b]	(51)	0.230 ±0.036
> 1000 MeV/nuc	119 ±3[b]	(290)	0.64 ±0.05
> 15 GeV/nuc	4.63 ±0.3[c]	(8)	0.026 ±0.010
> 22 GeV/nuc	2.46 ±0.2[d]	(8)	0.015 ±0.006
> 3.20 GV	126 ±5	(39)	0.60 ±0.11
> 4.35 GV	91.5 ±2.0	(115)	0.445 ±0.04
> 5.00 GV	79.7 ±1.6	(163)	0.391 ±0.03
> 11.1 GV	25.1 ±0.8	(67)	0.135 ±0.015

[a] Mt. Washington neutron monitor = 2350.

[b] Derived from spectra presented by Ormes and Webber (1968).

[c] Effective threshold = 16 GeV/nuc.

[d] Effective threshold = 24 GeV/nuc.

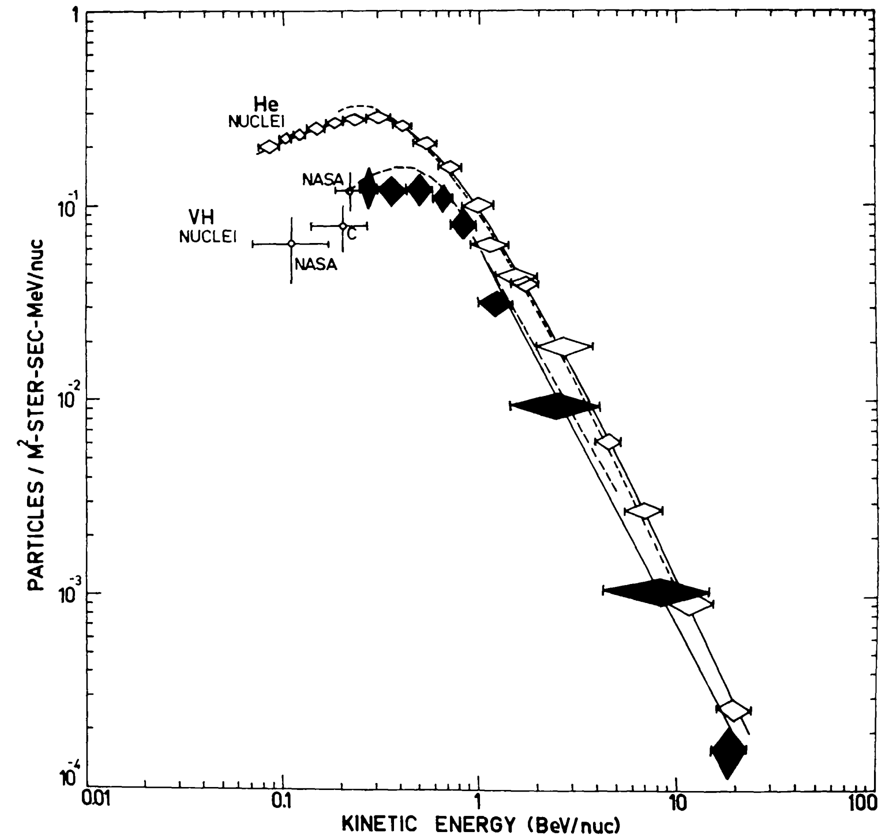

Fig. 2. Differential energy spectra of helium and VH nuclei (Epoch, 1966). Our data points shown as open and solid diamonds respectively. VH spectrum multiplied by 100. Dashed curves are the spectra of these nuclei used in the analysis of Freier and Waddington (1968). *N* represents the average of 1964–65 VH measurements of Reames and Fichtel (1967). *C* the measurement of Comstock *et al.* (1969).

of the VH spectra. These measurements are in good agreement with the more statistically accurate balloon measurements and are not shown in Figure 2. There are no major differences in the new spectra we present here and those used by Freier and Waddington. However, there are differences in detail as seen by a comparison of the

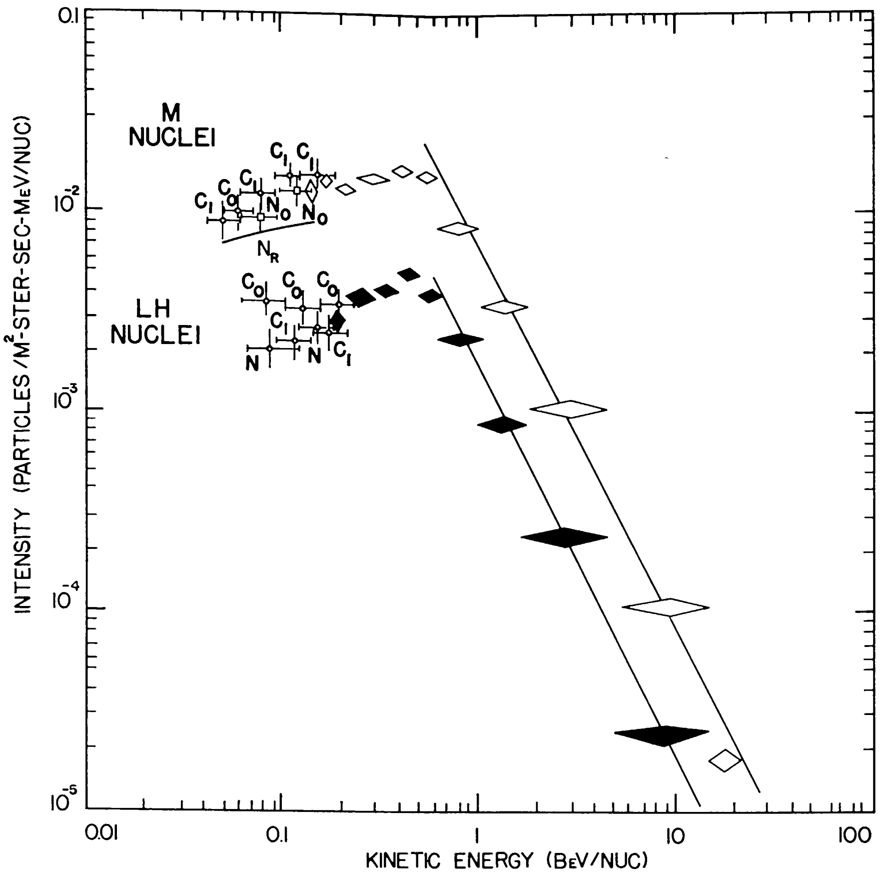

Fig. 3. Differential energy spectra of M and LH nuclei (Epoch, 1966). Our data points shown as open and solid diamonds respectively. Points labeled C_O are Chicago OGO-I results (Comstock *et al.* 1969); C_I are Chicago IMP-III results (Fan *et al.* 1968); N_R are NASA rocket results (Reames and Fichtel, 1967); N are NASA satellite results (Balasubrahmanyan *et al.*, 1966); and N_O are NASA OGO-I results (Hagge *et al.*, 1968).

dotted and solid lines in Figure 2. These lead to an appreciable difference in a comparison of the two spectra, particularly at low energies.

The differential spectra of M and LH nuclei obtained in this study are shown in Figure 3. The satellite results of Comstock *et al.* (1966, 1969), Balasubrahmanyan *et al.* (1966) and the rocket observations of Reames and Fichtel (1967) are also shown at low energies.

The integral rigidity spectra for helium and VH nuclei are shown in Figure 4, and for M and LH nuclei in Figure 5. Above 5 GV rigidity the exponents on these spectra are: helium nuclei = 1.54 ± 0.03, M nuclei = 1.51 ± 0.05, LH nuclei = 1.47 ± 0.06, VH nuclei $= 1.40 \pm 0.08$. In deriving these spectra a mass to charge (A/Z) ratio of 1.95 is taken for helium nuclei, 2.00 for M and LH nuclei and 2.15 for VH nuclei.

The ratios of the differential energy spectra of helium and VH nuclei are shown in Figure 6. The earlier results obtained on this ratio by Freier and Waddington (1968) are also shown in this figure. The peculiar 'kink' at 600–800 MeV/nuc which appears in their results and complicates the interpretation of the energy dependence of this ratio, is still present to some extent in our data. Our more detailed measurements at higher energies permit a clearer picture of the overall variation of this ratio to be obtained, however.

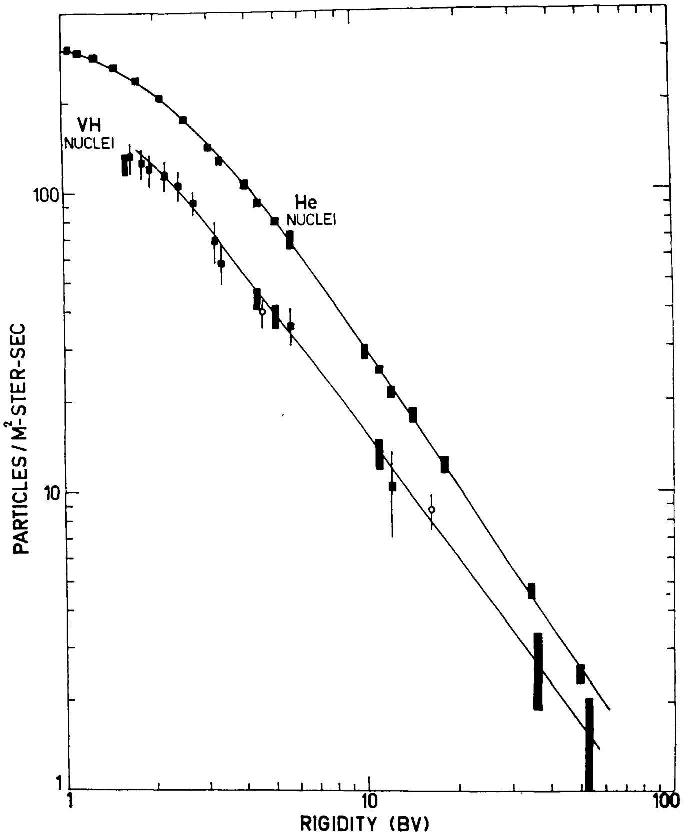

Fig. 4. The integral rigidity spectra of helium and VH nuclei (Epoch, 1966). VH spectrum is multiplied by 100. Helium and VH data from this experiment shown as solid rectangles, VH data from Paper I as solid squares with error bars. Instrumentally determined energies below 1 GeV/nuc adjusted to rigidities using a mass/charge ratio = 2.0 for He and 2.15 for VH nuclei. Freier and Waddington (1968). VH measurements shown as open circles.

In Figures 7 and 8 we show the He/M and He/LH ratios obtained in the series of measurements. Note that in the case of the He/LH ratio there is a 'kink' at ~400 MeV/nuc similar to that appearing in the He/VH ratio at ~700 MeV/nuc. This 'kink' is not apparent in the He/M ratio, however.

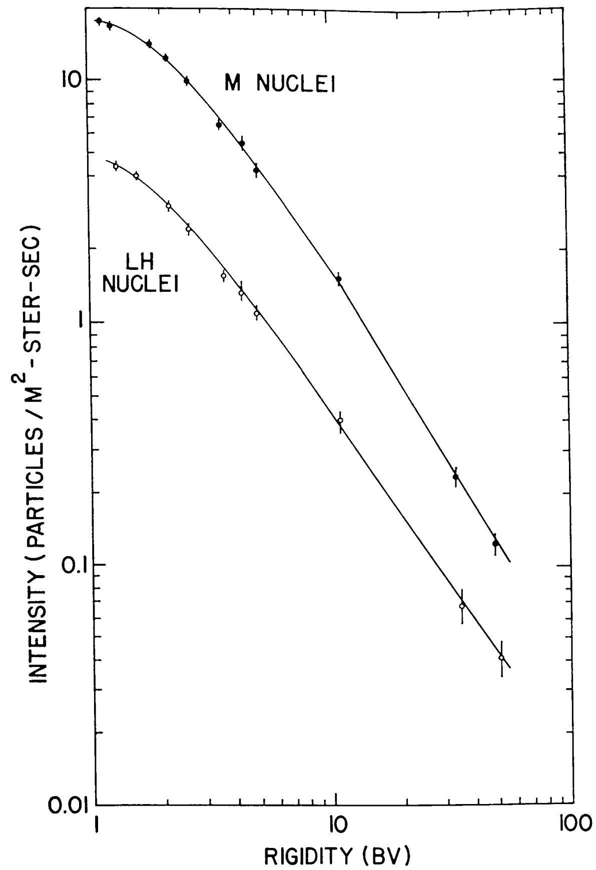

Fig. 5. The integral rigidity spectra of M and LH nuclei (Epoch, 1966). M nuclei data shown as solid circles, LH nuclei data as open circles. Instrumentally determined energies below 1 GeV/nuc adjusted to rigidities using a mass/charge ratio = 2.0 for M and LH nuclei.

5. Solar Modulation Effects

The differential spectra and ratios just presented represent the situation at the top of the atmosphere. Before we can make astrophysical deductions from the measurements we must attempt to correct for the effects of modulation in the solar environment. We do not have a completely adequate theory of solar modulation that will permit us to demodulate the respective spectra to obtain the spectra existing in interstellar space. It is generally accepted that the spectra of nuclei with the same A/Z ratio will be modified identically by the modulation process. The nuclei we are concerned with here have A/Z ratios which are different in some case and therefore solar modulation effects may distort the relative spectra. By simultaneously measuring the spectra of helium and heavier nuclei we have eliminated a source of distortion inherent in comparisons of these nuclei at different levels of solar modulation. However, residual solar modulation effects operative at the time of measurement cannot be removed by this procedure and indeed have not been considered in earlier discussions of the charge ratios.

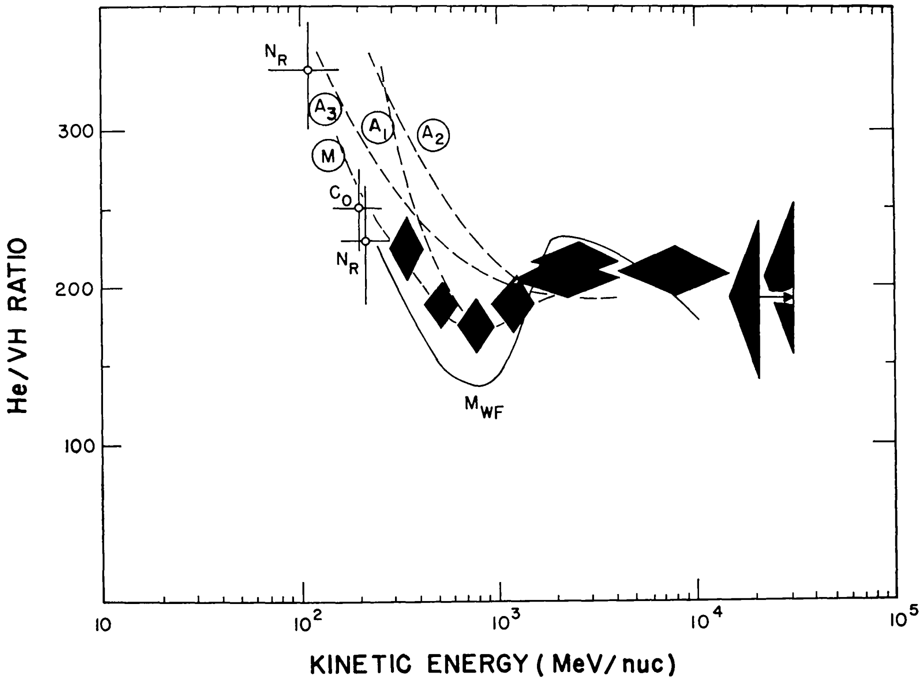

Fig. 6. The ratio of helium to VH nuclei as a function of energy. Our data points shown as solid diamonds. The explanation of the data symbols is as follows: C_0, Chicago OGO-I results (Comstock *et al.*, 1969), N_R, NASA rocket results (Reames and Fichtel, 1967), M_{WF}, smoothed curve through Minnesota results of Freier and Waddington (1968). Theoretical dashed curves A_1, A_2, and A_3 are from the work of Fichtel and Reames (1968) as described in the text. Dashed curve M is the calculation for a slab length $= 4$ g/cm^2 (equal total energy spectra) by Waddington and Freier (1968).

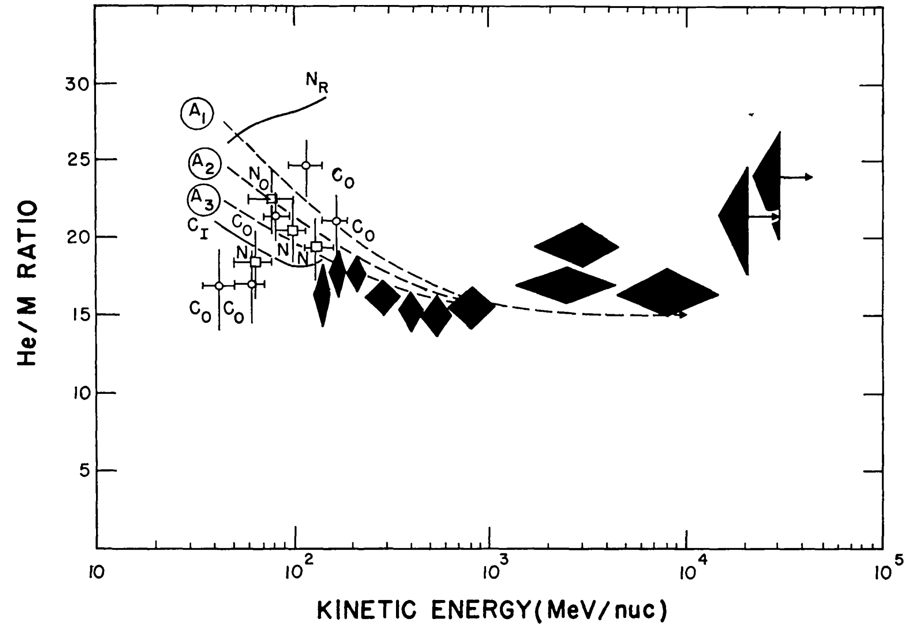

Fig. 7. The ratio of helium to M nuclei as a function of energy. Our data points shown as solid diamonds. The explanation of the data symbols is as follows; C_I, Chicago IMP-III results (Fan *et al.*, 1968); C_0 Chicago OGO-I results (Comstock *et al.*, 1969), N_R, NASA rocket results (Reames and Fichtel, 1967), N, NASA satellite results (Balasubrahmanyan *et al.*, 1966) and N_0, NASA OGO-I results (Hagge *et al.*, 1968). Theoretical dashed curves A_1, A_2 and A_3 are from the work of Fichtel and Reames (1968) and are described in the text.

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Two aspects of the solar modulation are of importance in the 'demodulation' of the spectra measured at Earth to those existing in interstellar space. They 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.

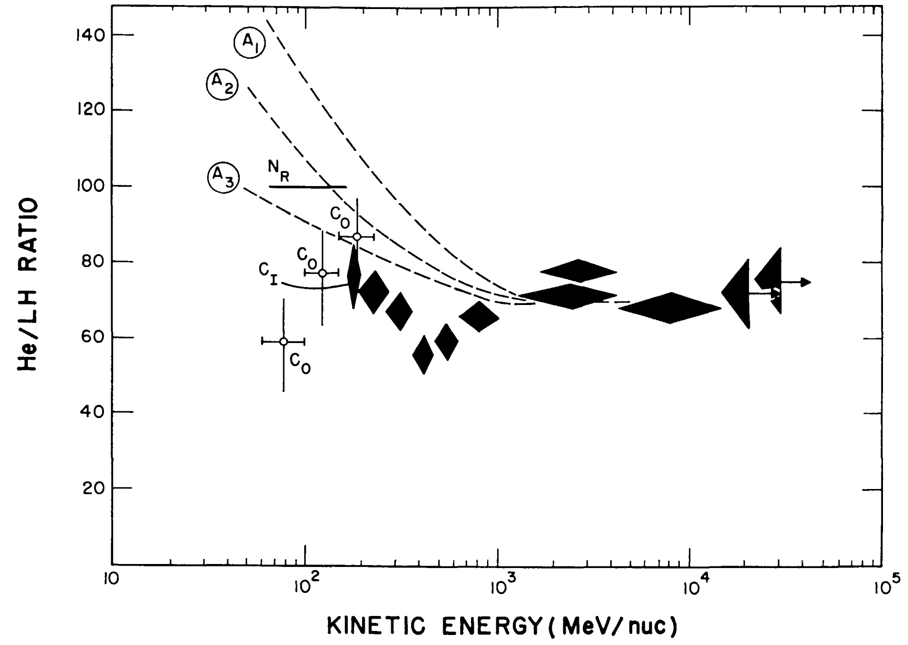

Fig. 8. The ratio of helium to LH nuclei as a function of energy. Our data points shown as solid diamonds. The explanation of data symbols and theoretical ratios is the same as in Figure 7.

The modulation M of a particular nuclear species is taken to be the ln of the ratio of intensities of that species at times t_1 and t_2 at a given kinetic energy/nucleon. Let us call $R_{AB}(t)$ the ratio of the differential intensities of species A and B at time t also at the same kinetic energy/nucleon. The modulation of a given species is described in the usual diffusion convection picture by a form $M = K(t)/D(\beta, P)$ where $K(t)$ is a quantity describing the level of the solar modulation (sometimes called the modulation parameter), D is the diffusion coefficient and P is the particle rigidity. The functional dependence of the modulation is contained in the diffusion coefficient. It is easy to show that velocity dependent solar modulation (e.g. $D \sim \beta$) will not change the ratio R_{AB}. Measurements indicate that above ~200 MeV/nuc the functional dependence of the diffusion coefficient is more closely $\sim \beta P$. The rigidity dependent factor will result in the ratio R_{AB} changing with the level of solar modulation. We have calculated this change for a residual modulation parameter, $K_R = 0.6$ GV, which is believed to be representative of the value necessary to demodulate spectra measured in 1965–66 at Earth to those existing in interstellar space (Gloeckler and Jokipii, 1967). The increase in the He/VH ratio that results is 3% at 600 MeV/nuc, 8% at 200 MeV/nuc and

15% at 100 MeV/nuc. The effects are less for the He/M and He/LH ratios because of their more nearly identical mass to charge ratios. These modifications are comparable to or less than the experimental errors in the ratios themselves and we have therefore not adjusted the ratios near the Earth shown in Figures 6, 7 and 8 for this effect.

It has been pointed out by Webber (1968) that certain experimental data are not in agreement with the predictions of the diffusion–convection model for the modulation of cosmic rays. Indeed a recent paper by Gleeson and Axford (1968) has investigated this problem and develops a modulation picture in which the effects of energy loss apparently determine the solar modulation. The predictions of such a model with regard to the variation of the respective charge ratios are substantially different than in the diffusion–convection picture where it is assumed that we are seeing particles at earth at the same energy at which they exist in interstellar space. These differences will be more pronounced at lower energies. According to Gleeson and Axford (1968) the energy loss corresponding to the residual modulation at sunspot minimum may be $\sim$100 MeV/nuc. Particles of 200 MeV/nuc observed at earth might then correspond to 300 MeV/nuc particles in interstellar space (i.e. the ratios of Figures 6, 7 and 8 would be shifted $\sim$100 MeV/nuc to the right to be representative of interstellar space). Propagational effects on the He/M, He/LH and He/VH ratios at low energies such as ionization energy loss that could be detectable in interstellar space might then be unobservable at Earth since we would be unable to see the appropriate energy particles.

At this stage of our understanding of the solar modulation process it is not feasible to make more detailed calculations based on the above hypotheses. It should be obvious that uncertainties in both the magnitude and functional dependence of the residual solar modulation are considerable and it is conceivable that the modifications of the charge ratios at low energies may not be negligible. This is certainly true in the case of the actual spectra themselves where residual modulation effects may completely alter the shape of the low energy portion of the spectra. For this reason we shall emphasize a study of the He/M, He/LH and He/VH ratios rather than a discussion of the features of the individual spectra themselves.

For the purpose of further discussion we shall consider the ratios presented in Figures 6, 7 and 8 as representative of those existing in interstellar space. We shall now consider briefly their interpretation.

6. The He/M, He/LH and He/VH Ratios and the Propagation of Cosmic Rays through Matter in Interstellar Space

It has been generally argued that heavy cosmic ray nuclei must have travelled through an average of 4 g/cm^2 of matter (taken to be interstellar hydrogen) (e.g. Shapiro and Silberberg, 1967; Beck and Yiou, 1968). This argument is based on measurements which show a substantial intensity of light nuclei (Li, Be, B) in cosmic rays. These light nuclei can be regarded as products of the fragmentation of heavier nuclei as they pass through matter. Calculations based on the observed intensities of other 'fragmentation' nuclei such as H^2 and He^3 lead to the same conclusion; that cosmic rays in general must have, at some time in their lifetime, passed through ~ 4 g/cm^2 of matter.

The effects of the passage of low energy heavy nuclei through the equivalent of 4 g/cm^2 of matter without a concurrent energy gain process are profound indeed. The enormous rate of energy loss by ionization of these heavy nuclei relative to helium will severely depopulate the low energy part of the spectrum and cause the initial He/M, He/LH and He/VH ratios to increase markedly at low energies. The problem then becomes how to reconcile the observed charge ratios at low energies which do not exhibit a sharp increase and therefore seem to suggest that only a small amount of matter is traversed and the measurements of the absolute abundance of fragmentation nuclei which imply passage through considerable matter.

The expected increase in the charge ratios depends importantly on the characteristics of the propagation of cosmic rays in interstellar space. It also depends on the initial or injection spectra which might not be identical. To make the problem tractable it is usually assumed that all charge species initially have the same spectra. Furthermore this spectrum is usually assumed to be a power law in total energy. In this way the effects of propagation may be examined separately.

The cosmic ray propagation problem has recently been treated in a comprehensive manner by Fichtel and Reames (1968). These authors have examined the effects of certain simplified propagation models on the various charge ratios. They solve the fundamental transport (diffusion) equation of cosmic rays in the galaxy including the effects of energy loss by ionization and fragmentation due to nuclear interactions. They consider certain limiting path length (material) distributions based on specific boundary conditions. Three path length distributions they consider seem to be appropriate for a comparison with the data. All of these distributions will as a first requirement reproduce the observed abundance of the 'fragmentation' nuclei Li, Be and B.

The first distribution is the simple slab length approximation in which all particles of a given energy traverse the same amount of matter, a δ-function approximation. The expected charge ratios when the matter thickness $= 4$ g/cm^2, constant with energy are shown as curves A_1 in Figures 6, 7 and 8. Here the full effects of matter traversal at low energies are observed, the resulting ionization loss causing the charge ratios as shown in these figures to increase rapidly at low energies. The data are clearly inconsistent with this type of path length distribution – indeed only a small fraction of the matter traversal (< 1 g/cm^2) could actually occur in interstellar space on this picture.

The second type of path length distribution arises from a point source diffusing into an infinite medium. This produces a roughly gaussian path length distribution for particles of a fixed energy. This smearing of path lengths tends to destroy the features of the charge ratios which depend on the specific energy dependence of the nuclear spallation cross sections (cf. the He/VH ratio in Figure 6). The expected charge ratios when the average of this gaussian distribution is 4 g/cm^2, constant with energy, are shown as curves A_2 in Figures 6, 7 and 8. The increase in the ratios at low energies is not as pronounced because of the existence of an appreciable fraction of short path lengths. However, the data is still, generally speaking, not in good agreement with such a path length distribution.

The third path length distribution arises from a uniform spherical distribution of sources with the sun at its center. Cosmic rays then diffuse throughout this region. The expected charge ratios when R_0^2/λ (R_0 = radius of region, λ = mean free path for diffusion) = 9.3 g/cm^2, constant with energy are shown as curves A_3 in Figures 6, 7 and 8. Here the distribution of path lengths is strongly weighted towards short path lengths, hence the increase in the ratios at low energies is least of all. In fact this model gives a reasonable fit to the measurements for all three charge ratios, He/M, He/LH and He/VH.

At this point it is certainly relevant to comment on the experimental errors inherent in the measurements of the charge ratios at low energies. In view of the large differences obtained by various observers (e.g. values of the He/M ratio range from 17 to >25*, values of the He/LH ratio from 60–100, at energies <200 MeV/nuc) it is clear that these uncertainties are substantial. This definitely complicates the interpretation of the results.

The third model discussed above is probably the most realistic from the point of view of our current understanding of the cosmic ray origin-propagation problem and the magnetic field structure of the galaxy (e.g. Davis, 1962; Ginzburg and Syrovatskii, 1964) although it does not represent a completely acceptable picture of this situation by any means. This model serves to illustrate the importance of considering a *distribution* of sources, however, and clearly represents a model which provides a path length distribution skewed to short path lengths. As such it minimizes the increase in charge ratios at low energies due to ionization energy losses.

This path length distribution will predict a decrease in the expected *L*/*M* ratio at low energies because of the preponderence of short path lengths. The curves presented by Fichtel and Reames (1968) show that the *L*/*M* ratio should decrease from ~0.29 at 4 GeV/nuc to 0.18 at 100 MeV/nuc. We believe that the data on the *L*/*M* ratio presented by Von Rosenvinge *et al.* (1969) is not inconsistent with such a decrease. Thus we believe that all of the current data on the spectra and relative abundance of helium and heavier nuclei can be explained in terms of Fichtel and Reames' model 3 or some other model of source distribution and propagation characteristics that results in a similar path length distribution.

The path length distribution arising from model 3 of Fichtel and Reames is in fact quite similar to the exponential path length distribution model suggested by Cowsik *et al.* (1967). The Cowsik model is equivalent to considering propagation in a bounded medium and will contain an even larger fraction of short path lengths. Obviously the charge ratios at low energies will be even less effected by ionization energy loss;

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* For example Comstock *et al.* (1969) from data taken aboard the OGO-I satellite find a He/M ratio actually decreasing markedly at low energies, whereas Fan *et al.* (1968) on the Imp-III satellite present an He/M ratio almost constant with energy. Moreover neither of these sets of ratios are consistent with those obtained on a rocket by Reames and Fichtel (1967) or reported by Hagge *et al.* (1968) (see Figure 7 for data points).

however, the variation of the L/M ratio to be expected at low energies is now too extreme to be consistent with the data on this ratio presented by Von Rosenvinge *et al.* (1969). This model must therefore be rejected on this basis.

Comstock (1969) has examined the variation of the charge ratios at low energies using OGO-I data only and Waddington and Freier (1968) have examined the variation of the He/VH ratio over a wide range of energies. All of these workers consider that a sharp increase in these ratios should be observed at low energies as a result of ionization energy loss. The data presented by these workers does not exhibit the expected increase (in broad agreement with our results). In both instances the authors have suggested, however, that the reason for this is the presence of a more or less well defined 'second' component of cosmic rays at low energies. It is postulated that this 'second' component traverses very little matter – hence no upturn in the charge ratios at low energies – and also has the proper chemical abundances and energy spectra to fit smoothly onto the known spectra for the high energy component.

We would like to draw attention to several differences between the calculations in the above papers and those of Fichtel and Reames regarding the propagation of cosmic rays in interstellar space and to consider alternatives to the approaches which lead to the two component models. The first point deals with the procedure used by both Comstock (1969) and Waddington and Freier (1968) for the calculation of the effects of ionization energy loss. Both of these papers consider a δ-function, or slab approximation, for the path length distribution. One would expect, then, that this calculation would be similar to model 1 developed by Fichtel and Reames (1968). There are important differences in the two sets of calculations, however. Fichtel and Reames solve a 3-dimensional transport equation, in the case of model 1 with the somewhat artificial condition of a δ-function path length distribution. The calculation of the change in spectrum due to ionization energy loss made by Comstock (1969) and Waddington and Freier (1968) is a one-dimensional slab length approximation. Waddington and Freier carry their calculation no further than this while Comstock goes on to integrate the solutions over one-dimensional Gaussian and exponential path length distributions.

The difference between the one dimensional and three dimensional slab approximations is quickly realized by considering an example. Energy loss by ionization is a dissipative process. A simpler energy loss process to consider, for the sake of an example, is that in a (conservative) electric field. Suppose therefore that there is a one-dimensional electric field (corresponding to a positive potential V) between the source and the observer. Following the reasoning of the slab approximation, we find that $j_{\text{OBSERVER}}(E-ZeV/A)=j_{\text{SOURCE}}(E)$. This is Liouville's theorem for one dimension. On the other hand, Liouville's theorem for three dimensions tells us that

$$\frac{j_{\text{OBSERVER}}(E-ZeV/A)}{p^2(E-ZeV/A)}=\frac{j_{\text{SOURCE}}(E)}{p^2(E)}=\text{constant}$$

in this case the observer spectrum is multiplied by an additional factor $[p^2(E-ZeV/p^2(E)] < 1$. The effects of energy loss on the spectra are amplified by this factor. At low energies, since $p^2 \sim E$, the spectral change calculated using the one-dimensional and 3-dimensional approaches will differ by a factor $\sim E$. A comparison of curves A_3 and M in Figure 6, which differ by a factor $\sim 1/E$ at low energy, shows that this additional factor is also apparently contained in the dissipative calculations as well.

Comstock then goes on to integrate the one-dimensional solutions over a distribution of path lengths. There are two problems to this approach: (1) Given a particular geometrical model, what is the proper distribution of path lengths? (2) Is the 3-dimensional Liouville's theorem (dissipative case) in fact satisfied? Comstock in no way addresses himself to either problem but merely considers two hypothetical path length distributions. The advantage of the Fichtel and Reames method is that Liouville's theorem in three dimensions is automatically satisfied (it is the starting point) and the machinery for obtaining the correct distribution of path lengths is also set up directly.

In order to justify a one-dimensional calculation one has to believe that during the propagation of cosmic rays they are rigidly tried to the galactic magnetic field lines with essentially no diffusion. Davis (1962) has studied this possibility and in fact presents arguments in favor of a highly 'ordered' motion of this type. It is therefore possible that the one dimensional approach used by Comstock (1969) and Waddington and Freier (1968) is more nearly correct. The limitation in the approach of these authors is therefore not so much in the type of propagation considered but that they do not consider realistic distributions of path lengths arising from a specific source distribution-magnetic field configuration. They have considered very specialized situations. The results of Fichtel and Reames (1968) show that the changes in charge ratios at low energies depend importantly on the characteristics of the propagation and of the source distribution itself.

We believe therefore that the difficulties Comstock and Waddington and Freier try to explain by a two component model are more readily understood in terms of a continuous path length distribution. It should be emphasized that a continuous spatial distribution of sources may be as important in determining this path length distribution as the actual propagation conditions themselves.

Before completing our discussion we should like to consider a further alternative to understanding the behavior of the various charge ratios at low energies.

If the ratios presented in Figures 6–8 are indeed found to remain essentially flat or even turn down at the very lowest energies (<100 MeV/nuc) then apparently this behavior cannot be completely explained by path length distribution considerations either in a one-dimensional or a three-dimensional approach. In this case two distinct component source models such as suggested by Comstock (1969) and Waddington and Freier (1968) are certainly an alternative explanation, however a simplier alternative is to retain a basic one component source model and allow for some traversal of matter in the source region itself. Under certain conditions, placing a fraction of the matter in the cosmic ray source is equivalent to providing for a preferential acceleration of heavier nuclei at lower energies. This arises when $(\mathrm{d}E/\mathrm{d}t)_{\text{acceleration}}$ is only slightly larger than $(\mathrm{d}E/\mathrm{d}t)_{\text{ionization loss}}$ for the highest charges accelerated. In this situation VH nuclei are not accelerated as rapidly to higher energies as are He nuclei. Energy loss by ionization does not depopulate the low energy end of the VH spectrum either. The net effect is an excess of VH nuclei relative to He at energies just above the injection energy as compared to the situation at high energies.

The mechanics of such a situation for a Fermi-accelerated total energy spectrum in the source have been discussed by Ramadurai (1967), who has illustrated the modification brought about. One of us (T. T. von Rosenvinge) is presently considering models in which some but not all of the material traversal occurs in the sources during acceleration and effectively obliterates the effects of ionization loss.

7. Summary and Conclusions

The results of this paper may be summarized as follows:

(1) We find the He/M, He/LH and He/VH ratios are essentially constant with energy in the range >100 MeV/nuc up to >22 GeV/nuc. A 'dip' that may be significant occurs in the He/LH and He/VH ratios at 500–1000 MeV/nuc. The average ratios above 100 MeV/nuc are 16 ± 1, 70 ± 3 and 200 ± 15 respectively. Large uncertainties (discrepancies), previously not pointed out, exist in the data on the charge ratios at lower energies as obtained on satellites.

(2) It is argued that solar modulation effects will not appreciably alter these charge ratios above a few hundred MeV/nuc. At lower energies the interstellar ratios could be considerably altered if the solar modulation can be described in terms of an energy loss. This might make an upturn that is present in interstellar space unobservable at earth.

(3) The influence of interstellar propagation on the changes in the relative spectra at low energies arising from ionization energy loss during matter traversal has been examined. Propagation models that contain a large number of relatively short path lengths significantly modify the expected effects of ionization energy loss at low energies. Specifically it is found that the presently measured constancy of charge ratios is consistent with the passage of the average radiation through considerable matter. At the present time 'two' source models are not required to explain this data and it seems to us more appropriate to think in terms of a spatial distribution of sources.

(4) It is pointed out that large differences exist in the approaches used in the literature to calculate the effects of matter traversal at low energies. These differences play an important role in our understanding of the propagation of cosmic rays and in our interpretation of the experimental results.

(5) Significant modifications of the charge ratios at low energies can be obtained by requiring that some of the matter traversal occur in the cosmic ray sources during the cosmic ray acceleration process. This may be sufficient to produce charge ratios that are essentially flat at low energies even in the presence of interstellar ionization loss.

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