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Some implications of the relative spectra of the different charge components in the primary radiation*

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Abstract. In accompanying papers we have presented the differential spectra of the individual charge components—protons through heavy nuclei—measured at different levels of solar modulation from 1963–1965. Utilizing the fact that the solar modulation affects particles of different charge-to-mass ratio in such a way that the ratio of intensities in differential rigidity intervals are not changed, we are able to compare the relative spectra prior to solar modulation. This comparison suggests the following: (i) The relative spectra of protons and helium nuclei are most reasonably interpreted in terms of identical rigidity spectra at the 'source' rather than energy/nucleon spectra. The large increase in P/He (P) ratio at low rigidities may in large part be due to production of secondary protons as well as ionization loss in the interstellar medium. (ii) The variation of the P/He, L/M and He/M ratios with energy can be interpreted in terms of ionization loss of the primary radiation moving through an amount of material which monotonically decreases with increasing energy. (iii) The spectra of heavy nuclei above 3 GV systematically become steeper with increasing charge.

In accompanying papers (SPEC 12, 13) we have presented the rigidity spectra of the charge components in the primary radiation—measured from about 1-16 GV. These spectra have been measured at different levels of solar modulation. Analysis of this modulation shows that it affects particles of different charge (charge-to-mass ratio) in such a way that the ratios of intensities in differential rigidity intervals are not changed whereas the relative differential energy per nucleon ratios are changed. We shall use this fact throughout the remaining discussion whenever the effects of the solar modulation are to be considered and shall proceed to a study of the astrophysical significance of the relative unmodulated spectra of the different charge components.

Considering the protons and helium nuclei first, figure 1 shows the ratio of the differential rigidity spectra of these two components between 0.8 and 16 GV. Figure 2 shows the equivalent ratios for the differential energy/nucleon spectra between the corresponding limits. It is apparent that the ratio P/He (P) is sensibly constant, at a value of approximately 8, above about 1.5 GV, increasing rapidly at lower rigidities to a value of about 50 at 0.75 GV, whereas the ratio P/He (E) seems to vary continuously over our range of measurement—from a value of about 5 at the lowest energies to about 20 at the highest energies. At even higher energies the very limited available data suggests that P/He (E) is more or less constant with a value of about 20 (Waddington 1960).

The results on the solar modulation suggests that P/He (P) remains constant during this process so that we may regard the measurements in figure 1 as appropriate to the unmodulated beam as well. As can be seen, however, P/He (E) changes with modulation. In order to estimate what these unmodulated ratios might be we need to know the degree of modulation at sunspot minimum. Lacking this, we can still determine (from the known energy dependence of the modulation and the measured ratios) that the solar modulation process can never produce P/He (E) = constant. Furthermore, unless we are seeing only a small fraction (<50%) of the true galactic particles at energies of about 1-2 GeV per nucleon the variation of P/He (E) that is seen must be close to that present in the unmodulated beam and certainly then P/He (E) is not a constant.

There are a number of different explanations for the behaviour just described. First, if the spectra of these components are viewed in terms of energy/nucleon spectra, as is the common assumption today, then it seems that the P/He (E) ratio at the 'source' must be almost identical to the measured ratio above about 1 GeV per nucleon since the effects of interstellar propagation on this ratio are believed to be minor in this energy range. For example, if a Fermi type acceleration in interstellar space were dominant and invoked to produce a changing ratio with energy, the differences in spectra arising from such a process would be expected to be much less pronounced than are actually observed. As a result, we are left with the assumption that the 'source' spectra are different on an energy/nucleon basis.

If the spectra are viewed in terms of rigidity, however, the following picture emerges. The observed constancy of P/He (P) above 1.5 GV is then a reflection of identical rigidity spectra leaving the source region and subsequently relatively unaffected by interstellar propagation. The rapid increase in P/He (P) below 1.5 GV then reflects a number of interstellar processes, the most common assumption being different rates of energy loss by ionization (at the same rigidity) in the interstellar medium. The rapidity of the increase in P/He (P) cannot be explained by ionization loss where the path length is constant with energy, however, and we must assume that the interstellar path length increases with decreasing energy (eg. Apparao and Ramadurai 1964). We illustrate this in figure 1 with a path length varying as $E^{-0.5}$ normalized to 2.5 g cm^{-2} at 3 GV. Although this gives a reasonable fit to the data we should point out that previous calculations have omitted the effects of secondary protons and helium nuclei arising from nuclear interactions in this same material. Calculations by Feit and Milford (1965 unpublished) show that this is a large effect for protons, with secondary protons actually dominating the spectrum below 100 MeV. Although corresponding calculations have not been carried out for He nuclei, our experience shows that in the atmosphere secondary low energy He nuclei are relatively much less important. Preliminary calculations using a diffusion model and taking into account both secondary particles and ionization loss indicate that the observed increase in P/He (P) at low energies can be explained by passage through about 3 g cm^{-2} of material—constant with energy.

Before discussing this point further, let us turn to the data on heavier nuclei. We have already seen (figure 3, see also SPEC 13) that the spectra of M and LH nuclei seem to be steeper than the He nuclei above 3 GV. The differences in the spectra of L nuclei are even more pronounced and the differential L/M ratio measured at different energies and rigidities is shown in figure 4. The decrease in this ratio is apparent both with increasing rigidity and increasing energy/nucleon.

As in figure 3, the broken curves show how the ratio would vary if m, the exponent on the differential spectra differs by

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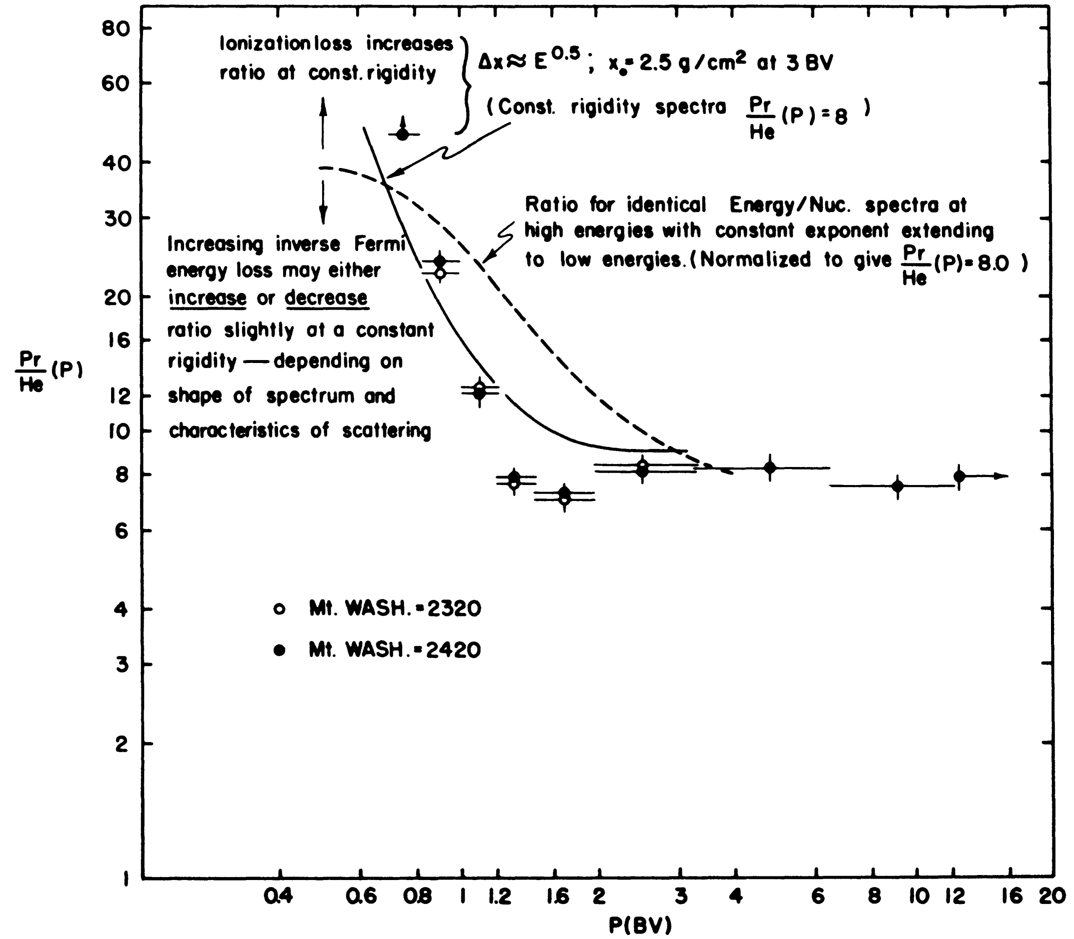

Fig. 1 Differential proton and helium nuclei intensities compared as a function of rigidity for two levels of solar modulation.

0. 1, 0. 2 etc. (Note from table 1 of the accompanying paper (SPEC 30) that no significant change in the Be/B ratio is apparent with energy. The limitations this presents on the decay of ^{10}Be and the lifetime of the cosmic rays are discussed by Durgaprasad (1963).)

The L nuclei are believed to be secondary from nuclear interactions in interstellar space, thus energy/nucleon seems to be the appropriate quantity to study to obtain the L/M ratio since these two groups of nuclei have slightly different charge-to-mass ratios. This will mean that solar modulation effects will change this ratio somewhat, but we shall neglect this effect which must certainly be small compared with the observed change. Accurate data on the L/M ratio at high energies are lacking and the previous results are conflicting (Waddington 1960, Durgaprasad 1963, Mathiesen and Stenman 1965, Nuclear Physics Rep. KS 6501, University of Lund). Our data, while based on the observation of only 36 L nuclei, are statistically the most accurate reported to date. The difference in the exponents of the L and M spectra of 0. 5 ± 0. 15 is certainly significant. An energy dependent L/M ratio has been postulated before and is usually interpreted in terms of passage of the M and H nuclei through an energy dependent amount of material. This might occur in the source regions or in the interstellar medium itself. If our results are interpreted in terms of such an effect then the amount of material X approximates to $E^{-0.5}$. It is also possible that energy dependent fragmentation probabilities for the L nuclei can produce this effect. Our atmospheric attenuation results for the L and M components—while showing some deviations from first-order fragmentation theory—are not sensitive enough to detect such an energy dependence.

The final aspect of the data which we wish to discuss concerns the relative spectra of the M, LH and He nuclei. Referring again to figure 3 we see that both He/M (P) and He/LH (P) begin increasing below about 2. 5 GV rigidity. Our results are in good agreement with those found at still lower rigidities by Fichtel et al. (1964 unpublished) and Lim and Fukui (1965) and interpreted again in terms of ionization loss in interstellar space by Fichtel et al. In Fichtel's study, 3 g cm^{-2} of material (constant with energy) was sufficient to produce the changes in He/M. The above estimate was made assuming the spectra of these nuclei were identical at higher energies. If, in fact, the M and LH spectra are steeper as our results seem to indicate, then the amount of material must increase with decreasing energy approximately as $E^{-0.5}$. This is illustrated in figure 3. If this occurs or indeed if the particles have passed through more than 1-2 g cm^{-2} of material the He/VH ratio should increase rapidly below 2-3 GV. It is clear from figure 3 that this does not occur. The He/VH ratio might remain essentially constant in the 1. 5-3 GV range only if the VH spectrum were substantially steeper than the He spectrum at high energies. Again this does not seem to occur although our results cannot rule out a systematic increase in spectral index with increasing charge. The slightly steeper M and LH nuclei spectra suggest that this may be occurring. It is interesting to recall that such an increase (more pronounced than the ones measured here) was originally suggested by Singer (1958) on the basis of measurements up to 1956. More recent summaries

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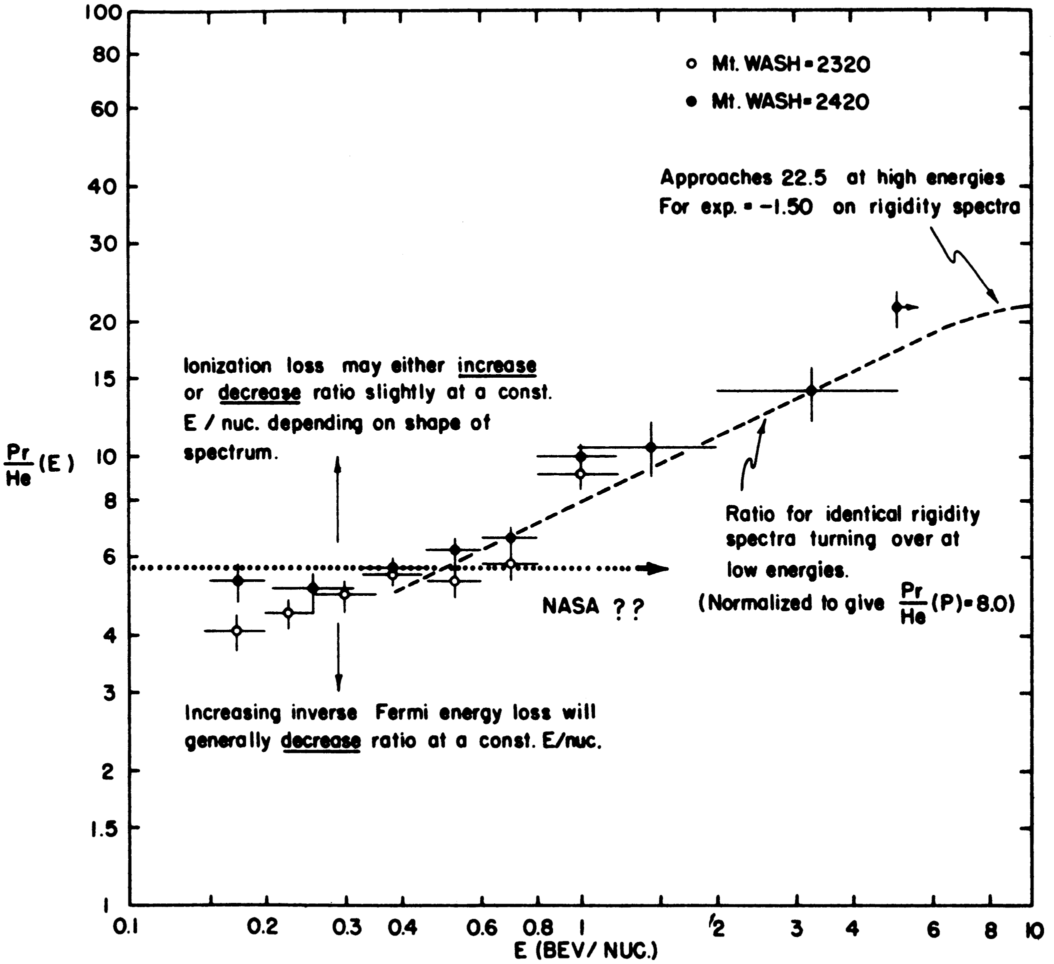

Fig. 2 Differential proton and helium nuclei intensities compared as a function of energy/nucleon for two levels of solar modulation.

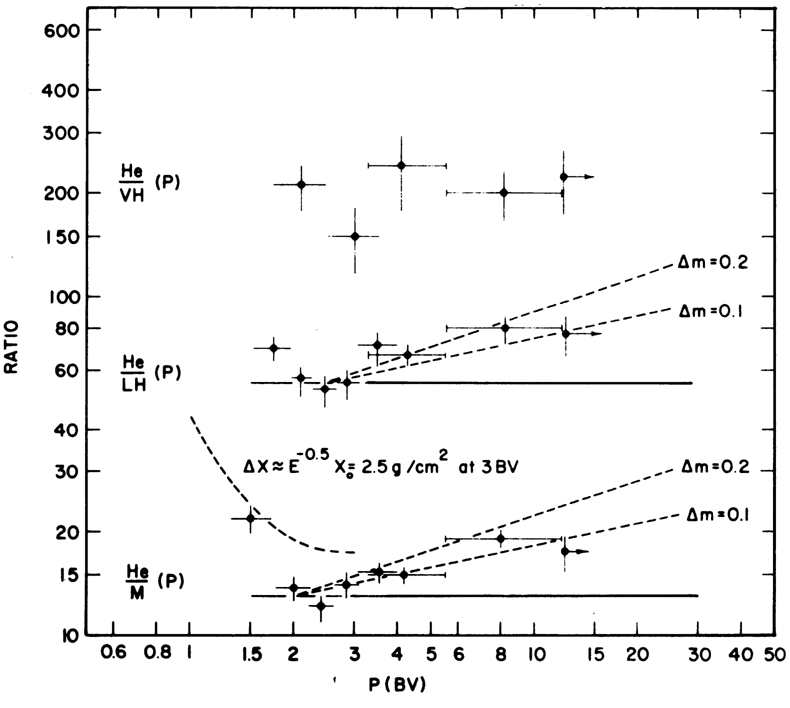

Fig. 3 Ratios of helium to M, LH, and VH nuclei respectively. Differential rigidity measurements in 1964 are shown except for the highest rigidity point which is an integral above 12.1 GV.

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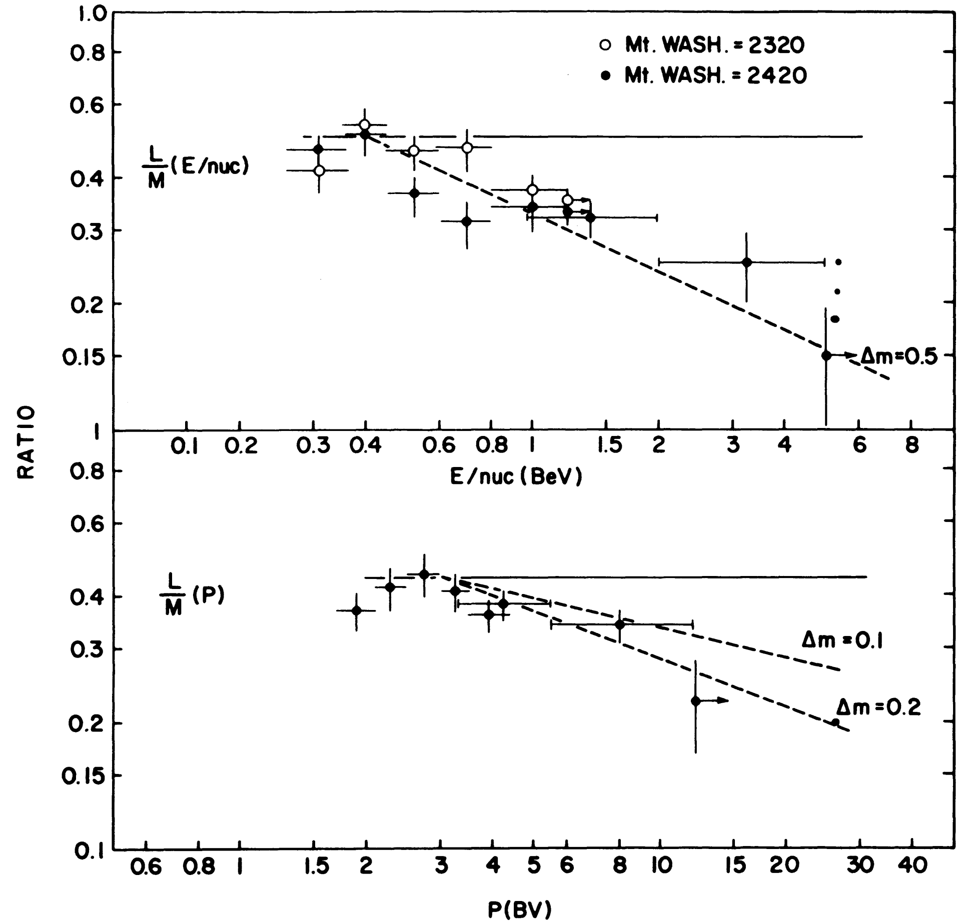

Fig. 4 Ratio of differential L to M intensities, compared as a function of rigidity (A/Z of L nuclei assumed to be 2.2) and energy/nucleon.

(Waddington 1960 and Webber 1966) have indicated that the differences in the spectra of heavier nuclei are small if they exist at all. Our measurements at high energies are statistically as accurate as any reported to date (>200 nuclei having been observed) and have the added advantage that all components are measured simultaneously at one latitude and the same detector is used for measurements at different latitudes.

In summary, our results on the relative spectra of the different charge components suggest the following: (i) The relative spectra of protons and helium nuclei are most reasonably interpreted in terms of similar source rigidity spectra rather than energy per nucleon spectra. The differences in these rigidity spectra at low energies are due to both the production of secondary protons and ionization loss in the interstellar medium. (ii) The variation of the P/He, L/M and He/M ratios at low and intermediate energies can be interpreted in terms of the passage of primary radiation after acceleration through an amount of material which monotonically decreases with increasing energy. (iii) A systematic steepening of the spectra of heavier multiply-charged nuclei with increasing charge appears to exist.

Some of these features are, however, less well defined than others, and our results show the clear need for measurements on each charge group in the rigidity range 5-50 GV with a numerical accuracy up to 10 times that obtained in our experiments. This is not only to define the characteristics of these spectra at high energies but to enable the definitive measurements that can be obtained at very low energies to be interpreted more easily. To cite one example, the very powerful means that a measurement of the comparative spectra of the different charges at low energies gives us for determining the distribution of cosmic ray sources cannot be fully utilized without a knowledge of the comparative spectra at higher energies.

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