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LETTER TO THE EDITOR

Mass dependence of the energy spectrum of primary cosmic rays

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Abstract. There is experimental evidence favouring a flatter energy spectrum for primary iron nuclei than for the other charged components of the primary cosmic ray beam, at least up to the highest energies at which measurements have been made ($\sim 10^{12}$ eV/nucleon). In the present work we examine the consequences of extrapolating this flatter spectrum to much higher energies.

Recent measurements with balloon-borne detectors (Juliusson *et al* 1972, Ormes and Balasubrahmanyan 1973, Webber *et al* 1973, Smith *et al* 1973) have indicated that the energy spectra of the various cosmic ray components do not have the same shape, at least below about 10^{12} eV/nucleon where the measurements have been made. It is customary, and almost certainly correct, to distinguish between the so-called primary (or better, 'primordial') particles and the 'secondaries'. The former, such as protons, carbon, oxygen and the iron group ($23 < Z < 28$) are presumed to be accelerated in the actual cosmic ray sources whereas the latter, such as Li, Be, B and the calcium group ($19 < Z < 22$) are generally regarded as arising from the fragmentation of the 'primaries' either near the source region or in their passage through interstellar matter.

The differences in spectral shape of the primary and secondary components has provoked considerable discussion (see for example the work of Adouze and Cesarsky 1973 and Meneguzzi 1973) about possible differences in lifetime within the galaxy of the various particles. In the present work we wish to study the consequences of an important result found by Balasubrahmanyan and Ormes (1973) and Ormes and Webber (1965) (and summarized by Ramaty *et al* 1973)—that the iron spectrum appears to be significantly flatter than that of the other primary elements. Examination of the summary of Ramaty *et al* indicates that the differential spectrum of protons and α particles has an exponent of about $-2{\cdot}75$ whereas that of iron has an exponent of about $-2{\cdot}1$. Figure 1 indicates the data; the full lines cover the regions over which the measurements exist and the dotted lines indicate our extrapolations.

Ramaty *et al* propose an interesting model in which cosmic rays are derived from two acceleration mechanisms: one, possibly acceleration at neutron star surfaces, produces the iron and the other is responsible for the remainder of the primary nuclei.

In the present letter we briefly examine indirect data at higher energies which allow something to be said about the extent to which an iron spectrum with the proposed exponent can continue.

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The problem of the mass composition of the primary radiation at high energies (ie $E_p \gg 10^{11}$ eV) has been referred to frequently; most recently in a paper by two of the present authors (Wdowczyk and Wolfendale 1973). In that work it was remarked that fluctuation studies of extensive air showers and other measurements indicated

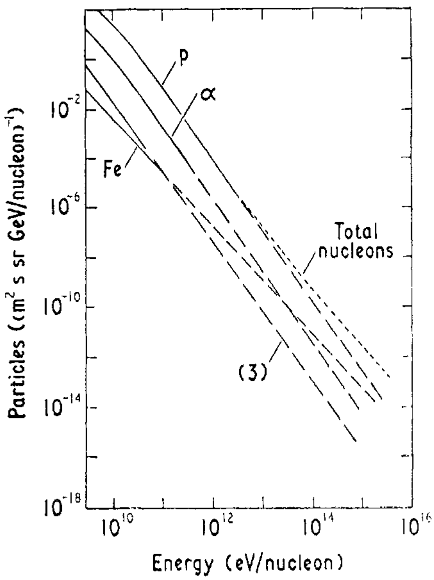

Figure 1. Energy spectra (in terms of numbers of particles against energy/nucleon) of the more common components of primary cosmic rays. The full lines come from the data of Ramaty *et al* (1973); the dotted lines are the extrapolations by the present authors. (3) denotes the (approximately equal) spectra of carbon, oxygen and nuclei with $10 < Z < 14$. 'Total nucleons' comprise the sum of all the spectra when the ordinate is the number of nucleons (not 'particles') as would be appropriate if all the nuclei fragmented completely before arrival.

that the evidence seemed to suggest that the composition in ther ange 10^{14}–10^{16} eV was not very different from that at 10^{10}eV. More particularly, work described therein indicated that an effective upper limit to the 'mean' primary mass at $E_p \sim 5 \times 10^{14}$ eV was approximately 6, a conclusion that came from a detailed analysis of the Utah measurements underground on multiple muons by Cannon and Stenerson (1971). It should be remarked that new calculations by the Utah group (Elbert *et al* 1973) give an even lower limit for the effective primary mass. The significance of these remarks is that if an extrapolation of the iron spectrum were allowed then iron nuclei would take over from protons in terms of particles having the same energy per nucleus at about 10^{13} eV/nucleus (figure 1 is plotted in terms of the number of particles against energy per nucleon—the procedure to convert to particles against energy per nucleus is to displace the ordinate for a particle of mass A to the right by a factor A and then downwards by a factor A). The multiple muon results thus indicate that the iron spectrum cannot be extrapolated to several times 10^{14} eV.

A more stringent limit can be set from considerations of the charge ratio of single unassociated muons at ground level. The sensitivity of this quantity to the ratio of neutrons to protons (the neutrons being bound in nuclei before entering the earth's atmosphere) has been realized for many years (see, for example, the work of Pal and

Peters 1964 and MacKeown and Wolfendale 1966). Previous conclusions have not been possible, however, because of uncertainties in the nature of high energy interactions and, indeed, it has usually been the case that the neutron to proton ratio has been assumed to correspond to that measured experimentally at approximately 10^{10} eV/nucleon and the experimental data have been used to derive quantities of nuclear physical interest. For example, MacKeown and Wolfendale (1966) pointed out the need for interactions with a small group of pions and with a large positive excess being produced; more recently, Frazer *et al* (1972), Garraffo *et al* (1973) and Hume *et al* (1973) have studied the consequences of the Feynman scaling model which has been found to have a measure of success in explaining accelerator data on p–p collisions at effective proton incident energies of about $1{\cdot}5\times10^{12}$ eV. Hume *et al* in particular have compared recent precise charge ratio data with expectation and found the result shown in figure 2, again using the n/p ratio in the primary beam appropriate

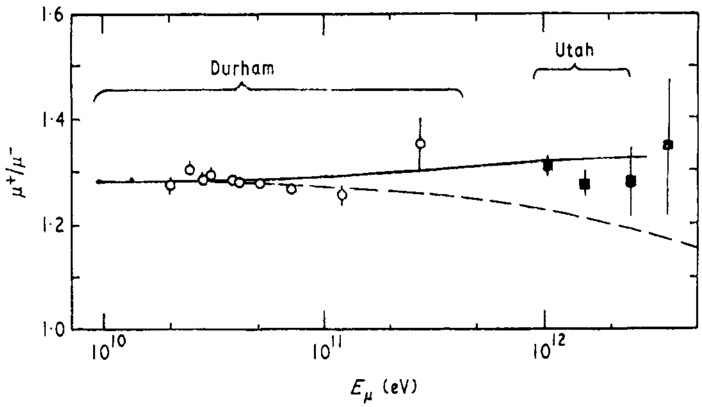

Figure 2. The charge ratio of muons at ground level as quoted by Hume *et al* (1973). The full curve is the expectation (normalized at $E_\mu = 10^{10}$ eV) for the case of a primary neutron to proton ratio equal to that at 10^{10} eV/nucleon and independent of energy. The broken curve corresponds to the particle spectra of figure 1 (no fragmentation)—the falling ratio is due to the increasing effect of iron nuclei.

to 10^{10} eV. The slow increase in the predicted curve is due to a combination of 'dilution' effects and the effect of a small admixture of kaons (uncertainties in both the K/π and K^+/K^- ratios make this prediction not too reliable in fact; a later extended publication will examine this problem in more detail). It should be pointed out that the experimental ratios above 10^{12} eV came from the underground experiments of the Utah group which although referring to muons of a few tens of GeV underground can give information about the ratio of such high energy muons at ground level if (as should be the case) positive and negative muons lose energy at identical rates.

The muon charge ratios can now be examined for the case of an increasing iron content. The data of figure 1 gave the n/p ratio in the incident beam shown in figure 3 and an approximate calculation of the muon charge ratio in the near vertical direction expected for this situation is shown as the broken curve in figure 2. It is interesting to note that below about 2×10^{11} eV the slowly falling ratio found in the work of Hume *et al* is reproduced, although this may of course be fortuitous due to the problems of kaons referred to in the previous section. Above 2×10^{11} eV muon energy ($\sim2\times10^{12}$ eV/nucleon primary energy) the measured ratios are clearly higher than those predicted for the enhanced iron spectrum. Taken at its face value this would indicate that the iron intensity starts to fall more rapidly above this energy.

It is interesting to speculate that perhaps the iron nuclei are accelerated on the neutron star surface with the 'flat' spectrum suggested to beyond 2×10^{12} eV/nucleon

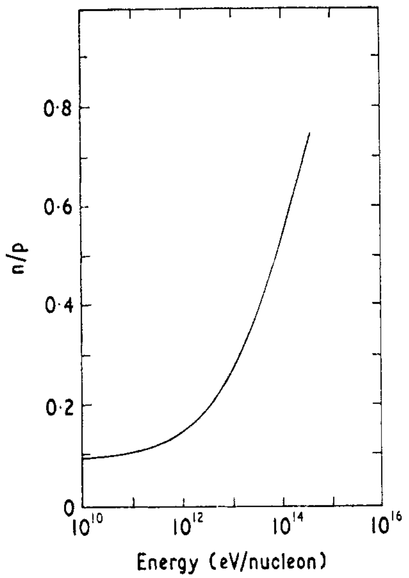

Figure 3. The neutron to proton ratio for the particle spectra of figure 1 (the neutrons are, of course, bound in nuclei prior to entry into the earth's atmosphere). Actually the true ratios are a little higher because of elements not included in figure 1.

but that local fragmentation sets in (such as postulated for supernovae sources by J Kinsey (unpublished) (see Cameron 1968), and put forward by Thompson *et al* (1970) to account for the apparent observation of a mainly protonic composition above 10^{15} eV). The freed neutrons would then decay to protons and join the existing protons. Some measure of support for this idea comes from the suggestion by Wdowczyk and Wolfendale (1973) that there may be an upward turn in the energy per nucleon spectrum above about 2×10^{12} eV/nucleon such as to give intensities at 10^{15} eV which would agree with those derived from measurements made on extensive air showers; the point here is that an extrapolation of the proton spectrum alone gives intensities too low by a factor of the order of 10 at 10^{15} eV. Wdowczyk and Wolfendale quote an average exponent for $2 \times 10^{12} < E_p < 10^{15}$ eV/nucleon of $-2{\cdot}47$; this is about what would result for the total nucleon spectrum if iron were to fragment as suggested (see figure 1 which shows the summed nucleon spectrum between 2×10^{12} eV and 10^{15} eV/nucleon; the mean exponent is $\sim -2{\cdot}55$).

It should be pointed out that an alternative explanation for the possible flattening of the primary spectrum above 10^{13} eV/nucleon, in terms of an increasing contribution of protons from pulsars, has very recently been put forward by Karakula *et al* (1974).

Finally, in view of recent statements by some of the present authors that the ideas of scaling and limited fragmentation may not be valid in the cosmic ray case, it should be remarked that the near agreement of the upper line in figure 2 with the experimental data does not necessarily support their validity. In deriving the line it was necessary to assume that the energetic pion secondaries of proton–'air' nucleus interactions have a charge ratio which depends in part upon the character of the struck nucleon (p or n) and this is not consistent with the idea of limited fragmentation. It seems likely that deviations from the scaling 'law' increase with increasing interaction energy and this could account for the fact that the spectrum of high energy muons does not appear to exhibit the flattening suggested for the primary spectrum. The rough constancy of both the charge ratio and the exponent of the muon spectrum would follow from a model in which fragmentation applies to some interactions and not others and in which the fraction of interactions in which it applies falls with increasing primary energy.

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