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LETTER TO THE EDITOR

Interpretation of the charge ratio of cosmic ray muons

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Abstract. An examination is made of the charge ratio of near vertical cosmic ray muons at energies up to 2×10^{12} eV in the light of recent accelerator results. The results can be understood if the charge ratio of pions emitted with energy in the region of 20% of the primary proton energy is smaller for p–air nucleus than has been measured for p–p interactions. This result appears to contradict the strict application of the fragmentation hypothesis.

Studies of the charge ratio of cosmic ray muons have been made for many years with continually increasing accuracy and at present there is a fair measure of precision to muon energies of about 2×10^{12} eV. After the first intimation that the ratio was not falling to unity above some tens of GeV (in the late 1950's and early 1960's) as had been expected on a simple pionization model for nuclear interactions, attention centred on models in which the very energetic particles in the interactions formed a separate group of low multiplicity and large charge excess. For example, Ramana Murthy (1963) and Pal and Peters (1964) interpreted the results in terms of isobar production from which small numbers of energetic pions resulted.

Very recent measurements with the CERN intersecting storage rings facility (ISR) have yielded characteristics of p–p collisions at energies in the region of interest to cosmic ray studies and which can be used to allow further conclusions of relevance to nuclear physics to be drawn.

To be specific the ISR data have given moderately precise charge ratios for the pions produced in p–p collisions at energies (with respect to a stationary proton) up to $1\cdot5\times10^{12}$ eV. Since the composition of the primary cosmic ray beam is known with reasonable accuracy to about the same energy there is the possibility of using the muon charge ratio to examine some of the characteristics of the p–n collisions which together with the (known) p–p interactions form the p–air nucleus collisions.

The main ingredients necessary for a full explanation of the muon charge ratio are as follows.

(i) The relative fluxes of protons and neutrons in the primary cosmic ray beam as a function of energy.

(ii) The π^+/π^- ratio against pion energy for p–p and p–n interactions and, less important, the same quantity for n–p and n–n interactions.

(iii) The same ratios for kaons.

(iv) The energy distribution and nature (neutron or proton) of the fast nucleon emerging from the interaction.

The ingredients can be considered in turn. The relative p to n flux at primary nucleon energies in the region of 10^{10} eV is generally considered to be about 89:11

and in what follows this ratio will be taken as constant, independent of energy. In fact, there is some evidence (Ryan *et al* 1972) that the ratio may be somewhat higher in the range 4×10^{10}–4×10^{11} eV/nucleon but the effect of any change on the muon charge ratio is quite straightforward and will not be considered further.

The pion charge ratios have been measured in a number of ISR experiments for p–p collisions. In the spirit of 'scaling' (Feynman 1969) the ratios have been presented in terms of x, the ratio of pion longitudinal momentum to the maximum possible value. As an example, the data of Ratner *et al* (1971) and Bertin *et al* (1972) give $\pi^+/\pi^- = 1{\cdot}4$, $1{\cdot}8$ and $2{\cdot}0$ for $x = 0{\cdot}1$, $0{\cdot}2$ and $0{\cdot}3$ and E_p in the range 5×10^{11}–$1{\cdot}5\times10^{12}$ eV. Although the frequency distribution of x values falls rapidly with increasing x, for a fixed E_p, in the cosmic ray case where the primary energy spectrum is also falling rapidly the effective value of x is comparatively large ($\simeq 0{\cdot}2$ for a differential primary spectrum of exponent 2·6). The appropriate pion charge ratio has been calculated to be 1·72. If the limiting fragmentation of Benecke *et al* (1969) were correct in its entirety, particles of 'large' x would have a charge ratio determined by the incident particle and not the struck particle. This would mean that the relevant p–p and p–n interactions would give pions with the same charge ratio (the effective value of x, 0·2, is 'large' in this context). However, as will become clear, and as has already been remarked by Frazer *et al* (1972), the assumption of equality leads immediately to a muon charge ratio much higher than observed.

The method adopted here is to assume that in a fraction f of the collisions the charge ratio is determined by the proton and in $(1-f)$ it is determined by a neutron. The value of f can then be determined which, after allowing for the other effects in the list, gives rise to the observed muon charge ratio at some particular energy. This value of the derived π^+/π^- ratio for p–light nucleus interactions can then be compared with that derived from the low energy (< 30 GeV) p–light nucleus experiments.

It is assumed that the ratios for n–p and n–n interactions are the appropriate inverses. Concerning kaons, the values given by Allaby *et al* (1970) are adopted; it is assumed that the K/π ratio is independent of energy.

Finally, under heading (iv) there is the problem of the contributions of secondary interactions in the atmosphere, for which the energy given to the forward proton, or neutron, is required. The effect of these later generations (the 'dilution effect') was calculated by MacKeown and Wolfendale (1966) for the case of equal probability of emerging p and n and shown to give a reduction in charge excess δ ($\delta = (R-1)/(R+1)$ where R is the charge ratio) by a factor of about 0·7 at $E_\mu = 100$ GeV. The relevant quantity has not been measured at ISR energies to any accuracy but an approximate result given by Morrison (1972) gives p/n $\simeq 1{\cdot}35$ at the effective x for emergent nucleons of 0·45. The resultant dilution factor is about 0·8.

The net result of relaxing f and applying all the corrections is shown in figure 1 where the fit point is the overall mean of the muon charge ratio (1·285) at 10^{10} eV. The appropriate f value is 0·68 and the corresponding π^+/π^- ratio for p–light nucleus interactions is 1·44.

The experimental muon charge ratios are derived from the experiment of Ayre *et al* (1972 and more recent data) below 5×10^{11} eV and from the underground experiment of the Utah group (Ashley *et al* 1971) at higher energies. There is seen to be a reasonable fit to the data by reducing the charge ratio of muons from kaons at the higher energies.

The π^+/π^- ratio for p–light nucleus collisions can now be compared with the directly measured quantity at lower energies. Useful data have been given by Allaby *et al* (1970)

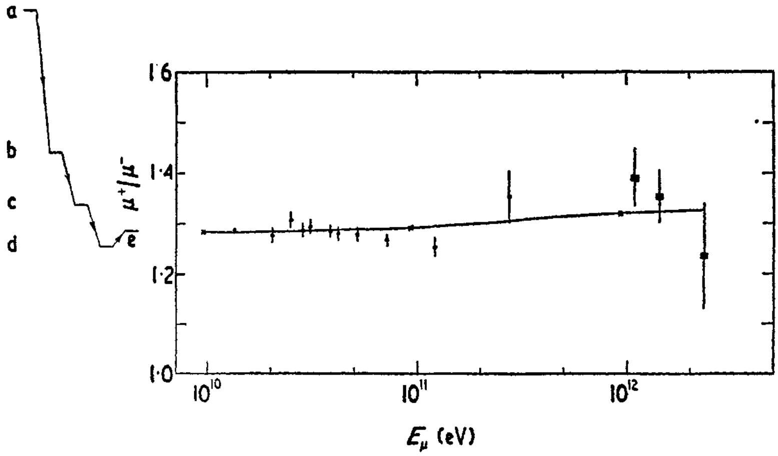

Figure 1. Charge ratio of near-vertical cosmic ray muons. The experimental values below 5×10^{11} eV are from the work of Ayre *et al* (1972) and those at higher energy are due to Ashley *et al* (1971). The letters, a, b, etc refer to the various steps in the calculation of the expected ratio.

a Pion charge ratio for p–p collisions (ISR).
b Muon charge ratio after one collision with 'air' nucleus, assuming primary radiation of 100% protons.
c Weighted muon charge ratio after two collisions, assuming primary radiation of 100% protons.
d Muon charge ratio with primary radiation 89% p–11% n.
e Final muon charge ratio including the effect of kaons.

at 19·2 GeV and Eichten *et al* (1972) at 24 GeV. As an example, the values given by Allaby *et al* for a transverse momentum of 420 MeV/c and x = 0·31 are π^+/π^- = 2·14, 1·71 and 1·71 for p–p, p–Be and p–Al collisions respectively. The work of Eichten *et al* (1972) extends to lower x values but does not include p–p collisions; their results for p–Al with $p_t \simeq$ 400 MeV/c and x = 0·20 give $\pi^+/\pi^- \simeq$ 1·46. This can be compared with the value of 1·44 derived for the cosmic ray case.

Such close agreement is no doubt fortuitous but the conclusion does appear to be that the behaviour exhibited in p–light nucleus collisions at 2×10^{10} eV continues to the much higher energies encountered in cosmic rays. This degree of lack of applicability of the fragmentation hypothesis is rather surprising in view of its success in accounting for other features. An alternative explanation is that the reason does not lie in a simple difference between p–p and p–n characteristics but in a more complex mechanism for p–light nucleus collisions; this latter appears to be the suggestion made by Garraffo *et al* (1973).

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