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LETTER TO THE EDITOR

An improved measurement of the charge ratio of cosmic ray muons in the range 10–300 GeV/*c*

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Abstract. The MARS instrument at Durham has been used to study the charge ratio of near vertical cosmic ray muons in the momentum range 10–300 GeV/*c*. No significant structure is seen and there is no firm evidence to favour a significant deviation from the mean value of $1{\cdot}284 \pm 0{\cdot}004$. Including the results from the Utah detector, which correspond to muon momenta in the range 1000–2000 GeV/*c*, there is the suggestion of near constancy from 10 GeV/*c* to 2000 GeV/*c*.

The ratio of the number of positive to negative muons in the cosmic radiation is an important parameter in that it is related to some aspects of high energy nucleon– and pion–nucleus collisions and to the mass composition of the primary cosmic rays. Experimental measurements have been made for many years, with gradually improving precision, and the present data represent the most accurate so far in the near vertical direction.

A number of studies have been made of the charge ratio expected for a primary mass composition the same as that measured directly at primary energies in the region of 10 GeV for particular assumptions about the character of the interactions. Pal and Peters (1964) and MacKeown and Wolfendale (1966) have described models involving significant kaon and isobar production and have shown that the resulting charge ratios are energy dependent. Frazer *et al* (1972), on the other hand, argue that the 'scaling' hypothesis of Feynman (1969) leads to a constant muon charge ratio. Wieder and Yeivin (1971) and Yekutieli (1972, *Weizmann Institute of Science, Israel* W15-72/6-Ph, private communication) have discussed the general problem of the derivation of information on interactions from measured ratios.

Precise observation should at least enable a distinction to be made between the broad types of model.

Returning to experimental data, from time to time observations are reported which appear to give evidence for comparatively sharp maxima or minima in the charge ratio. Such results, if real, would indicate the onset of new processes and are thus of considerable interest.

The new muon spectrograph at Durham, MARS (Ayre *et al* 1971, 1972) offers the possibility of making precise measurements of various phenomena related to cosmic ray muons and the present data are the first reported on the charge ratio. They are preliminary in the sense that they will be extended considerably, both by way of improved statistical accuracy and by an increase in the upper momentum limit available, but they represent data from one phase of the experiment and in view of their being of higher precision than hitherto they are reported now.

The data comprise measurements on $3\cdot99\times10^5$ near vertical muons of momentum above about 10 GeV/*c*, gathered in a running time of 777·5 h. The muon tracks were located with four layers of 'large' diameter flash tubes—internal diameter 15 mm—at each of three levels in the solid iron magnet spectrograph, using the flash tube digitization method described by Ayre and Thompson (1969). An electronic analysis of the discharged tubes enabled the path of each particle to be allocated to a cell of width 5 mm at each level. With this arrangement the maximum detectable momentum is 850 GeV/*c*. Coulomb scattering introduces an uncertainty of 12% into individual momentum determinations so that at any momentum p (GeV/*c*), the RMS uncertainty is $p\ (0\cdot12^2+p^2 850^{-2})^{1/2}$.

The experiment involved two different methods of data collection and for each method half the data were collected with the opposite magnetic field direction. The data were combined in such a way as to eliminate all the known (small) instrumental asymmetries.

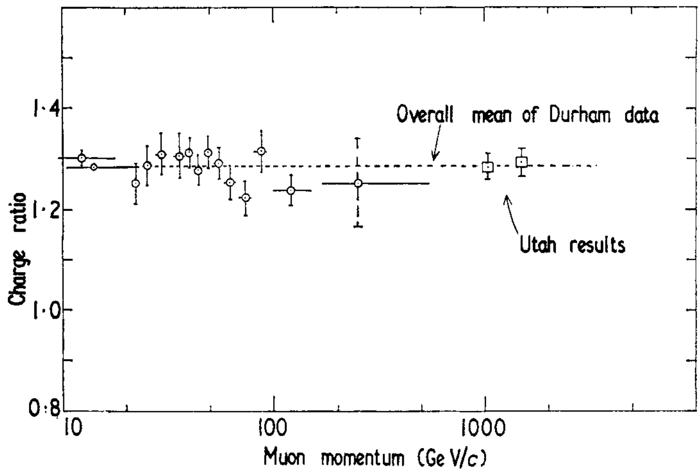

Figure 1. The ratio of the number of positive to the number of negative muons in the near vertical direction as a function of momentum. The point with dashed error is based on only a fraction of the running time.

The measurements above 1000 GeV/*c* refer to data from the Utah group (Ashley *et al* 1971) for inclined angles.

Figure 1 gives a summary of the results for the region where the statistical accuracy is reasonably good. The data have been grouped into convenient momentum intervals above 20 GeV/*c*. Below this momentum the data are grouped into a single cell extending down to 6·9 GeV/*c* due to instrumental reasons, but this is not detrimental in view of there being a number of previous, precise measurements in this region which have not shown evidence of structure. The horizontal lines attached to the points of figure 1 represent the momentum range from which $\frac{2}{3}$ of the particles come.

The first conclusion that can be drawn is that there is no evidence for any marked structure in the ratio; only one point differs from the overall mean value of $1\cdot284\pm0\cdot004$ by about two standard deviations and this is quite permissible in a sample of 15 points.

Having said that, it is interesting to note that the lowest value is in the same momentum region ($\simeq$ 70 GeV/c) as were the lowest values in the previous work with MARS (Ayre *et al* 1971). However, the possibility of a genuine minimum in this region does not draw support from the work of Allkofer *et al* (1971) who find a value some two standard deviations above the mean in this region and a point about three standard deviations below the line at about 100 GeV/c. Nandi (1970) found no unusual fluctuations at all in the range of momentum in question. The identification of a definite fine structure must await further, more precise, experimental data.

At this stage it can be commented that there is a limit set to the narrowness of the momentum range over which a rapid change of charge ratio can exist because of two facts: uncertainties in individual muon momenta due to Coulomb scattering, location errors etc (Aurela *et al* 1966, Judge and Nash 1968, Frohlich 1971) and the effect of π–μ decay. The latter effect is the 'decay spread' of energies of muons resulting from the decay of pions of fixed energy due to the random angle of emission of the muon in the centre of mass system. Calculations made by the present authors show that if a step function were present in the charge ratio of the parent pions, decay spread would yield a muon charge ratio variation such that 60% of the change in ratio occurred over $\pm$15% of the momentum. In the present experiment the uncertainty in momentum for muon momenta in the region of 70 GeV/c is 10 GeV/c and for the (unlikely) case of a step in the charge ratio of pions the result would be a variation of muon charge ratio such that 60% of the variation occurred over a range of 14 GeV/c. For spectrographs with smaller magnets the figure would be significantly bigger.

Turning to the average value over the whole momentum range above 10 GeV/c, the mean value from the present work is $1{\cdot}284 \pm 0{\cdot}004$. This can be compared with $1{\cdot}29 \pm 0{\cdot}02$ above 10 GeV/c found by Allkofer *et al* (1971) and $1{\cdot}260 \pm 0{\cdot}023$ for momenta above 11·5 GeV/c from the measurements of Nandi (1970). Previous measurements, of lower precision, are not inconsistent with these results.

Measurements have been made at much higher energies by the Utah group (Ashley *et al* 1971) using the indirect method of determining the charge ratio of low energy muons underground. The measurements referred to inclined directions but insofar as only a small angular variation of ratio was found in this experiment comparison with the present vertical values is probably valid. The ratios quoted are $1{\cdot}284 \pm 0{\cdot}026$ for a mean muon production energy $\langle E_\mu \rangle$ of 1044 GeV and $1{\cdot}292 \pm 0{\cdot}028$ for $\langle E_\mu \rangle = 1487$ GeV. The situation at present is, therefore, that there is no evidence for the muon charge ratio in the near vertical direction differing from 1·284 over the whole muon energy range 10–2000 GeV.

The interpretation of this result will only be examined briefly. At first sight it would appear to give strong support to the idea of scaling, with a constant primary composition, but the fact that the relative importance of the various particle generations in the atmosphere varies with energy causes complications. A detailed examination of the theory of the charge ratio will be given later.

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