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Electromagnetic interactions of cosmic ray muons in iron I. Search for a charge asymmetry

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Abstract. A search for a charge asymmetry in the interactions of cosmic ray muons in iron has been made using the Durham spectrograph MARS. The measurements cover the range of muon energy 6–200 GeV and refer to interaction secondaries varying in number from one to about 20.

The ratio of the interaction probability for positive muons to that for negative muons is $1{\cdot}08 \pm 0{\cdot}06$ for interactions having two or more secondaries. This value is less than that found in some previous experiments and does not give support to the existence of a charge asymmetry.

1. Introduction

The problem of why the muon exists at all is well known and is a question that has so far defied attempts to find an answer. The problem is particularly severe because no heavier leptons have been discovered and because the neutrino associated with the muon differs from that associated with the electron. A promising approach is to examine every facet of the muon's interaction with matter in an effort to find some feature that distinguishes it from prediction for a 'heavy electron'.

Many investigations have been made of the 'static' properties of the muon (and of the electron) such as studies of mesic atoms, gyromagnetic ratios and muon spin. So far, none of these investigations has revealed significant anomalies but this does not necessarily make certain the 'heavy electron' assignment to the muon. Rather further efforts must be made, particularly towards examining the dynamic properties of the muon at high energies (analogy with the situation in strong interaction physics is very relevant here).

A number of dynamic experiments have already been carried out using muons from accelerators up to about 12 GeV (μ–p elastic and inelastic scattering, bremsstrahlung, etc) and no differences from the behaviour expected for a 'heavy electron' have been found. In the present work we extend the search to higher energies using muons derived from the cosmic radiation.

The present paper concerns measurements which relate specifically to a search for a difference in the behaviour of positive and negative particles and in the following paper

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an examination is made of the actual magnitudes of the interaction probabilities. The measurements have been made with the Durham spectrograph MARS (Ayre *et al* 1971a, 1972a, 1972b) and refer to interactions in iron. The interactions concerned are mainly μ–e collisions (knock-on process) but at high muon energies direct pair production of electrons in μ–nucleus collisions becomes increasingly important and above 80 GeV predominates (for a transfer of 1 GeV). At high fractional energy transfers bremsstrahlung is also important.

Preoccupation with the possibility of a difference in interaction probability for the two signs of muon (to be referred to as the interaction asymmetry) arises because previous cosmic ray experiments had suggested the presence of such a difference. Thus, Deery and Neddermeyer (1961) and Kotzer and Neddermeyer (1965) found a ratio of the interaction probabilities, for energy transfers in μ–e collisions of about 1 GeV, of $1{\cdot}60 \pm 0{\cdot}30$. These workers found that the ratio was highest for small and medium energy transfers, with some suggestion of a value below unity close to the maximum energy transfer, that is at large fractional energy transfers. Allkofer *et al* (1971) examined the range of muon energy from 4 to 1000 GeV and a range of energy transfers from 0·2 to 100 GeV. The integral asymmetry ratio observed in this experiment was $1{\cdot}23 \pm 0{\cdot}11$ and again there was the suggestion of a fall of asymmetry with increasing fractional energy transfer.

A preliminary analysis of data from the MARS instrument (data included with later measurements in the present work) had also suggested an asymmetry, the ratio for events in which two or more secondaries were seen being $1{\cdot}32 \pm 0{\cdot}10$ (adopting a mean muon charge ratio of 1·28). Whilst this experiment was in progress, Sheldon (1972, private communication) reported first results from a similar study which gave $1{\cdot}33 \pm 0{\cdot}27$ for the integral ratio. There are thus, four cosmic ray experiments which are not inconsistent with there being a significant asymmetry and indeed if the results are combined the evidence looks rather strong.

Information from two other sources provided some cause for doubt, however, (in addition to the very low *a priori* probability of such an effect being true even if the muon does differ from a heavy electron) a cosmic ray measurement at a very large zenith angle and two experiments with muons from accelerators. The cosmic ray measurement is a re-analysis by the present authors of an experiment by Kelly *et al* (1968) in which interaction probabilities were measured for muons at a mean zenith angle of 87°. The integral asymmetry ratio for interactions with two or more secondaries is $0{\cdot}97 \pm 0{\cdot}11$. It must be remarked though that this in itself does not invalidate the other cosmic ray data for two reasons:
(i) statistical fluctuations would allow the ratio R_A to be about 1·2 and (ii) it is possible to have a variation of R_A with zenith angle at large angles by postulating that the asymmetry arises from the presence in the cosmic radiation of heavier leptons rather than muons (Grupen and Hamdan 1971, unpublished). This interesting suggestion would also have the advantage of allowing an explanation of the non-observation of the asymmetry in the accelerator experiments.

Turning now to the accelerator work, careful examination shows that the precision with which the asymmetry ratio is known is not high. Thus, in the work of Jain *et al* (1970) the published data give $R_A \sim 1{\cdot}1 \pm 0{\cdot}2$ for muons of energy 10·1 GeV (μ^+) and 14·5 GeV (μ^-) and energy transfers greater than 200 MeV and in the experiment of Kirk *et al* (1968) the data give $0{\cdot}9 < R_A < 1{\cdot}1$ for muons of energy 5·5 GeV (μ^+) and 10·5 GeV (μ^-) and transfers above 0·1 GeV.

The situation is thus equivocal and in view of the importance of studying even improbable muon phenomena the present studies have been carried out.

2. Experimental arrangements

The MARS spectrograph has been described in detail by Ayre *et al* (1972a, 1972b) and only a brief description will be given here. Figure 1 shows the detector arrangement. One side of the instrument is digitized and is being used for the measurement of the muon spectrum and charge ratio up to high energies. The neon flash-tubes which act as track detectors on the other side are not digitized so far and these are the ones that are used for interaction studies—the interactions in question being those of muons in the magnet iron just above the 'measuring trays'. The events are recorded photographically, in conventional fashion, by way of a mirror system.

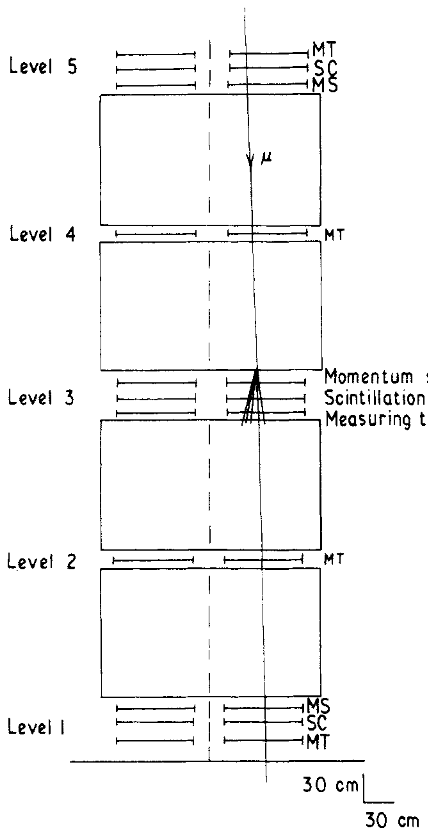

Figure 1. The MARS instrument.

In its normal mode the instrument is triggered by a three-fold coincidence of the large area scintillation counters at levels 1, 3 and 5 (figure 1) and the results for a preliminary run in this unbiased mode were presented by Ayre *et al* (1971b).

In order to improve the relative yield of interactions, higher pulse heights were demanded from either of the scintillators at levels 1 and 3: the so-called 'interaction run'. Two extra photomultipliers were attached to these scintillators and were calibrated in units of minimum ionizing particles in the usual way, linearity of response being achieved using a light diode of variable intensity for checking purposes.

In the interaction run a discrimination level of, nominally, six particles was arranged at levels 1 and 3. The majority of events thus showed bursts in the flash-tubes at one or other of these levels. A total of 4230 triggers were recorded in a running time of 350 hours. Of these 2950 photographs showed potentially useful events and 1280 showed extensive air showers. Out of the 2950 events only 217 showed single muons with no observable burst in the flash-tubes of the measuring trays.

In a separate run the charge ratio of single muons was determined. The charge ratio obtained with the 'interaction side' of MARS was $N_{\mu^+}/N_{\mu^-} = 1{\cdot}30 \pm 0{\cdot}04$ in good agreement with that obtained by the digitized side of MARS of $1{\cdot}284 \pm 0{\cdot}004$. The value of the charge ratio of muons is required for the corrections of the burst events to equal numbers of positive and negative incident muons.

3. Data analysis

The interaction events are recorded in the measuring trays of MARS. There are five such trays, each consisting of eight layers of flash-tubes. The flash-tube information from the trays is used both for momentum and sign determination and for an examination of the interactions.

A burst in one of the measuring trays blurs the accurate track information and consequently only four measuring trays can be used for the momentum analysis. The maximum detectable momentum (MDM) of MARS depends on which tray combinations are used. When the momentum determination is based on four (instead of five) measuring trays only, the MDM is still in excess of 3 TeV/c and more than adequate for the present investigations. Details about the momentum determination have been given by Thompson and Wells (1972).

To cancel out systematic errors the magnet field was reversed periodically and the data sampled comprised 50 % at positive field and 50 % at negative field. The momentum determination has been checked for 1000 events by a different simplified program which uses only one coordinate in each measuring tray for momentum determination. There is good agreement between the two methods. There was no change in any of the events so far as the sign of charge was concerned for events of muon momenta below the MDM.

In the present work, where accurate knowledge of the number of particles in a burst is not necessary, the total numbers of flashes N_f in the flash-tube trays at levels 1 and 3 are recorded. Isolated particles discharge on average 5 flash-tubes so that for an interaction having separated tracks the number of particles is about $\frac{1}{5}N_f - 1$. In most cases, however, overlapping occurs and the burst size is greater than this value.

An event was accepted as a 'burst' if 15 or more tubes had flashed in one of the measuring trays. Events with a number of flash-tubes less than 15 were considered to be events with single muons plus an extra electron. The information on momentum and sign and number of flashes in the interaction then forms the basic data for analysis.

4. Results on the asymmetry ratio

The analysis is based on 2097 bursts with $N_f > 15$ flashes and 636 single knock-on events ($N_f \simeq 10$).

The present data are plotted as a function of muon momentum in figure 2. Comparing the probabilities for positive and negative muons the asymmetry ratio for all events is $R_A = 1{\cdot}08 \pm 0{\cdot}06$. It can be seen that within the statistical errors there is no dramatic variation with muon energy, a feature that had already been observed in our previous work (Ayre *et al* 1971b). It is interesting to note that the mean values are above unity for muons of energy less than 100 GeV where the knock-on process predominates, although the difference from unity is not statistically significant.

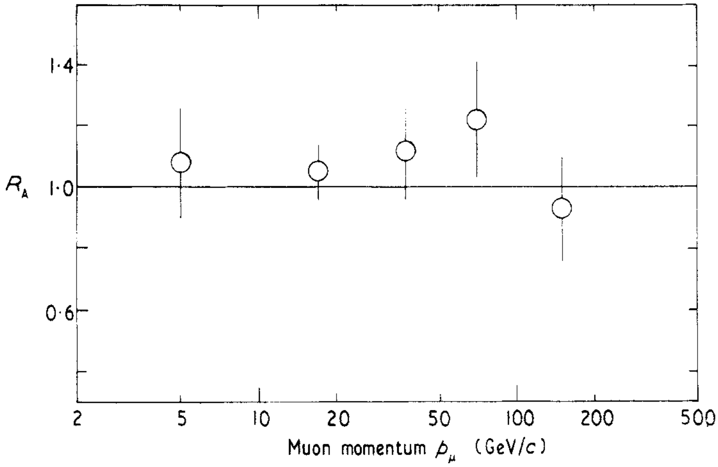

Figure 2. Asymmetry ratio as a function of muon momentum.

The same data have been analysed with respect to number of tubes flashed, N_f, with the result shown in figure 3. The events with $\overline{N}_f = 11$ correspond, in the main, to single knock-on electrons and, in agreement with previous work, there is no evidence whatever for a ratio other than unity. The mean values greater than unity in figure 2 reflect as higher values for $\overline{N}_f$ values above 11 but again there is nothing significant about the excess although it is interesting to note that the highest ratio is for $\overline{N}_f \sim 20$ (energy

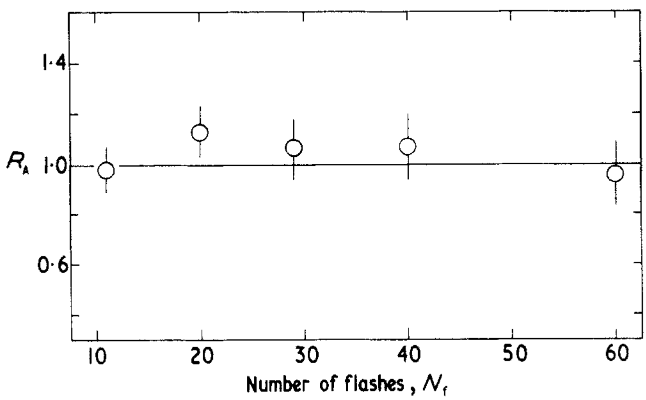

Figure 3. Differential asymmetry ratio as a function of number of flash tubes discharged by the burst, N_f.

transfers $\simeq$ 1 GeV), which is where previous workers had found most evidence for an asymmetry.

Bearing in mind the suggestion from earlier work that there may be an asymmetry which depends on the magnitude of the energy transfer, the data have been analysed with respect to N_f/p_μ (see figure 4), this quantity being, very approximately, proportional to the fractional energy transfer. In this figure the approximate fractional transfers are also indicated. Once more there is no evidence for a significant asymmetry.

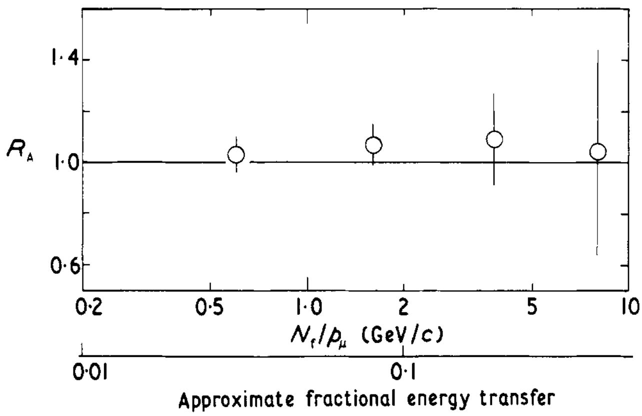

Figure 4. Dependence of the asymmetry ratio on the ratio N_f/p_μ. The approximate fractional energy transfer is also shown.

Finally, the events showing interactions at both levels have been studied. The total number of such double events is 413 (including events with $N_f < 15$) and the asymmetry ratio is $1{\cdot}07 \pm 0{\cdot}09$.

5. Conclusions

The analysis, based on a greater number of knock-on and burst events than included in our earlier work (Ayre *et al* 1971b), does not substantiate the tentative suggestion made there of an asymmetry ratio greater than unity. It appears that the earlier results (a ratio a little less than unity for single knock-ons and $1{\cdot}32 \pm 0{\cdot}10$ for bursts) arose through the presence of a small sample of events with a small number of secondaries which had, presumably through an upward statistical fluctuation, an unusually high ratio. In the earlier work these events were classed as bursts but using the present method where classification is on the basis of number of tubes flashed, many would contribute to the lowest N_f points, that is the point attributed mainly to knock-ons. Thus this point would rise and the ratio for bursts would fall.

The situation is that although the present results are not inconsistent with data from the other experiments which showed high ratios they do not lend significant support to them. It should be pointed out, however, that the present data are somewhat deficient in interactions with only two or three secondaries because of the triggering conditions, and what other evidence there is suggests that this may be where the asymmetry lies. At this stage, however, the onus of proof of the existence of an asymmetry still rests with the experimenters—clearly much higher statistical precision will be required before any useful conclusions can be drawn.

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