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LETTER TO THE EDITOR

Muon charge ratio and the mass composition of primary cosmic rays

A D Erlykin†, L K Ng‡ and A W Wolfendale§

†Lebedev Physical Institute, Lenin Prospekt, Moscow, USSR
‡Physics Department, University of Hong Kong, Hong Kong
§Physics Department, University of Durham, Durham DH1 3LE, UK

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Abstract. The charge ratio of single muons at ground level taken together with knowledge of the characteristics of high-energy nucleon–nucleus interactions in the atmosphere enables information to be gained about the mass composition of the primary cosmic radiation. In particular, the ratio of the number of neutrons (bound in nuclei) to protons and neutrons together can be determined. It is shown that the latest measurements from the Utah group (Ashley, Keuffel and Larson) can be interpreted in terms of a composition at primary energies of the order of 10^{13} eV/nucleon not very different from that below about 10^{11} eV/nucleon where direct measurements have been made.

In a recent publication by the present authors (Erlykin *et al* 1974, to be referred to as I) we examined the interrelation of the muon charge ratio, the characteristics of nucleon–nucleus interactions and the mass composition of the primary cosmic rays. It was pointed out that satisfactory agreement existed between observation and expectation for muon energies near 10^{10} eV where the muon charge ratio is known from many measurements, the primary mass composition is known at the relevant primary energy (about 10^{11} eV/nucleon) and measurements with the Intersecting Storage Ring experiment at CERN allow the necessary characteristics of nucleon–nucleon collisions to be determined with adequate accuracy. The agreement was taken to indicate that results for nucleon–nucleon collisions could be taken over directly to nucleon–air nucleus collisions, ie that intranuclear cascading is not too important under the conditions pertaining to the production of the fast pions (and kaons) which give rise to the detected muons.

At higher muon energies the corresponding primary nucleons have energies above those at which direct measurements of primary masses have been made and there is thus the possibility of gaining information about these masses (or more precisely the ratio of neutrons to all nucleons $\eta = N/(N+P)$) in an unexplored energy region. There is considerable interest in the composition above 10^{11} eV/nucleon for two main reasons.

(i) There is evidence from direct experiments (below about 10^{11} eV/nucleon) that heavier nuclei have flatter energy spectra than protons. In particular, iron appears to have a singularly flat spectrum (see the work of Webber *et al* 1965, Ramaty *et al* 1973 and Juliusson *et al* 1972, and the summary by Meyer *et al* 1974). An extrapolation of these flatter spectra would indicate a significant rise in the value of η with increasing energy and such an increase would reflect in the muon charge ratio (in figure 1 the prediction for what is probably the smallest integral exponent for the iron-group spectrum, $\gamma_{VH} = 1{\cdot}0$, is shown).

(ii) A number of authors, notably Wdowczyk and Wolfendale (1972) and Hillas (1974), have drawn attention to a possible flattening in the overall primary spectrum above about 10^{13} eV leading to a 'bump' in the spectrum in the range 10^{14}–10^{15} eV. Conceivably this could also be related to an increase in the relative flux of heavy nuclei.

In I we used as sources of experimental data on the muon charge ratio the results of the Durham group (Ayre *et al* 1973), which relate to muon energies below 10^{12} eV, and those from Utah (Morrison and Elbert 1973) at higher energies. The data below 10^{12} eV have been confirmed by measurements of lower statistical precision (see, for example, the summary by Thompson 1973), but the Utah work is unique in that no similar measurements have yet been made. The main conclusion in I was that, with a number of provisos, the value of η increases above its 'normal' value of approximately 0·14, which pertains to primary energies below about 10^{11} eV/nucleon, as one proceeds to higher primary energies.

Since that work was carried out, however, the Utah charge ratios have been revised upwards by a significant amount and it is necessary to examine the effect of this revision on the conclusions about the neutron–nucleon ratio. Such a re-examination is particularly important in view of the fact that the Utah measurements refer to the highest muon energies yet attained.

The new Utah data by Ashley *et al* (1975) comprise muon charge ratios grouped into six zenith angle (and corresponding depth) ranges. We have combined them into two groups as follows ($\langle\theta\rangle$ is the mean zenith angle and $\langle E_\mu\rangle$ is the corresponding average muon energy at production):

(*a*) $\langle\theta\rangle = 55°$, $\langle E_\mu\rangle = 1{\cdot}1\times10^{12}$ eV, $\mu^+/\mu^- = 1{\cdot}384\pm0{\cdot}022$

(*b*) $\langle\theta\rangle = 70°$, $\langle E_\mu\rangle = 3{\cdot}7\times10^{12}$ eV, $\mu^+/\mu^- = 1{\cdot}378\pm0{\cdot}045$.

Small corrections are necessary to convert to equivalent ratios for nearly vertical incidence: +0·026 and +0·032 using the method outlined in I. In deriving these corrections it is assumed that the important K/π and K^+/K^- ratios are independent of energy: it should be pointed out however that following the analysis of charge ratios as a function of zenith angle, Ng and Wolfendale (1974) pointed out that there may be a slow fall in K^+/K^- ratio, in which case the additions would be somewhat overestimated.

The median primary nucleon energies have also been calculated following the analysis in I, ie using the relation $\langle E_p\rangle_{median} = 7{\cdot}1\langle E_\mu\rangle$ (this relation is close to that derived independently by Ashley *et al*).

In a straightforward fashion the value of η has been derived for the new data with the results shown in figure 1. Also shown in figure 1 are the earlier, unchanged results from the analysis of the Durham data of Ayre *et al* (1973) with one addition: an upper limit to η at $\langle E_p\rangle_{median} \simeq 3{\cdot}2\times10^{12}$ eV which comes from a measurement of μ^+/μ^- given by Ayre *et al* (1973) but not used in I.

The situation above about 2×10^{12} eV is now seen to be very different from that given in I. There is now evidence for only a very small increase of η over and above the 'conventional' value of 0·136; the extension of the 'flat' iron spectrum (with $\gamma_{VH} = 1{\cdot}0$) to energies above 2×10^{12} eV/nucleon appears to be definitely ruled out. However, the possibility of $\gamma_{VH} = 1{\cdot}4$ remains.

There remains the apparent increase in η in the region $3\times10^{11} < \langle E_p\rangle_{median} < 2\times10^{12}$ eV/nucleon. Taken at its face value it would suggest that perhaps the heavy primary spectrum does continue for some way beyond 10^{11} eV/nucleon before effectively cutting off (fragmentation near the sources of the heavy particles?). However, caution is needed, for three reasons.

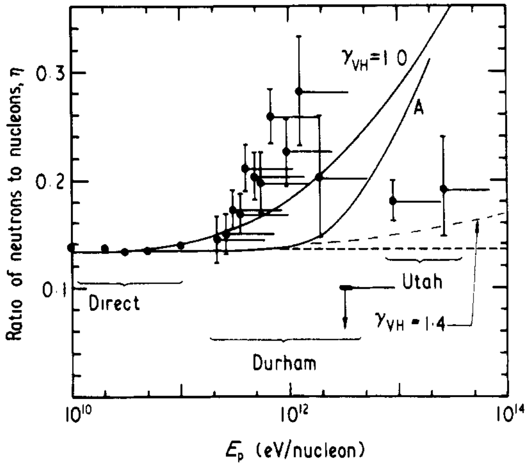

Figure 1. Ratio of primary neutrons to all nucleons as a function of primary nucleon energy. The 'Durham' data are those of Ayre *et al* (1973) and the 'Utah' points come from the work of Ashley *et al* (1975). γ_{VH} is the exponent of the integral spectrum of the iron group. The curve marked A (constant $Z > 1$ composition and steepening protons) comes from the measurements with the PROTON satellites by Grigorov *et al* (1970). The points indicate median energies and the other extremity of the horizontal line is the mean energy.

(i) As is well known, all errors of measurement depress the measured ratios and most measured values tend to 'increase with time' as the precision is improved (the Utah points are a good example of this fact).

(ii) There is still uncertainty in the ISR data. In I it was pointed out that the predicted value of μ^+/μ^- was uncertain to roughly $\pm 0{\cdot}07$, the error being essentially energy-independent if the scaling mechanism is operative. A depression of the predicted value of μ^+/μ^- by 0·07 would reduce the highest value of η shown in figure 1 ($0{\cdot}28 \pm 0{\cdot}05$) to about $0{\cdot}2 \pm 0{\cdot}05$—a value not statistically inconsistent with 0·136. However, to bring *all* the values of η to the 'conventional' line would demand a significant change in the character of the interactions over the small energy range in question and this is perhaps unlikely.

(iii) Most important, probably, are uncertainties in the effect of kaons. These are twofold. In I there was neglect of the effect of muons from the K^0 mode which, although not a large effect, is most serious for muon energies below about 10^{11} eV ($E_p \lesssim 10^{12}$ eV/nucleon) (see Osborne 1966) and is in the direction required; it appears to reduce the predicted muon charge ratio by about 0·01 for $E_\mu \simeq 10^{11}$ eV and would reduce the values of η in figure 1 by rather less than one standard deviation. The second problem concerns the respective mean free paths for inelastic interactions of pions and kaons. In I we assumed that $\lambda_K > \lambda_\pi (\lambda_K/\lambda_\pi = 1{\cdot}25)$, following accelerator measurements which show that $\sigma_K < \sigma_\pi$. However, at the higher energies the values are not known and some uncertainty results. It is relevant to point out that Elbert *et al* (1975) assumed that $\sigma_K > \sigma_\pi (\lambda_K/\lambda_\pi = 0{\cdot}91$ at $E = 100$ GeV) and thus their calculations yield a smaller increase due to kaons; adoption of this ratio would reduce the values of η given in figure 1 significantly.

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