

HADRONIC SCALING AND THE CHARGE RATIO OF COSMIC RAY MUONS

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The charge ratio of cosmic ray muons produced by meson decay has been calculated with the assumption of scaling for high energy hadronic interactions. The values obtained are in good agreement with experimental results for muons coming from primary collision energies up to 40 TeV. This agreement and the observed near energy independence of the measured charge ratios support the scaling hypothesis with the limitation that they are insensitive to secondaries produced at very small fractions of the primary energy.

1. Introduction. Cosmic ray muons arise from atmospheric decays of mesons in hadronic cascades initiated by primary cosmic rays. The cosmic ray muon charge ratio affords a test of particle production models up to hadronic collision energies well beyond those available at accelerators. Its observed approximate energy independence supports models of the scaling (Feynman 1969) or limiting fragmentation type (Benecke et al. 1969). We used scaling and accelerator hadron production measurements to predict the charge ratio and its energy and angular dependence.

2. Fits to Accelerator Data. In order to include intranuclear cascade and other nuclear target effects we applied scaling to production cross sections for mesons and nucleons produced by protons incident on air nuclei. These production cross sections were calculated by interpolating between extensive 19.2 GeV p-Be and p-Al collision results (Al laby et al. 1970) which were roughly proportional to $A^{2/3}$. When these factors were removed from the data, the differences between the beryllium and aluminum particle production cross sections were small enough that the interpolations for air data are expected to be accurate to within about the errors of the original 19.2 GeV results.

Scaling implies the existence of energy independent structure functions F_{ab} for production of particle b with energy E when particle a collides with an air nucleus. These structure functions are defined as

$$F_{ab}(x, P_T) = \frac{E}{\sigma_{in}} \frac{d\sigma_{ab}}{dP^3} = f_{ab}(x, P_T) / (2\pi P_T \sigma_{in}) \quad (1)$$

The variable x is the ratio, in the p-nucleon center-of-mass system, of the longitudinal momentum of particle b to the maximum value allowed by energy and momentum conservation. The production cross sections for positive and negative kaons and pions were each fitted with the functions f_{ab} by Mason and Elbert (1973). The functions for mesons of opposite charge were constrained to be equal at $x = 0$ to avoid divergent violations of charge and strangeness conservation at very high energies. The major

result of interest to the charge ratio calculation is the x dependence obtained by integrating the functions f_{ab} over P_T . For $x < 0.6$ the major x dependence was of the form $\exp(-\hat{a}x)$ with values of \hat{a} of 5.65, 7.81, 5.08, and 9.58 for π^+ , π^- , K^+ , and K^- respectively. It is apparent that the ratio of positive to negative kaons is greater at high x values than the corresponding ratio for pions.

3. Calculation. Basic discussions of the muon charge ratio in the framework of hadronic scaling are available (Frazer et al. 1972; Garrafo et al. 1973; Yekutieli 1972). In the at particle fluxes, the steep cosmic ray spectrum gives extra weight to particles produced with large values of x (which for $x > 0$ and high projectile energy is approximately the ratio of secondary to projectile laboratory energies). For a cosmic ray primary spectrum $dN/dE \propto E^{-\gamma}$, this effect is manifest in the energy independent quantities (Frazer et al. 1972)

$$Z_{ab} = \pi \int_0^1 \int_0^\infty dP_T^2 F_{ab}(x, P_T) x^{\gamma-2} \quad (2)$$

Each Z_{ab} gives a needed ratio of a flux of produced particles to an incident flux at the same energy after each incident particle has undergone a single interaction. Using $\sigma_{in} = 275$ mb (Belletini et al. 1966), $\tilde{a} = 2.7$, and our structure functions F_{ab} , defined in Eq.(1), we obtained $Z_{p\pi^+} = 0.0564$, $Z_{p\pi^-} = 0.0386$, $Z_{pK^+} = 0.0062$, and $Z_{pK^-} = 0.0022$,

In Fig. 1 we show $dZ_{p\pi}/dx$ for positive and negative pions produced by protons. The curves are normalized by division by $Z_{p\pi^+} + Z_{p\pi^-}$ and show the relative importance of the different x regions for production of muons by decay of pions produced by the baryon flux. The insensitivity of the charge ratio to the very low x region is demonstrated by this figure. In Fig. 2 integral distributions of the ratio of incident proton to produced pion energy are shown for cosmic ray fluxes. The region $x < 0.2$ ($E_p/E_\pi > 5$) contributes about 50% of $Z_{p\pi^+} + Z_{p\pi^-}$ but only 20% of $Z_{p\pi^+} - Z_{p\pi^-}$.

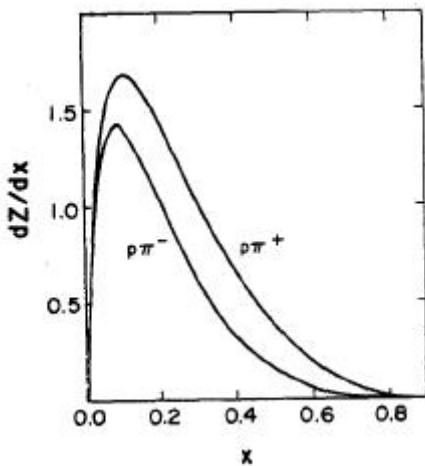


Fig. 1. Distribution of $x = E_\pi/E_p$ for fixed energy pions produced by the primary proton flux.

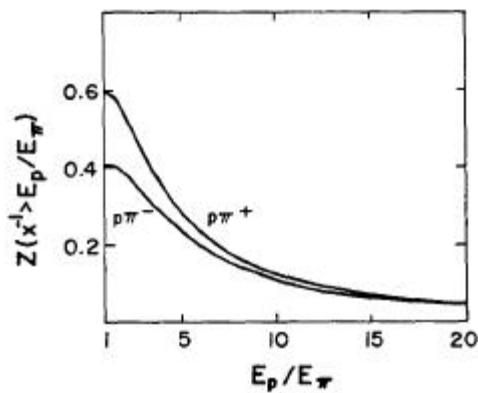


Fig. 2. Integral distribution for fixed energy pions produced by the primary proton flux.

It has been suggested (Ferbel 1972) that the scaling limit is approached at low energies for pion production in the fragmentation region of p-p collisions but deviations from scaling remain near $x = 0$ until higher energies. Such deviations would make only a small change in our calculated charge ratios, since the sensitivity to the region near $x = 0$ is reduced for cosmic ray intensity measurements because of the steeply falling primary spectrum. Mason and Elbert (1973) argue that their use of constraints in the fitting process and the use of accelerator data with $x > 0.3$ may have improved the agreement with very high energy particle distributions. Measurements at the Intersecting Storage Rings (ISR) at CERN give some support for this argument in the case of kaon production.

The charge ratio obtained for muons coming from pions produced in proton interactions was $Z_{p\pi^+} / Z_{p\pi^-} = 1.46$. Muons from kaons tend to increase the charge ratio, and hadronic cascades in the atmosphere tend to decrease it, as do neutrons present in primary nuclei.

We assumed that the structure functions for production of charged kaons were related by $F_{nK^{\pm}} = F_{pK}$ like the relation $F_{n\pi^{\pm}} = F_{p\pi}$ obtained for pions from isotropic spin symmetry with a charge symmetric target. A different type of fit (Mason and Elbert 1973) to proton production data gave $Z_{pp} = 0.20$ and a proton inelasticity of 0.58. The same values of the absorption length $\bar{E}_N = 120 \text{ gm/cm}^2$ and the interaction length $\bar{e}_N = 77.6 \text{ gm/cm}^2$ for nucleons in air that were used by Frazer et al. (1973) then yielded $Z_{pn} = 0.153$ and the absorption length of the difference of proton and neutron fluxes $\bar{E}_N' = 81.7 \text{ gm/cm}^2$. Inclusive data obtained from meson-proton collisions were used to calculate meson cascades by a method which included depletion of mesons by decay. In the high energy limit 12% of the muons came from mesons π produced by meson interactions and 20% from mesons produced in secondary nucleon interactions.

4. Results. The charge excess $(N_i^+ - N_i^-) / (N_i^+ + N_i^-)$ of muons is nearly proportional to the proton excess $(N_p - N_n) / (N_p + N_n)$ of cosmic ray primaries when incident nuclei are treated as made of free nucleons. With our assumptions, the charge ratio would be unity if the cosmic ray primaries were entirely α 's and would be slightly less than unity for a primary flux consisting of heavy nuclei having more neutrons than protons. The curve labeled "Proton Primaries Only" in Fig. 3 shows the predicted charge ratio for vertical muons if other primaries are ignored. All our other predictions result from using a primary proton excess of 0.81. This was obtained from a proton to alpha ratio of 22.5 found by averaging the two measurements at energies above 50 GeV/nucleon (Ryan et al 1972; Grigorov et al. 1971) and from the ratios of other primaries at 10 GeV/nucleon (Balasubramanian and Ormes 1972). Using the same proton excess of 0.74 as Frazer et al. (1972) would only have decreased our charge ratio

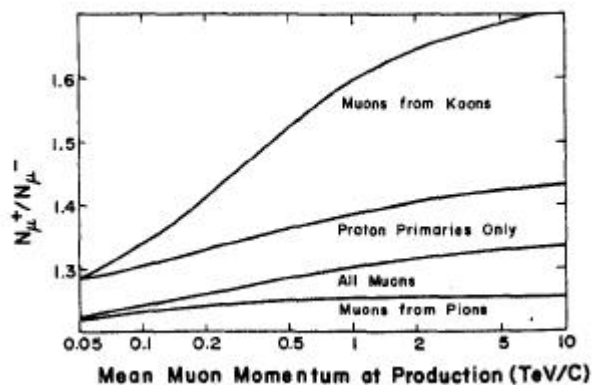


Fig. 3. Charge ratios of vertical muons from several sources.

predictions by 0.03. The implications for the charge ratio of a changing primary composition are discussed in another paper submitted to this conference (Elbert et al. 1973).

For $E_i < 0.2$ TeV the charge ratio of vertical muons is mainly determined by muons from pions, and it changes with energy and angle as changes occur in the probabilities of muons coming from different generations of hadron cascades. The lower curve of Fig. 3 shows the energy dependence of the charge ratio of muons from pions only and corresponds to a zero kaon to pion ratio. The upper curve of Fig. 3 shows that muons descended from kaons have a charge ratio which changes markedly with energy as changes occur in the relative importance of the contribution of two-stage production of muons through intermediate pions. However, for $E_i > 0.2$ TeV the dominant source of energy dependence of the predicted charge ratio of all vertical muons is the increasing relative importance of direct kaon decays as the energy increases. The charge ratio of muons from all sources is thus predicted to have an energy dependence resulting from the effects of meson decays, even though the ratio of charged pion and kaon fluxes at equal energies at production by the nucleon flux is fixed at $(Z_{pK^+} + Z_{pK^-}) / (Z_{p\pi^+} + Z_{p\pi^-}) = 0.088$. To a good approximation, meson decays make our predicted charge ratio a function of $E_i \cos \theta^*$ with θ^* an effective local zenith angle at production of the muons. For example, at a sea level angle of 83° we obtained a $\cos \theta^* = 0.16$. The energy and angular dependence of the charge ratio are thus closely related if scaling holds. Of course, energy-dependent violations of scaling would break this connection and are tested for by comparing prediction and experiment over a wide range of energies. An increase of K^+K^- pairs above our scaling predictions would bring Z_{pK^+} / Z_{pK^-} closer to $Z_{p\pi^+} / Z_{p\pi^-}$ and decrease the energy and angular dependence predicted for the charge ratio. Comparison of lower energy p-p collision results with ISR measurements (Morrison 1972) indicates that at high energies our value of Z_{pK^+} / Z_{pK^-} may be somewhat too large.

The effect of different choices of primary spectral index on the calculated charge ratio is shown in Fig. 4. An increase of the spectral index increases the relative contribution of higher x values (smaller E_p / E_π), for which positive mesons have greater dominance over negative mesons. We found that the predicted charge ratio increased by about 0.02 when the spectral slope of all cosmic ray primaries was increased by 0.1.

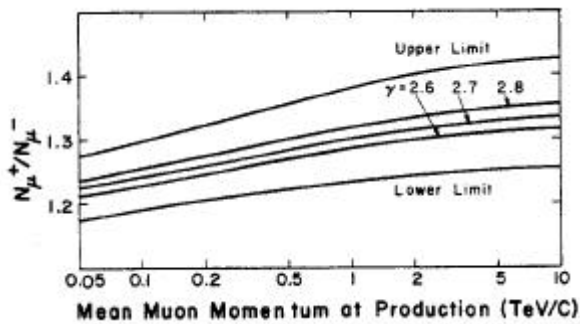


Fig. 4. Effects of spectral index and fitting errors on vertical charge ratio predictions.

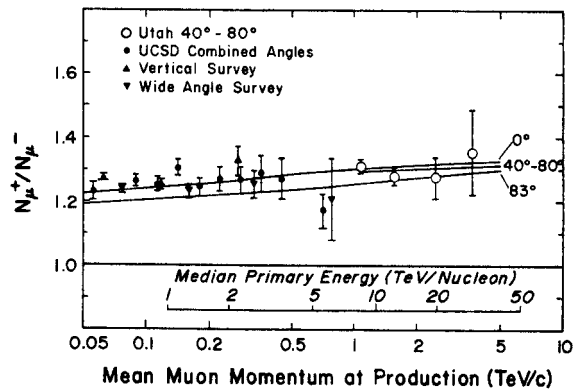


Fig. 5. Scaling predictions compared to measurements.

A major source of uncertainty in our predictions is due to the expected errors of the parameters obtained by Mason and Elbert (1973) in fitting the structure functions used to calculate the Z values. Adding the effects of errors for kaons and pions produced by protons to the effect of an uncertainty of 0.1 in \tilde{a} gave the limits indicated by the outer curves in Fig. 4. A given set of parameters gives predictions which fall on a curve approximately parallel to the curves in Fig. 4.

Predicted curves resulting from our calculations of the charge ratio are compared to the charge ratio of Ashley et al. (1973) and of others referred to in that paper. The agreement is good for muons produced with energies from 50 GeV up to 4.5 TeV. The median primary energies shown in Fig. 5 resulted from the scaling calculations of Mason and Elbert (1973). Our calculation of the charge ratio, which is made without any adjustable parameters, appears to give slightly lower values for N_1^+ / N_1^- than the main body of the data. In view of the discussion in the previous paragraph, this should not be disturbing. The data appear to show a slight rise with muon energy, and a decrease with increasing zenith angle. These trends are both in the expected directions, and their predicted size is sensitive to our choice of Z_K^+ / Z_K^- as discussed above. The Utah points, at the highest energies, are in satisfactory agreement with the curve labeled 40°- 80°. It was drawn through the predictions made for the four data points, which occur at different average zenith angles.

5. Discussion. Other charge ratio calculations have been made which used scaling but were based on p-p collision data. Frazer et al. (1972) used $Z_\pi^+ / Z_\pi^- = 2.02$ for p-p collisions and obtained a limiting value at high energies of $N_1^+ / N_1^- = 1.56$ for muons arising from pions only. This is significantly higher than our comparable result (1.26) shown in Fig. 3. Similarly, Garrafo et al. (1973) obtained $N_1^+ / N_1^- = 1.58$ for the same ratio using ISR p-p particle production data. They found that intranuclear cascade effects, calculated by assuming independent secondary collisions of particles in air nuclei, reduced the value of Z_π^+ / Z_π^- to 1.7 and reduced N_1^+ / N_1^- (from pions only) to 1.38. The lowest energy charge ratio data shown are for muons produced at energies overlapping energies available at ISR. Comparison of the measurements to our calculations support the contention that nuclear effects are important throughout the energy range covered by the data.

It has been suggested that the nuclear target effects arise from differences in charged pion production in the forward hemisphere in p-p and p-n collisions (Hume et al. 1973). However, accelerator experiments have given some support to factorization (Chen et al. 1971), which adds to scaling the assumption that the forward hemisphere distributions produced by collisions of elementary particles are independent of the target particle. Its approximate validity for elementary particle targets does not rule out intranuclear cascading. Factorization may result from the special simplicity of elementary particles and may not apply when nuclei are targets. Our use of nuclear target data avoids the necessity of identifying the source of the differences between p-p and p-air collisions.

The muon charge ratio is insensitive to the presence of an identical energy dependent factor in all hadronic cross sections. The interaction lengths for nucleons in air which we used correspond to $\sigma_{in} = 314$ mb, which is near the lower bound above 2 TeV found by Yodh et al (1972).

Scaling predicts an asymptotically flat charge ratio. Alternate models often have a power law growth of secondary meson multiplicity with primary energy $N_S(E_p) = E_p^{\hat{a}}$. If the growth of multiplicity is confined to secondaries of very low fractional energy, it may produce only very slow changes of the charge ratio. However, the simple assumptions that π^+ and π^- are produced with energy distributions of the same shape but different amplitudes and that the charge transferred to the meson component is constant gives a marked decrease of the charge ratio with increasing energy and multiplicity. Employing energy dependent Z values appropriate for this model, one finds the charge excess of pions produced by the primary proton flux is $(Z_{p\pi^+} - Z_{p\pi^-})/(Z_{p\pi^+} + Z_{p\pi^-}) = C E_p^{-\hat{a}}$. The charge excess of pions produced later in the hadron cascade also decreases at least this fast. The difference between the charge ratio of muons from pions and unity also decreases approximately as $E_i^{-\hat{a}}$, or by 50% between $E_i = 0.2$ and 3.2 TeV for $\hat{a} = 0.25$. This is inconsistent with the data of Fig. 5 unless a second muon component with an increasing charge excess is assumed.

We conclude that the near constancy of the charge ratio and the good agreement between measurements and our predictions support the applicability of scaling to pion production in the intermediate x region of hadronic interactions for laboratory energies up to 40 TeV.

Acknowledgements. This research is supported by the National Science Foundation (USA).

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