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PION EXCHANGE AND THE COSMIC RAY NUCLEON CASCADE*

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ABSTRACT

A model for $p + p \rightarrow n + X$ based on one pion exchange is shown to compare favorably with the propagation of the charged component of nucleons through the atmosphere.

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The property of Limiting Fragmentation or Scaling has led to a much broader understanding of high energy multiparticle reactions. Recently it has been shown^{1,2} that this feature of single particle inclusive spectra, when coupled with the empirical evidence for a power law behavior of the spectra of primary cosmic rays, enables one to uniquely correlate the spectra of secondary cosmic rays with accelerator data. For example, it was found that in spite of logarithmically rising multiplicities, the μ^+/μ^- ratio should be energy independent and can be simply related to the spectrum of secondary particles (pions, kaons, and nucleons) in the fragmentation region of the projectile nucleon.

In this note, we focus our attention on the cosmic ray nucleon cascade through the atmosphere. We show how the propagation of the charged component (proton flux - neutron flux) is essentially determined by a certain integral over the single particle spectrum for the process

$$p + p \rightarrow n + X \quad (1)$$

In anticipation of experimental data on this inclusive reaction, soon to be obtained at the CERN-ISR, a model has been proposed³ for this process based on the dominance of single pion exchange. We calculate in this model the atmospheric depth dependence of the charged component of nucleons and find rather good agreement with the empirical results.

We denote by $P(E, y)$ ($N(E, y)$) the proton (neutron) flux at energy E and atmospheric depth y (gm/cm^2) and describe the propagation of these particles through the atmosphere by the following transport

equations

$$\frac{\partial P(E,y)}{\partial y} = -\frac{P(E,y)}{\lambda_N} + \frac{1}{\lambda_N E} \int_E^\infty dE' \{P(E',y) f_{pp}(E,E') + N(E',y) f_{np}(E,E')\} \quad (2a)$$

$$\frac{\partial N(E,y)}{\partial y} = -\frac{N(E,y)}{\lambda_N} + \frac{1}{\lambda_N E} \int_E^\infty dE' \{N(E',y) f_{nn}(E,E') + P(E',y) f_{pn}(E,E')\} \quad (2b)$$

Here, λ_N is the nucleon interaction mean free path in air while

$$f_{pn}(E,E') = \frac{E}{\sigma_{inel}^{pp}} \frac{d\sigma_{p \rightarrow n}}{dE}(E,E') \quad (3)$$

is the invariant cross section for the process $p + p \rightarrow n + X$. The other f_{ij} are defined in an analogous way. The first term on the r.h.s. of eqs. 2a and 2b represents the attenuation due to inelastic collisions, while the second and third terms represent the restoration of the flux due to the inelastic collisions of nucleons at energies $E' > E$. In writing down these equations, we have ignored the production of nucleons due to inelastic collisions of mesons.

If we now apply the scaling hypothesis to our single particle spectra, which can be expressed as

$$\lim_{\substack{E, E' \rightarrow \infty \\ E/E' = x}} f(E,E') = \tilde{f}(x) \quad (4)$$

and assume a separable dependence on E and y for the proton and neutron fluxes,

$$P(E,y) = P(y) E^{-(1+\gamma)} \quad (5a)$$

$$N(E,y) = N(y) E^{-(1+\gamma)} \quad (5b)$$

our transport equations can be cast in the form

$$\frac{\partial P(y)}{\partial y} = -\frac{P(y)}{\lambda_N} (1 - Z_{pp}) + \frac{N(y)}{\lambda_N} Z_{pn} \quad (6a)$$

$$\frac{\partial N(y)}{\partial y} = -\frac{N(y)}{\lambda_N} (1 - Z_{pp}) + \frac{P(y)}{\lambda_N} Z_{pn} \quad (6b)$$

Here, we have defined

$$Z_{ij} = \int_0^1 x^\gamma - 1 \tilde{f}_{ij}(x) dx \quad (7)$$

and have used the charge symmetry relations⁴

$$\tilde{f}_{pp}(x) = \tilde{f}_{nn}(x) \quad (8a)$$

$$\tilde{f}_{pn}(x) = \tilde{f}_{np}(x) \quad (8b)$$

The solution of these equations are

$$P(E,y) = \frac{N_0}{2} (e^{-y/\Lambda_N} + \Delta_0 e^{-y/\Lambda'_N}) E^{-(1+\gamma)} \quad (9a)$$

$$N(E,y) = \frac{N_0}{2} (e^{-y/\Lambda_N} - \Delta_0 e^{-y/\Lambda'_N}) E^{-(1+\gamma)} \quad (9b)$$

where $\Lambda_N = \lambda_N (1 - Z_{pp} - Z_{pn})^{-1}$ is the nucleon attenuation length in the atmosphere and $\Lambda'_N = \lambda_N (1 - Z_{pp} + Z_{pn})^{-1}$. The initial primary flux at the top of the atmosphere is simply

$$P(E,0) + N(E,0) = N_0 E^{-(1+\gamma)} \quad (10)$$

where experimentally, $\gamma \approx 1.7$.

The propagation of the charged component, defined as

$$\frac{P(E,y) - N(E,y)}{P(E,y) + N(E,y)} = \Delta(y) \quad (11)$$

depends simply on the ratio of Z_{pn}/λ_N ,

$$\Delta(y) = \Delta_0 e^{-2Z_{pn} y/\lambda_N} \quad (12)$$

The model for the process³ $p + p \rightarrow n + X$ is depicted in fig. 1.

and we find the invariant distribution,

$$\tilde{f}_{pn}(x) = \frac{2x}{\sigma_{inel}^{pp}} \frac{1}{4\pi} \left(\frac{g^2}{4\pi}\right) \sigma_T^{\pi p} \int dt e^{a(t - \mu^2)} \frac{|-t|}{(t - \mu^2)^2} (1-x)^{-2\alpha_\pi(t) + \alpha_p(0)} \quad (13)$$

Here $\frac{g^2}{4\pi}$ is the pion nucleon coupling constant, $\sigma_T^{\pi p}$ is the asymptotic total cross section for $\pi - p$ scattering, and μ is the pion mass. $\alpha_\pi(t)$ and $\alpha_p(0)$ are the trajectory and intercept of the pion and pomeron regge poles respectively and a is a cut-off parameter which we take to be³ $\approx 6\text{GeV}^{-2}$. The factor of 2 on the r.h.s. of eq. 13 is due to isospin.

Before stating the numerical result for Z_{pn} we would like to comment on the model used for³ $p + p \rightarrow n + X$. First as the ρ and A_2 are weakly coupled to NN the pion exchange is expected to dominate. Secondly this model is applied for the spectrum of emitted nucleons which are produced mainly far from the central region (in the c.m. system). Thirdly the assumption that the model describes on the average most of the events makes the approach even more reliable for predictions derived from integrated quantities. Finally and most importantly, due to the scaling phenomenon and the primary cosmic ray spectrum behavior, the small x -region, in the expression for Z_{pn} , is de-emphasized and therefore the large x -region, where our model is mostly applicable, should give the major part of Z_{pn} . As anticipated the uncertainty in Z_{pn} is due to the inclusion of the small x -region. However, as discussed above, this uncertainty will not be large and obviously the true result for Z_{pn} should be nearer to the calculated lower bound (see below).

In calculating Z_{pn} , we chose $\left(\frac{g^2}{4\pi}\right) = 15$,

$$\sigma_{inel}^{pp} = 32\text{mb}, \sigma_T^{\pi p} = 25\text{mb}, \text{ and}$$

$$\alpha_\pi(t) = -.016 + 0.9t \quad (14a)$$

$$\alpha_p(0) = 1 \quad (14b)$$

The upper limit of integration in eq. 7 was taken to be 1 while the lower limit was varied between $x = .5$ and $x = 0$. The values of Z_{pn} thus calculated fell between

$$0.095 \leq Z_{pn} \text{ (predicted)} \leq 0.15 \quad (15)$$

If we take the experimental value⁵ for $\lambda_N = 77.6 \text{ gm/cm}^2$ together with the empirical result for $\Delta(y)$

$$\Delta(y) = \Delta_0 e^{(-0.0029 + .0019)y - .0008y} \quad (16)$$

we find that the experimental value of Z_{pn} falls in the range

$$0.081 \leq Z_{pn} \text{ (experimental)} \leq 0.185 \quad (17)$$

in very good agreement with the above model prediction.

Of course there is no substitute for a direct determination of Z_{pn} based on experimental analysis of the spectrum for $p + p \rightarrow n + X$, soon to be performed at the CERN-ISR. However, we are encouraged by the rather good result obtained by our simple model. Finally, we would like to emphasize that it is the novel scaling property which enables us to compare favorably the proposed model for $p + p \rightarrow n + X$, where its parameters are measured from accelerator data, with measurements performed in the very high energy regime of cosmic rays.

FOOTNOTES AND REFERENCES

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FIGURE CAPTIONS

- Fig. 1. (a) Kinematics and the pion exchange amplitude in
 $p + p \rightarrow n + X$.
- (b) Contribution of the diagram in (a) to the inclusive
differential cross-section of $p + p \rightarrow n + X$.

(a)

(b)

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