HADRON INTERACTIONS AT HIGH ENERGIES AND THEIR RELATIONSHIP TO SOME COSMIC RAY PHENOMENA

THESIS

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By
TAREK MOHAMED ABDEL HAMEED AWWAD
(B. Sc.)

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NOTE

Besides the work carried out in this thesis the candidate has attended the following postgraduate courses :

1- Quantum Mechanics

2- Electronics

3- Solid State Theory

4- Radiation Physics

5- Advanced Quantum Mechanics (Special Course)

He has successfully passed a written examination in these courses in partial fulfilment for the degree of Master of Science.

Approved
Head of Physics Dept.

M.A Keny

Prof. Dr. M.A. Kenawy

بسم الله الرحمن الرحيم

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يُرسَلُ عَلَيكُمَا شُوَاظٌ مِّن نَّارٍ وَنُحَاسٌ فَلَا تَنتَصِرَانِ ۝ فَبِأَيِّ ءَالَآءِ رَبِّكُمَا تُكَذِّبَانِ .

(صدق الله العظيم)

الأيات ٣٥، ٣٦ من سورة الرحمن

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SUMMARY

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A theoretical study has been made of high energy hadron-hadron interactions using results from recent accelerator experiments and the consequences to problems in cosmic ray physics.

The study is concerned with two main subjects; the first is the derivation of the degree of scaling violation in hadron inclusive reactions at accelerator energies up to $\sqrt{S} = 540$ GeV and the second deals with the derivation of cosmic ray muon spectra and the composition of primaries if scaling violation features are extrapolated to the much high cosmic ray energies.

An extensive amount of data on the inclusive cross section for charged pion production in pp interactions has been analysed in the centre-of-mass energy range $23 < \sqrt{S} < 53$ GeV in the x-p_T plane, where x is the Feynman scaling variable and p_T is the transverse momentum. The main results are as follows :

1) In the kinematical region $0 \leqslant x < 1.0$ and $p_T \leqslant 1.0$ GeV, the invariant cross section can be well described by the formula :

$$E\,\frac{d^3\sigma}{dp^3}\,(x,p_T) = a_1\,(1-x)^{a_2(p_T)}\,\exp\{-(a_3 p_T\, e^{-a_4 x})\}$$

where a_1, a_2, a_3 and a_4 are parameters.

2) The above proposed formula indicates scaling violations since introducing the parameter a_4 prevents factorization of the cross-section into separate functions of x and p_T.

In order to determine the degree of scaling violation for charged particle production in hadron inclusive reactions, the pseudo-rapidity distributions for the produced particles are derived for energies $\sqrt{S} < 53$ GeV as well as for the recent results from the SPS collider at the much higher energy $\sqrt{S}$ = 540 GeV. The main results are as follows :

1) The particle spectra can be described by a scale breaking formula

$$\frac{E}{\sigma_t} \frac{d^2\sigma}{dp_\ell dp_T^2} = (\frac{S}{S_o})^\alpha f(x(\frac{S}{S_o})^\alpha , p_T)$$

where S_o is a datum energy and (α) is a scale breaking parameter.

2) The scale breaking parameter (α) derived from the pseudo-rapidity distributions of all charged particles using a constant inelasticity is found to have a mean value $\alpha = 0.101 \pm 0.005$ over the energy range considered. Such value may be considered as a lower limit to the breakdown of Feynman scaling.

3) Another evidence for scaling violation is obtained from a slow variation of mean transverse momentum with energy in the form

$$\langle p_T \rangle = 0.231 + 0.03 \ln \sqrt{S}$$

In order to study the consequences of the above breakdown of scaling to cosmic ray phenomena, a detailed mathematical model has been put forward to describe the muon cascades initiated in the atmosphere by primary nuclei. The muon spectrum at sea level has been derived in the frame of multi-fireball production for three different models, namely : strict Feynman scaling, scaling violation model, and a conventional statistical model. The rise of pp cross section with energy as well as the contribution of kaons have been taken into consideration.

From predictions of the scaling violation model and a normal composition for primary nuclei, we derive a new estimate for the spectrum of Fe nuclei above 10^{13} eV in the form

$$J_{Fe}(E_N)dE = 6.569\times10^{-4}\ E_N^{-2.406}(\text{nuclei}, cm^{-2}s^{-1}sr^{-1}(\frac{GeV}{\text{nucleon}})^{-1})$$

with energy E_N in GeV/nucleon. This result shows that if the breakdown of scaling observed at accelerator energies continues to cosmic ray energies ($>10^{13}$ eV/nucleon) then the iron spectrum should be much steeper than that observed at low energies ($\sim 10^{11}$ eV/nucleon). This means that the conventional idea of a possible dominance of Fe nuclei in the primary beam at high energies has to be excluded and that the composition around 10^{15} eV/nucleon is in fact not much different from that at low energies.

INTRODUCTION

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Recently, the study of hadron interactions at extremely high energies has become a subject of great interest both in problems concerning the substructure of hadrons (i.e. Quarks and gluons) and in those problems relevant to the production of cosmic ray particles in the atmosphere and the mass composition of primary cosmic rays. The nature of ultrahigh energy hadronic reactions has now been enhanced by the great extension in accelerator energies made available by the CERN Intersecting Storage Rings (ISR) (20-60 GeV c.o.m. energy), the proton synchrotron at FNAL (200-400 GeV protons or mesons on a stationary target), the $p\bar{p}$ colliders (SPS) at CERN ($\sqrt{S}$ = 540 GeV) as well as the most recent $p\bar{p}$ experiment at CERN (SPO) in which the c.o.m. energy $\sqrt{S}$ reaches 900 GeV (e.g. Rushbrooke, 1985).

Two problems are in fact fundamental in the study of cosmic rays as a high energy physics subject. The first is the high energy interaction model which best describes hadrons' spectra while the second deals with the spectrum and composition of cosmic ray primaries at energies unattainable by direct measurements. The study of the production and propagation of cosmic ray muons in the atmosphere is considered as one of the important tests of the combination of an interaction model with a certain primary mass composition.

Muons are produced mainly as a result of the decay of charged pions and Kaons which are the products of the interactions of primary cosmic ray nuclei with air nuclei in the atmosphere. A variety of experimental techniques are now available for measuring muon intensities at sea level, under sea water and underground in the TeV energy region and at different angles from the vertical (e.g. magnetic spectrograph, burst γ-cascades, etc).

Conventionally, two interaction models have always been competing for the interpretation of cosmic ray high energy phenomena namely the CKP and Feynman's scaling models (e.g. Goned et al, 1975). Recently, however, the possibility of a significant breakdown in Feynman scaling has opened a new window onto the subject, (e.g. Wdowczyk and Wolfendale, 1984, 1987). Such scale breaking model carries features from each of the first two models and should have important consequences as to the problem of mass composition of primary cosmic rays at very high energies.

The CKP model of Cocconi et al. (1961) is based on the older two fireball model of Ciok et al (1958) and Cocconi (1958). This model is characterized by an energy distribution for secondary pions consistent with a statistical type emission and a dependence of pion (kaon) multiplicity n_s on primary energy E_p as $n_s \propto E_p^{\frac{1}{4}}$.

On the other hand, accelerator results in the late 1960s led to the so called "scaling" model of Feynman (1969) in