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PARTIAL INELASTICITY IN HIGH ENERGY HADRON-NUCLEUS COLLISIONS AND SOME MULTIPLE PRODUCTION MODELS

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Using some of the existing models for multiple production of hadrons we have computed here theoretically the inelasticity partial coefficients in proton-iron collisions at very high energies (≈ 0.5 TeV) and have compared our estimated values with the very recent measurements of Avakian et al. Calculations are intended to be done mostly for the central region ($x \approx 0$) for which Wong's model, although considered here, is not very suitable which explains its lack of satisfactory agreement with the data. So far as this parameter is concerned, barring QCD, all other models stand comparably quite well. The experimental data on the same parameter for pion-iron collisions too have also been analysed with the help of only a single model (SCM) and there is also a fair agreement between this model and the measurements. The lack of good agreement of the QCD model with the data is also quite easily explainable.

1. Introduction

In recent years an increased interest in the study of inelasticity factor has been shown by both theorists[1-4] as well as experimentalists[5-6]. The factor is defined by $K = W/\sqrt{S}$ where W is the invariant energy effectively used for hadronization and $\sqrt{S}$ the total available energy in case of different types of scattering. Physically, this parameter is an index of the degree of hadronization in ultrahigh energy collisions and is of special physical importance as it is related quantitatively in a direct way with the leading particle effect.

Our aim here is to calculate the partial inelasticity factor by using the radial scaling model[7], sequential chain model[8] and Wong's model[9] in order to make a comparative study of the values thus obtained with some other theoretical estimations and experimental measurement. The task by itself offers a nice opportunity to check the validity of the models under consideration at superhigh energies.

2. *Basic relations*

The partial inelasticity[5] is defined as

$$K_{\pi^0} = \int \frac{x}{(\sigma_{in})_{NA}} \frac{d\sigma^A}{dx} dx \tag{1}$$

where $\frac{d\sigma^A}{dx}$ is the π^0 inclusive spectrum of the nucleus, $(\sigma_{in})_{NA}$ is the total inelastic cross section of the nucleon interaction with the nucleus (with the production of at least one neutral pi meson) and x is the portion of the initial energy carried by a neutral pion

$$x = \frac{E_{\pi^0}}{E} = \frac{2p_L}{\sqrt{S}}.$$

Within the framework of multiple scattering theory proposed by Glauber one obtains the following expression for the value sought

$$K_{\pi^0}^{NA} = K_{\pi^0}(x_0) \frac{N(0, \langle\sigma\rangle)}{N(0, \sigma_{inNN})} \tag{2}$$

where

$$N(0, \langle\sigma\rangle) = \int d^2b \, (1 - e^{-\sigma T(b)})/\sigma \tag{3}$$

and

$$T(b) = \int \varrho(b, z) \, dz. \tag{4}$$

Physically $T(b)$ represents the projection of the one nucleon nuclear density on the plane of impact parameter, $\sigma_{in\,NN}$ is the total inelastic cross section of nucleon-nucleon interaction

$$K_{\pi^0}(x_0) = \int_{x_0}^{1} x \frac{1}{\sigma_{in\,NN}} \frac{d\sigma}{dx} (NN \to \pi^0 X) \, dx \tag{5}$$

where x_0 is determined by the registration efficiency of π^0 mesons and

$$\langle\sigma\rangle = \sigma_{in\ NN} - \int_{x_0}^{1} x \frac{1}{n}\frac{\mathrm{d}\sigma}{\mathrm{d}x}(NN \to NX)\,\mathrm{d}x \tag{6}$$

where n is the (average) multiplicity of the secondary particles in the elementary process. The energy range of our concern is 0.5—5.0 TeV. For the one-nucleon nuclear density we use the form

$$\varrho(r) = \frac{\varrho_0}{1 + \exp\left[(r - R)/a\right]} \tag{7}$$

with parameters taken from Ramanamurthy et al.[10]. All these taken together suffice to compute theoretically the values of the partial inelasticity coefficient. We will select the cases of iron-nucleus ($A = 56$) as the target and pion and nucleon as the projectile. The results for proton-iron and pion-iron inelastic cross section are used from Fig. 1[6] and Fig. 2[6], respectively. Our calculations are based on

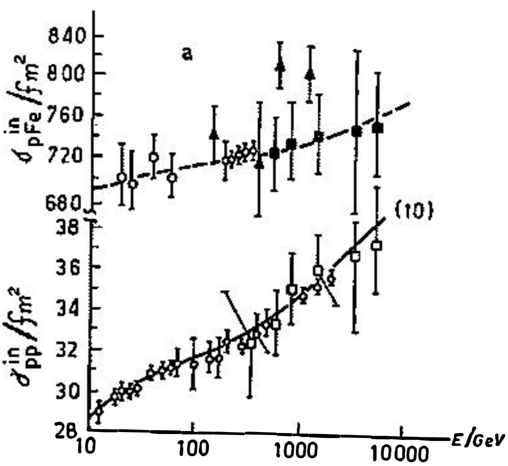

Fig. 1. Dependence of σ^{in}_{PP} and σ^{in}_{PFe} on energy in case of PP inelastic cross section, PFe inelastic cross section, respectively.

Avakian et al.; O Accelerator data (Refs. 1, 15, 17 of Avakian et al.[6]). Ref. 3 of Avakian et al.[6]; Conversion of the data of Avakian et al.

expressions and data fit which are valid for ISR range of energies, $\sqrt{S} < 63$ GeV and the data of Avakian et al.[5] are available for higher (0.5 to 5 TeV) energy region. Hence we calculate the results for accelerator range of energy and extrapolate them to higher energies by using a correction factor. The standard practice for calculating the inclusive cross section for neutral pion in PP collision is

$$E\frac{\mathrm{d}^3\sigma}{\mathrm{d}p^3}\bigg|_{PP\to\pi^0x} = \frac{1}{2}\left[\left(E\frac{\mathrm{d}^3\sigma}{\mathrm{d}p^3}\right)_{PP\to\pi^+x} + \left(E\frac{\mathrm{d}^3\sigma}{\mathrm{d}p^3}\right)_{PP\to\pi^-x}\right] \tag{8}$$

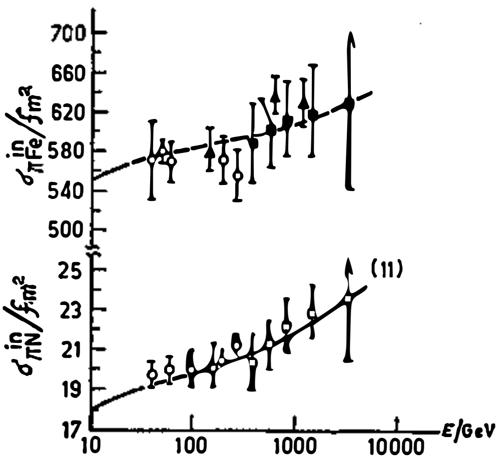

Fig. 2. Dependence of $\sigma^{in}_{\pi N}$ and $\sigma^{in}_{\pi Fe}$ on energy in case of PP inelastic cross section, PFe inelastic cross section, respectively. — — Avakian et al.; O — Accelerator data (Refs. 1, 15, 17 of Avakian et al.[6]) — — Ref. 3 of Avakian et al.[6], — Conversion of the data of Avakian et al.

and in all the model dependent calculations we have followed this. In this work p and k are used to mean the same, that is, four momentum of the detected secondary.

In calculational procedure we have always made use of the relation (1) directly with an up to date nature of the empirically observed A-dependence of the hadron-nucleus collisions. The values thus obtained have now been verified with the much more complicated relations given by expressions (2) to (7) which just provide a little more sophisticated way of arriving at the values of the same parameter. But these complications do not at all appreciably change the theoretical values of the partial inelasticity coefficient which we are really interested in.

3. *Summary of the models used and theoretical calculations*

(a) *Radial scaling model*

In studying single particle inclusive cross sections a set of variables needs to be chosen such that the inclusive cross section displays a simple behaviour. This forms one of the motivations for seeking some sort of scaling in high energy hadronic collision processes. The searches[7] made in terms of the scaling variable $x_R = (E^*/E^*_{max})$ called radial scaling variable showed in general that the proton-proton single particle inclusive cross section at sufficiently high $\sqrt{S}$ ($\sqrt{S} \geqslant 10$ GeV) can be expressed as a function of two variables, p_T and x_R

$$E\frac{d^3\sigma}{dp^3} = f(p_T, x_R) \tag{9}$$

where E^* is the energy of the detected particle in the centre of momentum frame (c. m.) and E^*_{max} is the maximum energy kinematically available to the detected particle in the c. m. frame. The range of x_R is $0 < x_R < 1$ for all p_T, and the case $x_R = 1$ corresponds to the exclusive limit. Since this variable is independent of the centre of momentum angle and depends on only the radial distance from the kinematic boundary, the authors have called it the »radial« scaling variable. This variable x_R is also written as $x_R = \sqrt{x_L^2 + x_T^2}$. More specifically, the inclusive cross section is expressed in the factorized form

$$E \frac{\mathrm{d}^3\sigma}{\mathrm{d}p^3} = F(p_T)\, G(x_R) \tag{10}$$

and more explicitly

$$E \frac{\mathrm{d}^3\sigma}{\mathrm{d}p^3} = A(p_T)^{-N} (1 - x_R)^M. \tag{11}$$

The factors N and M are chosen in a hand-inserted way and are different for various types of secondaries. The proposal for this scaling came first probably from Kinoshita and Noda[7f)] in 1971 although apparently it had been discussed by Feynman in 1969 as commented by Taylor et al. 1976[7d)]. Anyway the differences between the Feynman scaling and the radial scaling hypotheses are worth-mentioning.

In fine, for single particle inclusive reactions use of the radial scaling variable x_R leads to an earlier scaling of the invariant cross sections than use of the x_F $\left(\text{the Feynman scaling variable} = \frac{2p_L}{\sqrt{S}}\right)$. The radial scaling limit is always approached from above for gradually rising S and is reached very near to $\sqrt{S} = 10$ GeV whereas the Feynman scaling limit is approached either from below or from above or the scaling is exact depending on the dominance of phase space effects, dynamic effects or the coincidental cancellations of these two effects, respectively. At small x_F (≈ 0.05 to 0.20) there are gross violations of Feynman scaling due to large changes in the phase space suppression and this suppression continues for large-p_T (especially for P and K data) production of particle at ISR energies[7d)].

For the last five years or so there has been a decline in the studies in the radial scaling hypothesis, maybe due to the overwhelming sweep made by the QCD. But that QCD may not be the solution to all the problems with many particle production phenomena is also recognized[11,12)] by now for which we have mainly resorted here to the models not exactly based on the typical quark-gluon ideas. The result obtained on the basis of this model is given in a tabular form subsequently.

(b) *Sequential chain model*

This model proposes that all hadronic interactions are basically pion-pion interactions as the nucleons are composed of pions and spectators. The production of secondary pions takes place through successive $\varrho\omega\pi$ chains; the baryon-antibaryons are produced through the decay of the (virtual) secondary pions and the kaons through $\varrho\pi\varphi$ coupling[8)]. This model has the following cardinal features:

i) the model treats both the low-p_T and large-p_T phenomena on a uniform dynamical footing with only changes in the kinematics,

ii) the model derives a power law for average multiplicity ($\sim S^{1/5}$ for pions) and obtained that the Feynman scaling should, in general, be violated[8a)],

iii) the model observes the «jettiness» features of particle production as two-sided «sprays» of hadrons[8b)],

iv) the model explains theoretically and quantitatively the recently established leading particle effect in hadron-hadron collisions (proposed long ago and observed first by the cosmic ray physicists) in an in-built manner[8c)],

v) this model explains[8c)] in an unambiguous way the by-now established quantitative 'universality' of lepton-and hadron-involved interactions as well as of e^+e^- annihilations,

vi) the model explains the majority of events at both ISR and $P\bar{P}$ collider energies,

vii) there is only a singular parametrization in the model but for which all other factors are either derived or determined from experiments. And the source of uncertainties lie only in the experimental errors.

This model is mainly confined to the region $x < 0.15$ because of much availability of experimental data in the central region. According to this model for $PP \to \to \pi^c X$ the inclusive distribution is given by

$$\frac{1}{\sigma_{in}} k_0 \frac{\mathrm{d}\sigma}{\mathrm{d}^3k}\bigg|_{PP\to\pi^\pm x} = \frac{0.9}{\langle n_{\pi_-}\rangle} \frac{25}{4} \frac{1}{4\pi} \frac{f^2_{\varrho\omega\pi}}{16\pi^2} \exp\left[-26.88 \frac{k_T^2}{1-x}\right] \exp\left[-2.38\langle n_{\pi^-}\rangle x\right] \tag{12}$$

with

$$\langle n_{\pi^+}\rangle_{PP} = \langle n_{\pi^-}\rangle_{PP} = \langle n_{\pi^0}\rangle_{PP} = 1 \cdot 1\ S^{1/5} \tag{13}$$

and identity of k_T and p_T physically.

In the ISR energy range $S = 10^3$ (GeV)^2, $\langle n\rangle_{\pi^-} = 3.5$ and taking[13)]

$$f^2_{\varrho\omega\pi}/4\pi = 17/\mathrm{GeV}^2$$

we find

$$k_0 \frac{\mathrm{d}\sigma}{\mathrm{d}^3k}\bigg|_{PP\to\pi^- x} \approx 88.87 \exp\left[-7.68 \frac{k_T^2}{1-x}\right] \exp\left[-8.33x\right] \frac{\mathrm{fm}^2\mathrm{c}^3}{(\mathrm{GeV})^2}. \tag{14}$$

Here we have taken $\sigma_{in}^{PP} = 35$ fm^2. The nuclear factor introduced below is due to the A dependence of nucleon-nucleus collision and as proposed by Levin and Ryskin[14)]

$$x \frac{\mathrm{d}\sigma^A}{\mathrm{d}x} = \left[\pi \int \left(E \frac{\mathrm{d}^3\sigma}{\mathrm{d}k^3}\right)_{PP\to\pi^0 x} \mathrm{d}k_T^2\right] A^{0.9}. \tag{15}$$

Here A is the atomic number of the specific nucleus. For our calculation $A = 56$.

Again as we are considering nucleon-nucleus collision instead of nucleon-nucleon collision a correction term $\sigma_{in}^{pp}/\sigma_{in}^{pA}$ is to be introduced[15]. Here $\sigma_{in}^{pp} = 35\ \text{fm}^2$, $\sigma_{in}^{pA} = 735\ \text{fm}^2$. Then for small p_T and small x we get

$$K_{\pi^0}^{pFe} \approx 0.19. \tag{16}$$

(c) *Wong's model*

In order to discern coherent processes from incoherent and collective processes in nucleon-nucleus reaction at high energies Wong[9] used an incoherent multiple collision model. According to this model[9] the projectile nucleon makes successive inelastic collisions with nucleons in the target nucleus, the probability of such collisions being given by the thickness function and the nucleon-nucleon inelastic cross section. Wong found that though this model can explain the inelastic proton data, the pseudorapidity distribution data $dN^{PA}/d\eta$ and the total nucleon-nucleus absorption data it fails to explain the single particle fragmentation data for non-leading particles. The modified model gives cross section for different reactions in the projectile fragmentation region in good agreement with experiment. The experimental differential cross section for the reaction $PP \to CX$ can be represented by Brenner et al.[16] as

$$\frac{d\sigma\,(PP \to bX)}{dx\, dp_T^2} = \frac{1}{x}\, C\,(c \cdot p_T)\,(1 - x)^{\eta(c)} \tag{17}$$

where b denotes the produced particle in a reaction. Wong has parametrized C as a Gaussian function in p_T^2 with the same standard deviation as that for $PP \to PX$

$$C\,(c, p_T) = \frac{A\,(C)}{2\pi\,\sigma_t^2} \exp\left[-\frac{p_T^2}{2\sigma_T^2}\right] \tag{18}$$

where $A\,(C)$ can be obtained from the tabulated values of $C\,(c, p_T)$ and $\eta\,(\pi^\pm)$ from Table 16 of Brenner et al.

$$\eta\,(\pi^+) = \eta\,(PP \to \pi^+X) = 3.39. \tag{19}$$

For $P_T = 0$ to 5 GeV/c

$$A\,(C) = 17 \qquad \sigma_t = 0.31\ \text{GeV/c}.$$

The final expression for the cross section in $PA \to \pi^\pm X$ according to this incoherent multiple collision model is given by

$$\frac{d\sigma\,(PA \to CX)}{dx\, dp_T^2} = \frac{A}{\nu}\,[1 - (\nu - 1)\,K]\,\frac{d\sigma\,(PP \to CX)}{dx\, dp_T^2} \tag{20}$$

where ν is the average number of collisions

$$\nu = \frac{A\,\sigma_{in}^{PP}}{\sigma_{in}^{PA}}$$

with $\sigma_{in}^{PP} = 35\ \mathrm{fm}^2$, $\sigma_{in}^{PA} = 700\ \mathrm{fm}^2$ from Ref. 6, $A = 56$ is the atomic number of iron nucleous and K is a reduction parameter ≈ 0.15. Finally

$$\frac{\mathrm{d}\sigma\,(PFe \to \pi^{\pm}X)}{\mathrm{d}x\,\mathrm{d}p_T^2} = 411.69 \exp\left(-5.208\, p_T^2\right)(1-x)^{3.39}\,\mathrm{d}p_T^2\,\mathrm{d}x.$$

Using the relation

$$E\frac{\mathrm{d}^3\sigma}{\mathrm{d}p^3} = \frac{x}{\pi}\frac{\mathrm{d}\sigma}{\mathrm{d}x\,\mathrm{d}p_T^2} \tag{21}$$

we get,

$$E\frac{\mathrm{d}^3\sigma}{\mathrm{d}p^3} = \frac{411.69}{\pi}\,\frac{[\exp\left(-5.208\, p_T^2\right)\mathrm{d}p_T^2]}{[x\,(1-x)^{3.39}\,\mathrm{d}x]}. \tag{22}$$

The result obtained, according to this model, is

$$K_{\pi^0}^{PFe} = 0.37. \tag{23}$$

4. *Model-dependent results*

The results we arrive at on the basis of all the above mentioned models are given along with some other theoretical and experimental results in the following tabular form (Table 1).

TABLE 1.

Name of the experiments and models	Value of the inelasticity partial coefficient for neutral pion in PFe collision at c. m. energy	
	50 GeV	250 GeV
Experimental results[5]	Nil	0.20
Radial scaling model	0.18	0.19
SCM	0.10	0.11
Wong's model	0.35	0.37
Hagedorn's model[17]	0.18	0.195
MQGS model[17]	0.178	0.2
QCD[17]	0.02	0.02

5. *Inelasticity partial coefficient for neutral pions in πA collisions and a sequential chain model (SCM)*

In case of $\pi P \to \pi X$ the inclusive distribution is obtained after modifying Eq. (13) for σ_{in} and pion multiplicity $\langle n \rangle_{\pi P}$. In this case $\sigma_{in} = 24$ fm^2 and

$$\langle n \rangle_{\pi P}^{\pi^0} \approx 1.2 \, \langle n \rangle_{PP}^{\pi^0} \approx 4.2. \tag{24}$$

Then we have

$$k_0 \frac{\mathrm{d}\sigma}{\mathrm{d}^3 k}_{\pi P \to \pi x} \approx 50.78 \exp \left[-6.4 \frac{k_T^2}{1-x} \right] \exp \left[-10x \right] \frac{\mathrm{fm}^2 \mathrm{c}^2}{\mathrm{GeV}^2}. \tag{25}$$

Halliwell[17] after analysis of experimental data from FINAL experiment found an A dependence of cross section which in case of pion-nucleus collision can be fitted to the following empirical form $(p_T \equiv k_T)$

$$E \frac{\mathrm{d}^3\sigma}{\mathrm{d}p^3} (x, p_T, A) = \sigma_0 (x, p_T) \, A^{\alpha'} (x, p_T). \tag{26}$$

The correction term to be used in the calculation of $K_{\pi 0}^{\pi Fe}$ is $\frac{\sigma_0 A^{\alpha'}}{\sigma_0^{in}}$. For small p_T and small x

$$K_{\pi_0}^{\pi Fe} \approx 0.26. \tag{27}$$

Here $|\sigma_0| = 10$, $\alpha' = 0.5$, $A = 56$.

This result is compared with experimental results[6] in Table 2.

TABLE 2.

Name of the experiments and model	Value of the inelasticity partial coefficient for natural pion in πFe collision at c. m. energy	
	50GeV	250GeV
Experimental result[5]	0.24	0.26
Sequential chain model (SCM)	0.24	0.26

6. *Discussion and concluding remarks*

The numerical results we have arrived at have been doubly checked by analytical methods as well as by numerical methods. The quantitative agreement of the theoretical results with experimental measurements (or just the lack of it) reflects the relative intrinsic strengths (or the weakness) of the models. The expression for the total inelasticity coefficient (in the absence of any recharge effect) for proton-nucleus collisions is given by

$$\langle K^N \rangle = 3 \langle K_{\pi^0} \rangle_{PA}. \tag{28}$$

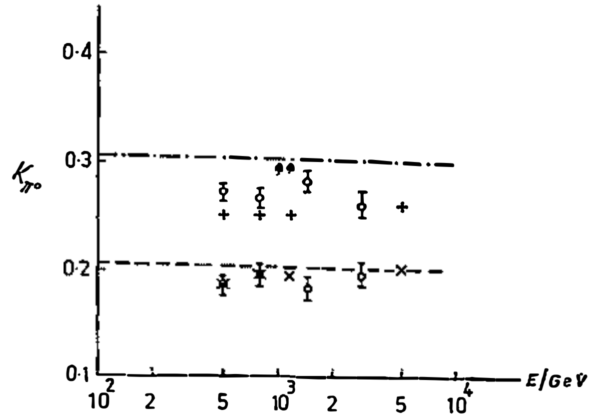

Fig. 3. The inelasticity partial coefficients for the pion and proton interactions with iron nuclei PFe experiment; X — Calculation by MST; — —— Theory (Shabelsky 1981).

Fe: O Experiment; + Calculation by MST; —·— — Theory (Shabelsky 1981).

The relation shows that the total inelasticity factor is ≈ 0.6 according to the sequential chain model and some other models as well. Wong's model leads to some high values whereas the calculations with the QCD-based relations give much lower values and the fall with QCD is by nearly one order of magnitude. This is just natural as the QCD-based models account for only the hard scattering processes which constitute less than one percent of the total inelastic events. The numerical value of the inelasticity factor that we have derived on the basis of some models giving $K \approx 0.6$ is also in consonance with the ideas and the measurements connected with the leading particle effect which, in general, shares at most nearly 50% of the total interaction energy. The rest should and do actually go to the particle production which is nicely depicted by the value of $K \approx 0.6$. Of course, we have accepted here the physics of multiple collisions presented by Glauber and have used all the usual high energy approximations with calculations for $x \to$ very small values. This might be the factor responsible for the discrepancy between theoretical value on the basis of Wong's model and the actual measurement by Avakian et al.[5].

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PARCIJALNA NEELASTIČNOST U VISOKOENERGETSKOM HADRON-JEZGRA RASPRŠENJU I NEKI VIŠEČESTIČNI MODELI PRODUKCIJE

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Izračunat je parcijalni neelastični koeficijent u proton-željezo sudaru na visokim energijama ($\approx$ 0.5 TeV) u modelima višečestične produkcije te je uspoređen s mjerenjima. Eksperimentalni podaci za pion-željezo analizirani su upotrebom modela jedne čestice (single model) i nađeno je razumno slaganje tog modela i mjerenja. Nedostatak dobrog slaganja sa QCD i podacima se može jednostavno objasniti.