Ref.TH.2511-CERN

INCLUSIVE $\pi^- C^{12}$ INTERACTIONS AT 40 GeV AND THE MULTIPARTICLE PRODUCTION MECHANISMS

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ABSTRACT

A detailed comparison of recent data on inclusive reactions $\pi^- C^{12} \to \pi^+ (\pi^-) X$ with modern theories of multiparticle production off nuclei is presented. The mean multiplicities and the inclusive spectra observed agree well with quark-parton model predictions. It is shown that the fragmentation of the nucleus could be understood in the cascade model framework.

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Ref.TH.2511-CERN
12 June 1978

1. INTRODUCTION

Particle nucleus interactions are attracting a great deal of attention nowadays because of the peculiar features of the nuclear spectra possess. The most interesting observation is that newly produced hadrons interact only weakly inside the nucleus, in spite of the fact that they are hadrons. This transparency of the nuclear matter was completely unexpected and a number of theoretical approaches were proposed recently to explain it. These approaches differ drastically in their underlying assumptions and in their predictions for nuclear spectra. Unfortunately, data available so far were very scanty and, in fact, almost all model builders could claim to be at least not at variance with these data.

In this paper we confront the predictions of current theories of multiparticle production off nuclei with data on inclusive reactions :

$$\pi^- C^{12} \rightarrow \pi^+(\pi^-) X \qquad (1)$$

at 40 GeV. The data analyzed were collected by the Bucharest-Cracow-Dubna-Sofia-Tashkent-Ulan Bator collaboration during the exposure of the JINR 2-metre propane bubble chamber in a 40 GeV/c π^- beam at the Serpukhov proton synchrotron 1). These data are of particular interest for several reasons. First, it is a rather high-statistics experiment (the analyzed sample contains 3406 events), with a clear identification of secondary particles. Secondly, the momenta of all secondary particles have been determined, whereas in all the other high energy data only production angles [pseudorapidities $\eta = -\ell n(\mathrm{tg}\Theta_L/2)$] were measured. This allows one to perform a rather detailed test of the various approaches despite the fact that only one nucleus was used. Here we compare these data with the predictions of :

i) the energy flux model by Gottfried (hereafter called GM) 2);

ii) the Fishbane-Trefil two-phase model (FTM) 3);

iii) the Glauber eikonal multiple scattering model (EM) 4)-8);

iv) the fan diagram dominance model (FDDM) 9),10); and

v) the additive quark model (AQM) 11).

Our main conclusions are that data prefer the latter model and give strong evidence for the existence of large formation lengths of secondary hadrons.

2. MEAN MULTIPLICITY IN $\pi^- C^{12}$ INTERACTIONS

The normalized mean multiplicity of all secondary particles including neutral pions was found to be $^{1)}$:

$$R_{EXP} = \langle n_{\pi^- C} \rangle / \langle n_{\pi^- N} \rangle = 1.18 \pm 0.02 \qquad (2)$$

One should compare this number with the following set of predictions :

$$R_{GM} = \frac{2}{3} + \frac{\langle \nu_\pi \rangle}{3} \qquad (3)$$

$$R_{FTM} = \frac{1}{2} + \frac{\langle \nu_\pi \rangle}{2} \qquad (4)$$

$$R_{EM} = \langle \nu_\pi \rangle \qquad (5)$$

$$R_{FDDM} = 1.22 \qquad (6)$$

$$R_{AQM} = 1.22 \qquad (7)$$

In these equations $\langle \nu_\pi \rangle$ stands for the mean number of pion absorption lengths in the target nucleus. The value of $\langle \nu_\pi \rangle$ is model-dependent and depends slightly on the definition. The one which has been widely used recently is $^{12)}$:

$$\langle \nu_h \rangle = \frac{A \sigma_{in}^{hN}}{\sigma_{in}^{hA}} \qquad (8)$$

and for the $\pi^- C$ interactions, it gives :

$$\langle \nu_\pi \rangle_1 = 1.38 \qquad (9)$$

If, on the other hand, one starts with the Glauber multiple scattering theory, one arrives at the following definition $^{13),14)}$:

$$\langle \nu_h \rangle = \frac{\sum_{n=1}^{A} [(n-1)!]^{-1} \cdot \int_0^\infty db\, b\, [\nu_h(b)]^n \exp[-\nu_h(b)]}{\sum_{n=1}^{A} [n!]^{-1} \int_0^\infty db\, b\, [\nu_h(b)]^n \exp[-\nu_h(b)]} \qquad (10)$$

where

$$\nu_h(b) = \sigma_{in}^{hN} \int_{-\infty}^{+\infty} dz\, \rho(z,b) . \tag{11}$$

Using a Gaussian parametrization for the density of nuclear matter, one gets for $\pi^- C$ interactions

$$\langle \nu_\pi \rangle_2 = 1.53 \tag{12}$$

After a substitition of these values of $< \nu_\pi >$ into Eqs. (3)-(5), we obtain :

$$R_{GM}(\langle \nu \rangle_1) = 1.13 \qquad R_{GM}(\langle \nu \rangle_2) = 1.18 \tag{13}$$

$$R_{FTM}(\langle \nu \rangle_1) = 1.19 \qquad R_{FTM}(\langle \nu \rangle_2) = 1.27 \tag{14}$$

$$R_{EM}(\langle \nu \rangle_1) = 1.38 \qquad R_{EM}(\langle \nu \rangle_2) = 1.53 \tag{15}$$

It should be noted that Eqs. (3) and (4) were derived in the original papers $^{2),3)}$ neglecting energy-momentum conservation constraints. In the EM framework, finite-energy corrections were studied in Ref. 8). The result is that R_{EM} decreases from $R_{EM} = 1.53$ to

$$R_{EM} = 1.26 \tag{16}$$

One should expect that the values of R-1 given by GM and FTM will be reduced by finite-energy corrections to the same extent as is the case in EM. Thus, GM predicts too low multiplicities. As for the other models, the numbers given by Eqs. (6), (7), (14) and (16) are very close to each other and to the experimental value of R, so that none of these models is favoured.

3. INCLUSIVE SPECTRA OF THE SECONDARY PIONS

It is interesting to consider the normalized spectrum :

$$R_x = \left(\frac{1}{\sigma_{in}} \cdot \frac{d^3\sigma}{d^3k}\right)_{\pi^- A} \Bigg/ \left(\frac{1}{\sigma_{in}} \cdot \frac{d^3\sigma}{d^3k}\right)_{\pi^- N} \qquad (17)$$

It turns out that different models differ drastically in their prediction for R_x. Experimental data on R_x are presented in Fig. 1, together with the theoretical curves.

The Gottfried model 2)

In this model nuclear matter should be transparent (i.e., $R_x = 1$) for all secondary hadrons with rapidities

$$y \geq y_c = Y/3 \qquad (18)$$

and $R_x = \langle \nu \rangle$ at smaller rapidities. In the 40 GeV $\pi^- C$ interactions this critical rapidity y_c corresponds to the laboratory momentum $k \simeq 1.5$ GeV/c. The data shown are at variance with this behaviour of R_x. At low momenta, R_x is substantially larger than $\langle \nu_\pi \rangle$. There is some evidence for $R_x = 1$, if any, only at very high momenta, $k \gtrsim (5-10)$ GeV/c.

The Fishbane-Trefil two-phase model 3)

In this model it is predicted that

$$R_x^{ch} = 1 + (\langle \nu \rangle - 1)(1 - y/Y) \qquad (19)$$

One should compare this with the π^- spectrum in the projectile fragmentation and with the average of the π^- and π^+ spectra in the central and nucleus fragmentation regions. No quantitative agreement is found.

The eikonal multiple scattering model 4)-8)

As regards multiparticle production off nuclei, this model corresponds to the successive inelastic rescatterings of the projectile 8). The number of inelastic interactions is just $\langle \nu \rangle$, so that neglecting finite-energy corrections, one rapidly gets $R = R_x = \langle \nu \rangle$. But, in the multishower process the energy per shower decreases, and only the single-shower process contributes to the projectile fragmentation 15). There were claims that, as a result, the equality $R_x = 1$ should hold in a wide region of rapidities in the fragmentation region 5),7). A more detailed analysis shows that it is true for the newly produced particles (π^+ mesons in π^-A collisions), while π^- mesons leave the fragmentation region due to the subsequent interactions. As a result, one has at $y \to Y$,

$$R_x^{\pi^-} = \langle \nu_\pi(b)\, e^{-\nu_\pi(b)} \rangle_b < 1 \qquad (20)$$

Theoretical spectra, presented in Fig. 1, demonstrate that the finite energy corrections are extremely important. The naïve expectation of $R_x = \langle \nu \rangle$ holds (in theoretical curves) only in the backward hemisphere. The data shown contradict the EM : leading π^- mesons are absorbed more weakly than is dictated by EM; there is clear evidence for the cascading which the EM does not take into account at all.

Parton model in the fan-diagram dominance approximation

In this model the transparency of the nuclear matter is explained by the growth of the formation lengths ℓ_f of the secondary hadrons at high energies 9),10) :

$$\ell_f \cong k/m^2 \qquad (21)$$

There are no intranuclear interactions provided the formation lengths exceed the dimensions of the nuclei : $\ell_f \gtrsim R_A = r_o \cdot A^{1/3}$. In order to get a correct magnitude of the multiplicity, the mass m which determines the scale of the formation lengths should be taken rather large : $m^2 \simeq 2(\mathrm{GeV})^2$ 10). The resulting theoretical spectra presented here were calculated using the approach of Ref. 10). While the model reproduces the qualitative trends of the data, the quantitative agreement is poor. In the FDDM there should be no absorption of the leading particles as far as $\ell_f \gtrsim R_A$, whereas the data give a clear evidence for the absorption of the leading π^- mesons. Also, the striking difference in the spectra of the leading and non-leading pions could not be understood in this simple-minded approach. Nevertheless, the basic concepts of the parton model approach are not invalidated by the data if the composite nature of the hadrons is taken into account, as we shall demonstrate below.

Formation lengths and the additive quark model 11)

In the additive quark model the Levin-Frankfurt impulse approximation 16) is supposed to hold in hadron-hadron collisions. Let us say that in $\pi^- N$ collisions one of the constituent quarks of the pion is a spectator. Leading pions are formed via the fusion of this spectator quark with one of the newly produced quarks. These are the newly produced quarks whose formation lengths are given by Eq. (21) and whose spectra should not depend on the target, provided that $\ell_f > R_A$. As for the spectator quarks, they were present already in the initial state and they are capable of strong interaction immediately after break-up of the incident hadron. Thus, they are absorbed in nuclear matter with an absorption cross-section :

$$\sigma^{in}_{qN} \cong \frac{1}{2}\sigma^{in}_{\pi N} \tag{22}$$

The yields of the spectator quarks will be proportional to the factor

$$R_x^{Sp} \cong \left\langle 2\left[e^{-\frac{1}{2}\nu_\pi(b)} - e^{-\nu_\pi(b)}\right]\right\rangle_b \tag{23}$$

The spectra of all fragments, one of whose constituents is a spectator quark, should be proportional to this very factor R_x^{Sp} 11). $\pi^- A$ collisions are of particular interest since π^+ and π^- mesons have no common constituent quarks ! Therefore, π^+ mesons produced in the fragmentation are true newly-produced hadrons and there should be no signs of absorption of π^+ mesons. This prediction is in perfect agreement with the data.

Interactions of spectators lead to the production of additional particles. In the FDDM, one has $R_x = 1$ as far as $\ell_f > R_A$. In the AQM, on the contrary, one obtains in the central region

$$R_x = 1 + (1 - R_x^{Sp}) \tag{24}$$

At the lower momenta, where $\ell_f \lesssim R_A$, rescatterings lead to a dip in R_x, followed by a cascade region of steeply rising R_x. An energy of 40 GeV is not high enough for all these trends to be fully developed and instead of the plateau region where both $R_x^{\pi^+}$ and $R_x^{\pi^-}$ are given by Eq. (24), we obtain only a bump in $R_x^{\pi^+}$. The theoretical curves shown were calculated using $m^2 \simeq 0.7(\mathrm{GeV})^2$; this value of m^2 was chosen in Ref. 11) to fit the data on the mean multiplicities.

Fragmentation of the nucleus

None of the models considered above is reliable in the nucleus fragmentation region. An important observation is that in the parton models only relatively low-momentum pions with momenta $k < R_A m^2$ participate actively in the cascading. At these momenta, formation lengths are irrelevant, and the resulting cascading is quite similar to that induced by the incident pion of momentum $p_c \simeq R_A m^2$. As is well known, the ordinary cascade model is quite reliable at low energies 17). Thus, it is tempting to describe the nucleus fragmentation using the ordinary cascade model. We have done this by putting $p_c = 4(\mathrm{GeV}/c)$. This value of p_c was chosen according to the analysis of the momentum distribution of intranuclear interactions in the parton model. In toto, 14301 interactions were simulated using the Monte Carlo cascading programme. The spectrum thus obtained is presented in Fig. 1 by a shaded area. Statistical errors, as well as the uncertainties in the input data, were taken into account. The calculated spectrum agrees well with the data and joins smoothly the FDDM and the AQM spectra at momenta $k \approx (0.5-1)$ GeV/c.

Conclusions

Our analysis demonstrates that the detailed data on the nuclear spectra discriminate reliably the models of multiple production off nuclei. Data on $\pi^- C$ interactions agree perfectly with the AQM supplemented by the cascade model in the nucleus fragmentation region. There is good evidence for non-absorption of the secondary π^+ mesons. An apparent absorption of the leading π^- mesons is well explained by the composite two-quark structure of mesons. The degree of absorption observed experimentally is weaker than that expected in the eikonal model, where one neglects the formation lengths of leading particles.

The present paper updates a previous preprint published as an L.D. Landau ITP preprint under the same title. The main difference lies in a more complete treatment of the AQM approach in the present paper.

ACKNOWLDEGEMENTS

We thank all the members of the Dubna 2-metre argon bubble chamber collaboration for useful discussions. We are grateful to Dr. A.Ya. Ostapchuk for help with the calculations. One of the authors (N.N.N.) would like to thank the CERN Theoretical Physics Division, where this paper was completed, for hospitality and friendly atmosphere.

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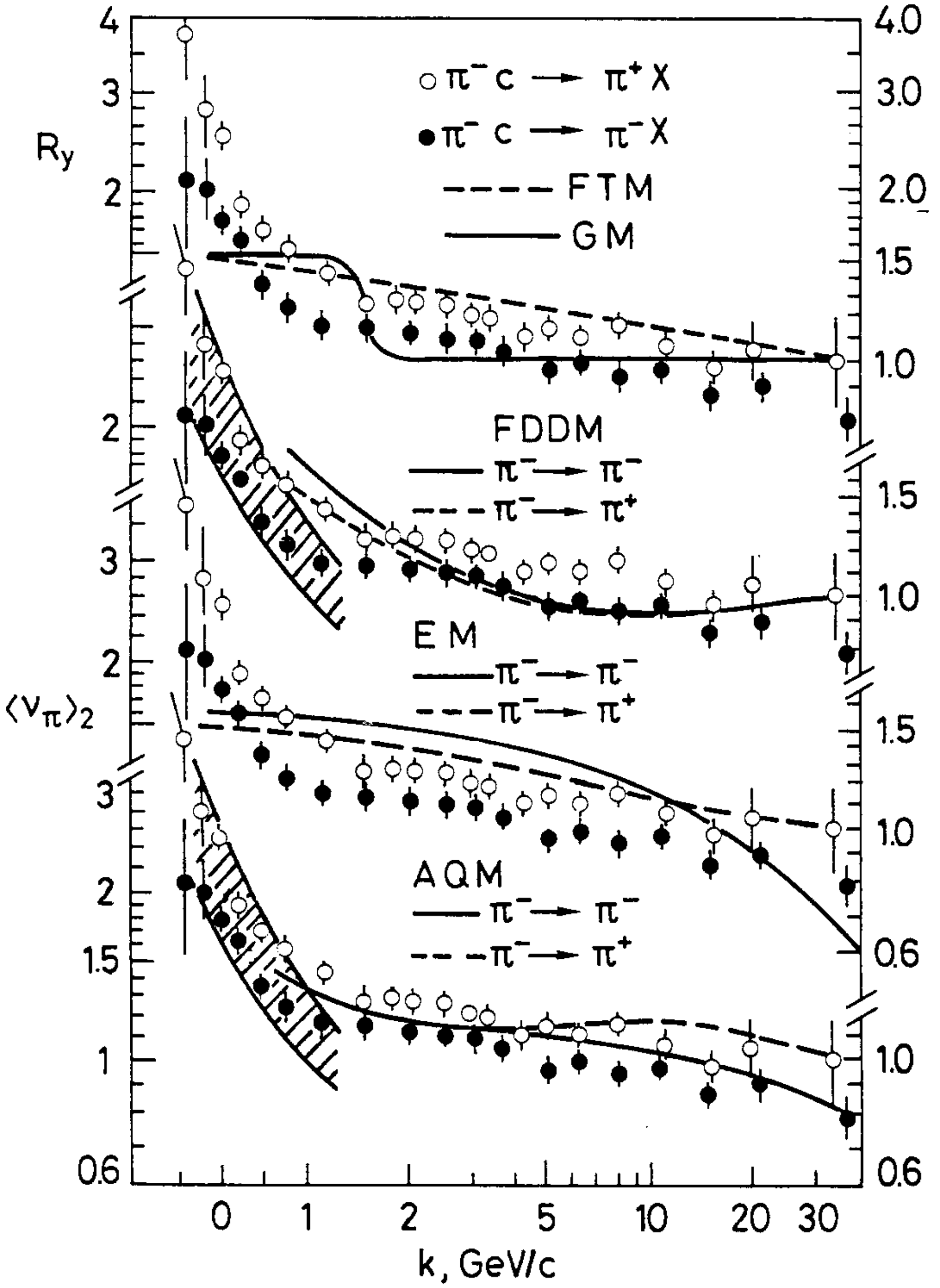
FIGURE CAPTION

Data on the normalized inclusive spectra R_x in the $\pi^- C^{12}$ interactions at 40 GeV/c are compared with predictions of the models discussed in the text. Note that for longitudinal momenta $k > 1$(GeV/c) the scale is linear in $\ln k_L$, whereas for the smaller momenta the scale is linear in k_L.



R_y
$\langle \nu_\pi \rangle_2$
○ $\pi^- c \rightarrow \pi^+ X$
● $\pi^- c \rightarrow \pi^- X$
FTM
GM
FDDM
$\pi^- \rightarrow \pi^-$
$\pi^- \rightarrow \pi^+$
EM
$\pi^- \rightarrow \pi^-$
$\pi^- \rightarrow \pi^+$
AQM
$\pi^- \rightarrow \pi^-$
$\pi^- \rightarrow \pi^+$
4
3
2
2
3
2
3
2
1.5
1
0.6
4.0
3.0
2.0
1.5
1.0
1.5
1.0
1.5
1.0
0.6
1.0
0.6
0
1
2
5
10
20
30
k, GeV/c