PARTICLE PRODUCTION IN HIGH-ENERGY HADRON-NUCLEUS INTERACTIONS

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ABSTRACT

The pseudorapidity (η) distributions of fast particles ($\beta > 0.7$) emitted in inelastic hadron interactions with carbon, copper and lead were measured for incoming energies from 50 to 150 GeV at the CERN Super Proton Synchrotron. Their dependence on target mass (A) and projectile (h) obeys $\langle v \rangle$ -scaling as expected. Their energy dependence is in contrast with most model predictions.

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1. INTRODUCTION

High-energy physics has concentrated on studying the short-distance behaviour of strong interactions, since a theory -- quantum chromodynamics (QCD) -- has been found to provide a successful description of it. However, the most common event in strong interactions -- production of many hadrons with low p_T -- is outside the proper domain of applicability of QCD as it is intimately connected with the unsolved quark-confinement problem. Nevertheless, in the last few years several attempts were made to describe low- p_T strong interaction by QCD-inspired phenomenological models [1]. Some of them, certainly the most interesting ones, try to connect QCD intuition with older successful theories like Reggeon field theory [2,3].

Nuclear targets have been considered for a long time as a test laboratory for models of the hadron-nucleon (hN) interaction. In the new context of QCD they provide another medium -- nuclear matter, as opposed to the vacuum surrounding a single nucleon -- to study the propagation of partons, or the mechanisms of confinement and of multiple colour exchanges within short space-time intervals.

By extrapolation from the multihadron final states as observed in hN interactions to the ones expected for hA interactions, various models arrive at quite different predictions. Thus one would think that a measurement could easily decide between the different models. However, the neglect of cascading effects on the low-energy side of the spectrum of emitted particles, and of energy conservation on the high-energy side, in most models, renders a direct comparison with experiment difficult. Measurements at very high energy, where the target- and projectile-fragmentation regions are well separated with a central pionization region in between, would be more crucial but they were not available.

It was felt that a systematic measurement of the energy dependence at the CERN Super Proton Synchrotron (SPS) energies could already show the trend and indicate the asymptotic behaviour. A simple detector was set up to measure multiplicities and angular distributions of charged particles and to distinguish

between slow particles (which are mostly protons from the nucleus) and fast particles, mostly pions. The cut between fast and slow particles was at a velocity $\beta \approx 0.7$.

Results at incoming energies of 20 and 38 GeV were already published some time ago [4]. In a preceding paper [5] a separate study of the nuclear response -- the slow particles -- was reported. The present paper deals mainly with the fast particles. We present their total multiplicity and η -distributions, as well as their dependence on target mass, projectile and energy and on the number of slow particles, N_g . We compare our results with those from other experiments and with predictions from some current models.

2. EXPERIMENT

The measurement of high multiplicities requires a fine-granulated detector. A hodoscope with 57 scintillation counters covers 100% of the solid angle for polar angles $\theta < 13^\circ$. The θ -interval between 13° and 165° is covered by another set of counters, each a combination of a CsI(Tl) scintillator and a lucite light-guide. The lucite guide acts -- for fast particles -- as a Čerenkov radiator. The combined counters are arranged in seven rings around the beam axis and divide the covered θ -range into intervals of about half a unit in pseudorapidity (Fig. 1a). The threshold velocity for the identification of a fast particle is $\beta = 1/n_{\text{lucite}} \approx 0.7$. Particles with higher β are called 'fast' or 'shower' particles and their number is denoted by N_s ; those with lower β are called 'slow' or 'grey' tracks and their number is denoted by N_g , following the convention used in emulsion work. In Ref. [5] a detailed explanation of the method of discrimination between fast and slow particles is given.

Figure 1b shows the arrangement of the beam counters in the unseparated H3 beam of the CERN SPS West Area. An incoming hadron was defined by a coincidence of the counters in the beam -- B•S•T -- and an anticoincidence of counters surrounding the beam -- AH•AL•AR•AU•AD. The event trigger required in addition, that at least two of the counters in the detector, except the one at $\theta = 0^\circ$, fired and that there was no signal in the beam veto counter AB ($\theta < 0.08^\circ$).

The projectile identification was done in the off-line analysis using the recorded information of the two threshold Čerenkov counters Č1 and Č2.

Corrections have been applied to the raw data for the following:

- i) Geometrical acceptance: The solid angle covered by the 130 counters of the detector is 65.4% of 4π .
- ii) Interactions outside the target: This background was measured separately for every run and subtracted (about 25% correction).
- iii) π^0 decay and subsequent γ -conversion in the target: Dependent on the target material and the angle, this background was of the order of 1% (for carbon) to 30% (for lead at $\theta = 90^\circ$).
- iv) δ -electrons: They are produced in the air between the target and the counters (5% correction).
- v) Multiple hits in the counters: For backward-produced particles the correction was calculated to be 1% and it increases in the forward direction to 5%.
- vi) Secondary interactions inside the target: For the used target thickness of 1% absorption length it was about 5%.
- vii) Secondary interactions inside the counters: They mainly take place in the light-guide of the counters and as a result the forward hodoscope is illuminated by secondary produced particles in the counters of rings 6 and 7. Dependent on the multiplicity in this angle range, the correction for the forward hodoscope is of the order of 3% to 30%.

3. RESULTS

3.1 Multiplicities

The mean multiplicities of fast particles are shown in Fig. 2 and Table 1. They are plotted for different projectiles, targets and energies versus the variable $\langle \nu \rangle = A\sigma(\text{hp})/\sigma(\text{hA})$, which is commonly used as a measure for the mean number of collisions of a projectile going through the nucleus [6]. Within the

errors the mean multiplicity depends only on $\langle \nu \rangle$; the dependence is linear and the data follow the prediction of $\langle \nu \rangle$ -scaling. The mean multiplicities are arranged in three different bands according to the incoming energy. This energy dependence can be eliminated if one divides $\langle N_s \rangle_{hA}$ by the mean multiplicity of the corresponding elementary interaction $\langle N_s \rangle_{hp}$. From the measured charged multiplicity [7] in hadron-proton collisions $\langle N_{ch} \rangle_{hp}$, the mean multiplicity of shower particles $\langle N_s \rangle_{hp}$ is obtained by the empirical formula $\langle N_s \rangle_{hp} = \langle N_{ch} \rangle_{hp} - 0.5$ [8]. Figure 3 shows the ratio

$$R = \frac{\langle N_s \rangle_{hA}}{\langle N_{ch} \rangle_{hp} - 0.5}$$

for different projectiles, targets and energies. Now all experimental points are well described by one straight line. In Fig. 3 we also display the corresponding data from a FNAL counter experiment [9], which exhibit a similar linear dependence on $\langle \nu \rangle$. Both experiments are consistent inasmuch as they show a linear relation between R and $\langle \nu \rangle$. Further, they are in good agreement for the copper target, but the FNAL data are systematically lower for carbon and higher for lead.

3.2 Pseudorapidity distributions

In Fig. 4 the variations of the pseudorapidity distributions are shown as a function of (a) the projectile, (b) the target mass, and (c) the incoming energy.

The dependence on the projectile is weak but shows the same trend as the dependence on A , i.e. an increase in the target fragmentation region and a depletion at high rapidities, for increasing $\langle \nu \rangle$ ($\langle \nu \rangle$ rises with the elementary cross-section σ_h^N and, of course, with A). This shows that changing the species of the incident hadron is equivalent to a corresponding change of the target. The dependence on E_{inc} exhibits the familiar increase at high rapidities and constant particle density at low rapidities.

In Fig. 5 we compare our 50 GeV proton-copper data with those from the FNAL counter experiment [9] and an emulsion experiment [10]. The average $\langle \nu \rangle$ is about the same for copper and emulsion, i.e. $\langle \nu \rangle_{Cu} \approx \langle \nu \rangle_{emulsion} \approx 2.6$ for protons, and also the total $\langle N_s \rangle$ is apparently the same for the three measurements.

All three distributions agree well for the forward produced particles ($\eta > 2.5$). In the backward region ($\eta < 1.5$) the FNAL data differ from our data as well as from the emulsion data. Concerning the over-all shape of the pseudorapidity distribution, our data agree better with the emulsion data than with the data from the FNAL experiment. Since in the region $\eta < 2$ the solid angle is covered by the combined counters, which allow a very precise off-line definition of a fast particle (by making use of the recorded energy loss and the time information [5]) and moreover since we have applied all corrections for background (in particular the γ -conversion), we believe our data to be correct.

3.3 Normalized pseudorapidity distributions

Theoretical predictions for the particle spectrum of a high-energy hadron-nucleus collision are usually given as the ratio of particles produced from a nucleus to those produced from a single-nucleon target. Since we have not made measurements with a hydrogen target, and no such data with the same trigger bias are available, we extrapolated the pseudorapidity distribution corresponding to one collision -- $[d\langle N_s \rangle / d\eta]_{\langle \nu \rangle=1}$ -- from the measurements on different nuclei. For each η -interval, the differential multiplicity $d\langle N_s \rangle / d\eta$ is plotted versus $\langle \nu \rangle$ and a straight line is fitted to the data. In the $\langle \nu \rangle$ -range which we cover, the dependence is compatible with being linear. If, however, the slope $d^2\langle N_s \rangle / d\eta d\langle \nu \rangle$ depends on $\langle \nu \rangle$ at small $\langle \nu \rangle$, the extrapolated pseudorapidity distribution for $\langle \nu \rangle = 1$ would not correspond to one collision. But this modification would not be important for our conclusions. An example of the extrapolation procedure is shown in Fig. 6 for incoming pions and protons at 50 GeV. From the fit we extract the pseudorapidity distributions for fixed values of $\langle \nu \rangle$ and form the ratio:

$$R(\eta) = \frac{(d\langle N_s \rangle / d\eta)_{\langle \nu \rangle=3}}{(d\langle N_s \rangle / d\eta)_{\langle \nu \rangle=1}}.$$

Figure 7a shows the projectile dependence of $R(\eta)$ for pions, protons, and antiprotons at 50 GeV. For $\eta > 2$ the curves for the different projectiles are almost identical, thus demonstrating the validity of $\langle \nu \rangle$ -scaling also for the

differential multiplicities (cf. $\langle v \rangle$ -scaling for the integrated multiplicities; see Section 3a and Refs. [9] and [11]). At lower η , the ratio $R(\eta)$ decreases as the elementary cross-sections increase (going from π to p to $\bar{p}$). This decrease with increasing cross-section can partly be explained by the correspondingly decreasing target mass (at fixed $\langle v \rangle = 3$, the target mass is $A \approx 200$ for π , $A \approx 100$ for p and $A \approx 70$ for $\bar{p}$) and by the occurrence of a largely projectile-independent slow intranuclear cascade (as was already observed for recoil protons [5]).

The most remarkable feature of $R(\eta)$ is its weak energy dependence over the whole η -range (Fig. 7b). This is in contrast with most models and will be discussed in Section 4.

In an earlier paper [5] we discussed the emission of slow particles from the nucleus. The multiparticle final state consists of created mesons and a certain number of nucleons which were knocked out of the nucleus during the interaction. The number of recoil protons in an event, N_g , is related to the impact parameter of the interaction and might be used as an experimental measure of the number of collisions $\langle v \rangle$ of a projectile in a nucleus.

Therefore instead of extrapolating to different $\langle v \rangle$ -values, as described above, we can study the ratio $R(\eta)$ of the pseudorapidity distributions for different classes of events associated with a fixed number of recoil protons. Figure 7c shows the ratio of particle densities for events with $N_g = 2$ to events with $N_g = 0$. (In Ref. [5] it was shown that $N_g = 2$ and $N_g = 0$ correspond to $\langle v \rangle \approx 2.4$ and $\langle v \rangle \approx 1.4$, respectively)

$$R(\eta) = \frac{(d\langle N_s \rangle / d\eta)_{N_g=2}}{(d\langle N_s \rangle / d\eta)_{N_g=0}}.$$

We arrive at the same picture as before: multiple collisions inside a nucleus lead to an enhanced particle production at low rapidities and to a depletion in the projectile fragmentation region. Again this ratio $R(\eta)$ depends only very weakly on the energy between 50 and 150 GeV.

For comparison, we applied the already described fitting procedure to the data of the FNAL experiment [9] forming the ratio of the differential multiplicities for 3 collisions to 1 collision. These data, however, show a much steeper behaviour in the target fragmentation region, no depletion in the forward direction, and a more pronounced energy dependence (Fig. 8a).

Figure 8b shows the corresponding ratio for emulsion data [10,12,13]. In this case the ratio is formed for different N_g bins ($N_g = 0$ to 2, and $N_g = 3$ to 5, respectively), which is equivalent to the ratio of Fig. 7c. We find very good agreement in shape and absolute height between the emulsion and our data.

4. SUMMARY AND DISCUSSION

We have shown new data for the total multiplicities and pseudorapidity distributions of fast particles produced in $\pi^\pm$, $K^\pm$, p , and $\bar{p}$ interactions with nuclear targets.

In the following we will discuss the behaviour of the normalized pseudorapidity distribution in the light of recent quark-parton models for the multiparticle production process from nuclear targets. Predictions for the normalized differential multiplicity $R(\eta)$ are shown schematically in Fig. 9 for two energies (50, 150 GeV).

For the discussion it is helpful to divide the whole η -range into different intervals, indicated in Fig. 9 by the critical pseudorapidities η_c and η'_c . The critical pseudorapidity η_c is defined as the upper bound of the cascading region, where we have multiple interactions inside the nucleus and therefore $R(\eta < \eta_c) > 1$ [14]. The second critical pseudorapidity η'_c is defined by $R(\eta'_c) = 2$. In the models these two values represent roughly the border between the projectile-fragmentation and the central region and between the central and the target-fragmentation region, respectively.

All models account for an increase in the incoming energy by a stretching of the central region. This fact is well established experimentally, as can be seen, for example, in the pseudorapidity distributions in Fig. 4c.

According to the planar multiperipheral parton model (MPM, Fig. 9a [15,16]) only partons below a critical rapidity η_c can undergo secondary collisions in the nucleus. Therefore the model predicts an energy-independent value of the critical pseudorapidities η_c , η'_c and a well-developed plateau of height $R(\eta) = 1$ in the central region. The data (Fig. 9d) could be almost consistent with energy-independent critical pseudorapidities η_c and η'_c . Their differences for 50 and 150 GeV are $\Delta\eta_c = \eta_c(150) - \eta_c(50) \simeq 0.9 \pm 0.4$, and $\Delta\eta'_c \simeq 0.2 \pm 0.2$, respectively.

In the additive quark model (AQM, Fig. 9b [14]), the constituent quarks of the incoming hadron (2 quarks for mesons and 3 for baryons) can interact independently, and moreover hadrons produced with rapidities below η_c can reinteract.

In the dual fragmentation models (DFM, Fig. 9c [2,3]) and related ones [17] all valence and sea quarks can interact independently of each other. In most of these models reinteractions of hadrons produced inside the nucleus are neglected. But, in practice, the difference between AQM and DFM, i.e. whether at most 2 or 3 valence quarks or any number of quarks can interact independently, is not large.

In the AQM and the DFM the critical pseudorapidity η_c moves by about one unit, which is in good agreement with the experimental observation $\Delta\eta_c \simeq 0.9$. These models also predict an energy dependence of η'_c , which is stronger than indicated by the experiment. But the small value of $\Delta\eta'_c$, as given by the AQM ($\Delta\eta'_c \simeq 0.4$), comes very close to the experimental observation.

Recent results from αp and $\alpha\alpha$ interactions in the CERN ISR [18] and from NA5 at the CERN SPS [19] have shown that the ratio of particle densities in the central region and the slope of $R(\eta)$ are in agreement with the predictions of both the AQM [20] and the DFM, but they rule out the MPM, since $R(\eta)$ is larger than one in the central region. However, both measurements were unfortunately taken at only one energy each.

Combining these latter results with the present study, the AQM is left as the only candidate to cope with the energy dependence and the slope of $R(\eta)$ in the central and projectile-fragmentation region.

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Table 1

Mean multiplicities of fast particles $\langle N_s \rangle$

Projectile	Target	E _{inc}		
		50 GeV	100 GeV	150 GeV
K^+	C	7.48 ± 0.14		10.37 ± 0.24
	Cu	8.71 ± 0.23		11.51 ± 0.34
	Pb	10.17 ± 0.39		13.46 ± 0.58
K^-	C	7.63 ± 0.14	9.23 ± 0.17	
	Cu	8.92 ± 0.23	10.72 ± 0.28	11.91 ± 0.34
	Pb	10.38 ± 0.40	12.57 ± 0.48	14.62 ± 0.56
π^+	C	7.62 ± 0.14	9.19 ± 0.17	10.01 ± 0.18
	Cu	8.81 ± 0.23	10.41 ± 0.27	11.57 ± 0.30
	Pb	10.11 ± 0.38	11.54 ± 0.44	13.08 ± 0.50
π^-	Cu			12.03 ± 0.31
	Pb			14.55 ± 0.55
p	C	7.88 ± 0.15	9.25 ± 0.18	10.58 ± 0.19
	Cu	9.52 ± 0.24	11.40 ± 0.29	12.93 ± 0.33
	Pb	11.31 ± 0.43		14.95 ± 0.57
$\bar{p}$	C	8.42 ± 0.15	9.87 ± 0.18	
	Cu	10.30 ± 0.26	11.92 ± 0.31	
	Pb	12.02 ± 0.45	14.16 ± 0.54	14.86 ± 0.57

Figure captions

- Fig. 1 : a) Detector.
b) Layout of the beam counters.
- Fig. 2 : Mean multiplicity $\langle N_s \rangle$ versus the mean number of collisions $\langle \nu \rangle$ for 50, 100, and 150 GeV incoming energy. Linear fits to the data are indicated by straight lines.
- Fig. 3 : Normalized multiplicity $R = \langle N_s \rangle_{\text{hA}} / (\langle N_{\text{ch}} \rangle_{\text{hp}} - 0.5)$ versus $\langle \nu \rangle$ for different energies, projectiles, and targets. For comparison the results of the FNAL experiment [9] are shown.
- Fig. 4 : Pseudorapidity distributions of fast particles $d\langle N_s \rangle/d\eta$.
a) Projectile dependence for 50 GeV π^+ , p, and $\bar{p}$ on carbon.
b) Target-mass dependence for 50 GeV π^+ on carbon, copper, and lead.
c) Energy dependence for 50, 100, and 150 GeV π^+ on copper.
- Fig. 5 : Comparison of $d\langle N_s \rangle/d\eta$ for 50 GeV proton-copper and proton-emulsion interactions. For clarity the error bars are omitted, but can be seen in Fig. 4.
- Fig. 6 : Differential multiplicities versus $\langle \nu \rangle$ for 50 GeV π and p interactions with carbon, copper, and lead in different η -bins. Straight lines are fitted to the data in order to extrapolate to the particle densities at $\langle \nu \rangle = 3$ and at $\langle \nu \rangle = 1$.
- Fig. 7 : The normalized pseudorapidity distributions $R(\eta)$.
a) Projectile dependence of $R(\eta)$ for π , p, and $\bar{p}$ at 50 GeV.
b) Energy dependence of $R(\eta)$ for 50, 100, and 150 GeV incoming π^+ .
c) $R(\eta)$ from events with $N_g = 2$ divided by $N_g = 0$ for 50, 100, and 150 GeV π^+ -lead interactions.

- Fig. 8 : a) $R(\eta)$ from the FNAL experiment. These data were obtained by applying the extrapolation procedure described in the text to the results of Ref. [9].
- b) $R(\eta)$ from the emulsion experiment [10,12]. Similar to Fig. 7c, $R(\eta)$ is shown for events with a fixed number of slow particles N_g . The corresponding $\langle v \rangle$ values are taken from Ref. [13].

- Fig. 9 : Model predictions for $R(\eta)$ and comparison with data. The critical pseudorapidities η_c and η'_c are indicated as defined in the text.
- a) Multiperipheral parton model [15,16].
- b) Additive quark model [14].
- c) Dual fragmentation and related models [2,3,17].
- d) Corresponding experimental data for incoming π^+ at 50 and 150 GeV.

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