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THE NUCLEAR RESPONSE IN HIGH-ENERGY HADRON-NUCLEUS INTERACTIONS

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ABSTRACT

In an experiment at the CERN Super Proton Synchrotron (SPS) studying hadron-nucleus interactions, slow particles which are mainly knock-out protons were measured with an electronic detector. Their dependence on the target mass, incoming energy, and projectile is shown. We discuss the use of the number of protons as a measure for the number of interactions of the projectile and conclude that the emitted protons measure the impact parameter of the reaction.

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I. INTRODUCTION

The dominant mode of hadron-nucleon interactions at high energy is inelastic and leads to multiple production of hadrons, mostly pions. In a nucleus, multiple inelastic interactions with nucleons may occur within a time interval shorter than the one required to reach the asymptotic final state. The problem of understanding the very complex processes leading to multiparticle final states in hadron-nucleon and hadron-nucleus interactions is very old [1], but the past five years have seen many new attempts to solve it. Most of them seek to reduce it to interactions on the level of hadron constituents -- quarks or partons [2]. In models dealing with hadron-nucleus interactions, the experimental particle spectrum after a single hadron-nucleon interaction is frequently used as the input to predict the particle spectrum after ν interactions with the nucleons [3].

Fundamental for the interpretation of experiments measuring the particle spectrum from hadron-nucleus interactions is the knowledge of the number of elementary interactions which takes place within the nucleus. As a measure for this number the parameter

$$\langle \nu \rangle = A \sigma_{hp} / \sigma_{hA} \quad (1)$$

is frequently used [4], where A is the target mass number, and σ_{hp} and σ_{hA} are the production cross-sections on nucleons and nuclei, respectively. This quantity represents the number of collisions, averaged over the impact parameter, made by an incoming hadron moving along a straight trajectory through the nucleus, if it is assumed that the hadron-nucleon cross-section is constant, i.e. independent of the number of collisions experienced.

For protons interacting with heavy nuclei, like lead, $\langle \nu \rangle$ may reach a value of ~ 4 . However, the actual number of collisions will vary appreciably from the mean in individual events. Therefore it is desirable to search for a method to determine ν in individual events.

The number of knock-out protons has long been used in emulsion experiments as a measure of the number of collisions in hadron-nucleus interactions [5]. This

was particularly important because in emulsion experiments one does not know the mass of the nucleus hit by the hadron. Knock-out protons are identified in emulsion to a large extent as grey prongs. These are tracks with an ionization density between 1.4 and ~ 10 times the minimum, corresponding to a velocity $\beta = v/c$ between 0.3 and 0.7, or a kinetic between 30 and 300 MeV for protons [6]. Tracks with grain density lower than 1.4 are called shower particles. At high incoming energy these are mainly pions. Tracks with a grain density higher than ~ 10 are called black tracks. They are mainly due to evaporation of nucleons and of small nuclear fragments. The number of grey prongs in an event is denoted by N_g , the number of shower particles by N_s . In the forward direction, a small fraction of the knock-out protons will have $\beta > 0.7$ and will be identified as shower particles. On the other hand, only few pions with $\beta < 0.7$ will appear as grey prongs.

In the experiment presented in this paper, a systematic study of the production of slow particles has been undertaken. The conditions for identification of slow particles have been chosen to agree as closely as possible with the conditions for identification of grey prongs in emulsions. This choice allows checking of the validity of the analysis of emulsion experiments. The first systematic study of the production of slow particles in hadron-nucleus interactions on pure targets by π^+ , K^+ , p , and $\bar{p}$ was done at incoming energies of 20 and 37.5 GeV [7]. The present experiment, with a slightly modified set-up, extends these measurements to incoming energies between 50 and 150 GeV.

II. THE EXPERIMENT

The slow and fast particles are separated by means of a combined counter consisting of a CsI(Tl) crystal, 3 mm thick with a diameter of 50 mm, which is glued to a lucite light-guide. The light output of the CsI scintillator is proportional to the energy loss of the particles in the crystal, and if the velocity is larger than $\beta = 1/n \approx 0.7$, n being the refractive index of lucite, the lucite light-guide acts as a Čerenkov radiator. The anode signal evoked by the Čerenkov radiator is a short pulse, around 500 mV for a typical amplification of the phototube, whereas the CsI produces a long signal, 50 mV for minimum ionizing particles, with a decay

time of 1 μ s. The rise-times of the CsI and Čerenkov pulses are different; the latter is determined by the intrinsic resolving time of the tube and signal cable, while the CsI crystal typically has a rise-time of 30 ns. This difference is utilized for separating fast and slow particles in the off-line analysis. The anode signal is split between a discriminator and an analogue-to-digital converter (ADC). The outputs from the discriminator are led to a time-to-digital converter (TDC) and a pattern-unit. The TDC and ADC (energy loss) of each counter are recorded on tape together with the pattern information.

Seventy-three of these combined counters cover 52% of the total solid angle and form seven rings of roughly equal size in pseudorapidity $\eta = -\ln(\tan \Theta/2)$, Θ being the laboratory polar angle with respect to the beam axis (Fig. 1). There are no counters at $\Theta > 165^\circ$. The forward direction ($\Theta < 13^\circ$) is covered by a lucite hodoscope, consisting of four rings (56 counters), and one counter situated at $\Theta = 0^\circ$. Since the forward cone represents only 1% of the total solid angle and recoil nucleons moving forward are expected to be mostly fast in any case, the discrimination between fast and slow particles is considered to be irrelevant.

The low-energy cut for slow particles (20 MeV for protons) is given by the absorbing material between the target and the counters. Because the target itself is 5 mm thick for carbon (lucite) and 2 mm thick for Cu and Pb, the cut increases on the average to 30 MeV kinetic energy for protons. Obviously, the low-energy cut is not sharp and its width is about 20 MeV. The transverse diameter of the target was 8 mm.

The interaction trigger was $\text{BEAM} \cdot \text{OR} \cdot \overline{A_B}$, where "BEAM" was defined as $B \cdot S \cdot T \cdot \overline{A_H} \cdot \overline{A_L} \cdot \overline{A_R} \cdot \overline{A_U} \cdot \overline{A_D} \cdot f(\check{C}_1, \check{C}_2)$, $f(\check{C}_1, \check{C}_2)$ being a combination of the gas Čerenkov counters to select the desired beam particles (Fig. 1b). The "OR" required signals from any two of the 130 counters, except the one at $\Theta = 0^\circ$ which was not included in the trigger. The systematic error in the inelastic cross-section, introduced by requiring two tracks, is negligible, and if only one track is requested the background due to accidental coincidences increases considerably.

The first step in the off-line analysis was the calibration of the counters. A continuous and automatic calibration was provided by the minimum ionizing particles emitted from the target. They gave the reference points in time and energy loss for each counter. Based on this calibration the cut constants for the final selection of good tracks and for the separation between slow and fast particles were determined.

The term 'observed number' of slow (= grey) particles will be used for the number of tracks found per event after these initial cuts. Whenever average values such as $\langle N_g \rangle$ and $d\langle N_g \rangle/d\Omega$ are quoted, it implies that a series of corrections have been applied to obtain the true expectation values. These corrections are listed below.

The largest background came from interactions outside the target, especially from the target counter (0.15% absorption lengths), which was located right behind the target. We accounted for this contribution by empty-target measurements which were finally subtracted from the raw data. The whole empty-target correction was of the order of 25%.

Background due to δ -electrons from the air between the target and the counters and from the target itself increases the counted number of particles by roughly 1 to 30% per track, dependent on the angle. A correction of the order of 1% comes from secondary interactions in the target. Finally the acceptance correction was applied, where an effective acceptance, depending on the multiplicity of fast particles in every event, was taken into account.

The unseparated H5 beam at the CERN SPS was used. The measurements were performed by projectiles $\pi^\pm$, $K^\pm$, p, and $\bar{p}$ at energies of 50, 100, and 150 GeV on carbon, copper, and lead targets. Two gas Čerenkov counters were used to distinguish between different projectiles.

III. RESULTS

The energy loss ΔE of protons in the CsI crystal gives a rough estimate of the particle energy. Thus slow particles have been divided into three groups

according to their ΔE . In Fig. 2a the angular distributions for the three groups are shown. While the angular distributions of the high-energy tail (low ΔE) is strongly forward-peaked, the low-energy tail more and more approaches isotropy. This behaviour, already known from emulsion work [8], is expected and it reflects the transition from the more direct, energetic knock-out protons to the low-energy thermal protons. The information on the energy by means of ΔE , however, seems too crude to allow for a meaningful subdivision of the slow particles, so we have not taken advantage of this information. Some admixture of evaporation particles (black tracks in emulsion experiments) are thus present among the slow particles.

Averaged over all ΔE the angular distributions show a significant dependence on A (the target mass number). It is stronger forward-peaked for lighter targets than for heavier ones (Fig. 2b). Shape and height of the angular distributions do not depend on the incoming energy E_{inc} . This independence of the energy is another well-known fact from emulsion work [9]. Finally, at fixed A the dependence on the projectile is only weak (Fig. 2b lower part).

The dependence of the total average multiplicity $\langle N_g \rangle$ of slow particles -- the integral over the angular distribution -- on A and h is displayed in Fig. 3 as a function of the variable $\langle v \rangle$ from Eq. (1). The values are also listed in Table 1. While, undoubtedly, the angular distribution contains more information on the process in the nucleus, which leads to slow particle emission, the strength of the dependence on the different parameters E_{inc} , A , and h can already be seen in $\langle N_g \rangle$.

Figure 4 gives examples of the dependence of the multiplicity distribution on target mass A , energy E_{inc} , and projectile h . It should be noted that these distributions are uncorrected for acceptance, δ -electrons, and secondary interactions in the target, whereas the average angular distributions shown before were corrected.

In the next section we will examine whether the data can be understood by the qualitative picture that knock-out protons originate through an intranuclear

cascade and whether the slow particles provide a measure of the number of collisions inside the nucleus. We will only make use of the multiplicity distributions, and of their dependence on A and h, when we confront the data with a simple model.

IV. A MODEL

The model used for the following interpretation is similar to earlier proposed models by several authors [10,11]. It assumes that the incoming projectile h collides successively with individual nucleons, moving on straight trajectories through the nucleus. Each recoiling nucleon initiates a slow intranuclear cascade which leads to a distribution of knock-out nucleons. After folding with the acceptance of the detector, the distribution is compared with the measured number of slow tracks. The particle production in the intranuclear collisions is not considered to take part in the cascading of the nucleons. For the fast emitted particles associated with the projectile, this assumption can be justified since they do not separate from the projectile within the nucleus or, in other words, the excited projectile does not decay until after it has traversed the nucleus. If, however slow particles are emitted at large angles the assumption is obviously bad.

At a given impact parameter b, the average number of hadron-nucleon collisions is

$$\langle v(b) \rangle = \int_{-\infty}^{+\infty} \sigma \rho(z, b) dz ,$$

where ρ is the nucleon density, which was taken as a Woods-Saxon distribution

$$\rho(z, b) = \rho_0 / \left\{ 1 + e^{[(z^2 + b^2)^{1/2} - r_0]/a} \right\}$$

with the mean radius $r_0 = 1.15A^{1/3}$ fm, the surface diffuseness $a = 0.65$ fm, and the central density ρ_0 determined by the integral over the nucleus.

The probability for v collisions at a given impact parameter was assumed to follow a Poisson distribution with mean $\langle v(b) \rangle$. After integration over the impact parameter b the probability distributions $P_v(A, h)$ for having v collisions

are obtained (Fig. 5). The projectile-nucleon interaction cross-sections were $\sigma_{\pi N} = 2.45 \text{ fm}^2$ and $\sigma_{pN} = 4 \text{ fm}^2$ for incoming pions and protons, respectively.

Each collision causes one primary nucleon to recoil and to initiate an independent intranuclear cascade. The distribution of slow particles emitted as a result of the intranuclear cascade was calculated in two ways: firstly, by a Monte Carlo simulation, and secondly, by assuming a Poisson distribution with the mean value $\langle N_g(v=1, A) \rangle = N_0 A^{1/3}$, where N_0 was determined by a fit to all multiplicity distributions. In the Monte Carlo calculation the cross-section governing the cascade was taken to be $\sigma_{NN} = 4.5 \text{ fm}^2$ and one A-independent, arbitrary parameter was introduced which suppressed tertiary tracks.

If $W_{v=1}(N_g, A, h)$ is the multiplicity distribution of nucleons emitted as a result of one recoiling nucleon, the distribution for v collisions, i.e. v recoiling nucleons, is obtained by the recursion formula

$$W_v(N_g, A, h) = \sum_m W_{v-1}(N_g - m, A, h) W_{v=1}(m, A, h) .$$

This distribution has to be folded with $P_v(A, h)$ and with the acceptance of the detector, which is 60% for charged nucleons.

Both calculations gave very similar results. Figure 6 compares the curves calculated by the Monte Carlo simulation with the experimental points.

From this model we can derive a relation between $\langle v \rangle$ and observed N_g which depends on the target mass and on the projectile. An example is shown for incoming π in Fig. 7. Since the primary interaction cross-sections are practically energy-independent in the energy range under consideration, the curves in Figs. 6 and 7 are valid for all energies. This agrees with the experimental observation that the distributions of slow particles are independent of the incident energy.

According to the model the average $\langle N_g \rangle$ at fixed A is proportional to the number of primary recoil nucleons, i.e. $\langle N_g \rangle = \langle v \rangle f(A)$ [12]. Consequently, for fixed A , one expects the average $\langle N_g \rangle$ for different projectiles to fall on straight

lines through $\langle v \rangle = 0$ in Fig. 3 (dotted lines). One expects a correspondingly strong dependence of the multiplicity distributions on the projectile, which is demonstrated by the Monte Carlo results for incoming pions and protons in Fig. 6.

V. DISCUSSION

It was shown in the previous section that a simple model with only one free parameter can reproduce several features of the data very well, like the shape of the multiplicity distributions, their dependence on the target mass A , and their independence of the incoming energy.

However, the data show a significantly weaker dependence on the projectile than predicted by the model. This weak experimental projectile dependence is in agreement with earlier emulsion experiments where the differences in pion and proton distributions are of the same order, as observed in the present experiment (references 9 to 15 in Stenlund and Otterlund [13]).

This disagreement between calculation and experimental observation could be easily cured by revising two previous assumptions of the model: one was that all created particles can be neglected for the purpose of slow-cascade calculation; the other was that each cascade initiated by a primary recoil nucleon develops independently from the others. An alternative description could be derived from the standard two-component picture according to which after one collision a fast excited projectile emerges and decays only after having traversed the nucleus, whereas the recoil nucleon and low-energetic or large-angle secondary pions act as independent hadrons in the nucleus (see for instance the energy-flux-cascade model by Gottfried [14]). It is these slow particles emerging from the first primary collision that can act against the independence assumption of the individual cascades and can give a dominant weight to the first collision. The downstream nucleons which may be hit by the excited projectile are also likely to be hit by the jet of slow particles from the first interaction. As a consequence, after the first collision the cross-section leading to emission of further nucleons would tend to be more independent of the projectile. For the extreme assumption

that there is only one large cascade -- the one initiated by the first collision -- a projectile dependence would be only caused by the different average depth in the nucleus at which the first interaction took place, depending on the cross-section of the incoming projectile.

It is then natural to conclude that the extent of this large cascade does not depend directly on the number ν of primary collisions, but depends on the average depths of the first interaction and on the remaining thickness of the nucleus at given impact parameter. Hence the number of slow particles measures the peripherality or centrality of a hadron-nucleus collision.

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Table 1

Mean multiplicities of slow particles $\langle N_g \rangle$

Projectile	Target	$E_{inc} = 50 \text{ GeV}$	100 GeV	150 GeV
K^+	C	0.81 ± 0.04		0.80 ± 0.04
	Cu	1.92 ± 0.10		1.93 ± 0.10
	Pb	3.43 ± 0.17		3.23 ± 0.16
K^-	C	0.80 ± 0.04	0.83 ± 0.04	
	Cu	2.00 ± 0.10	2.02 ± 0.10	2.07 ± 0.10
	Pb	3.62 ± 0.18	3.60 ± 0.18	4.02 ± 0.20
π^+	C	0.85 ± 0.04	0.81 ± 0.04	0.84 ± 0.04
	Cu	1.99 ± 0.10	2.04 ± 0.10	1.99 ± 0.10
	Pb	3.42 ± 0.17	2.89 ± 0.14	3.31 ± 0.17
p	C	0.91 ± 0.05	0.82 ± 0.04	0.89 ± 0.04
	Cu	2.23 ± 0.11	2.26 ± 0.11	2.27 ± 0.11
	Pb	4.04 ± 0.20		3.75 ± 0.19
$\bar{p}$	C	0.94 ± 0.05	0.92 ± 0.05	
	Cu	2.36 ± 0.12	2.27 ± 0.11	
	Pb	4.24 ± 0.21	4.08 ± 0.20	4.08 ± 0.20

Figure captions

- Fig. 1 : a) The detector.
b) The layout of the beam counters.
- Fig. 2 : Angular distributions of slow particles $d\langle N_g \rangle / d\Omega$.
a) $d\langle N_g \rangle / d\Omega$ for different intervals of the energy loss ΔE in the CsI crystal. ΔE is given in units of the energy loss of minimum ionizing particles. The corresponding kinetic energies of the protons are the following in (MeV): I) 100 to 300; II) 30 to 100; III) < 30 .
b) $d\langle N_g \rangle / d\Omega$ for 50, 100, and 150 GeV π^+ on C, Cu, and Pb (upper part), and 50 GeV π^+ , p, and $\bar{p}$ on Pb (lower part).
- Fig. 3 : The average multiplicity of slow particles $\langle N_g \rangle$ for different incoming energies, targets, and various projectiles, as a function of $\langle \nu \rangle$ from Eq. (1). The dotted line corresponds to the expected projectile dependence of $\langle N_g \rangle$ on $\langle \nu \rangle$ for fixed A (see Section 4).
- Fig. 4 : Multiplicity distributions of slow particles $F(N_g)$.
a) Projectile dependence (fixed A and E_{inc}).
b) Energy dependence (fixed A and h).
c) Target dependence (fixed E_{inc} and h).
The errors are of the order of 5% and comparable to the size of the symbols.
- Fig. 5 : Calculated probability $f(\nu)$ that an incident proton collides ν times in C, Cu, and Pb nuclei.
- Fig. 6 : Comparison of experimental and calculated multiplicity distributions of slow particles for incident pions and protons on (a) carbon, (b) copper, and (c) lead.
- Fig. 7 : The mean number of collisions $\langle \nu \rangle$ as a function of the number of observed slow particles, as calculated from the model in Section 4.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7