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NEW EXPERIMENTAL RESULTS FOR PARTICLE PRODUCTION FROM NUCLEI

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ABSTRACT

Particle production from nuclei was studied for π , p , and $\bar{p}$ interactions at 20 to 150 GeV/c at the CERN SPS. The detector distinguishes between fast and slow particles, mainly pions and recoil protons, respectively, with a cut at a velocity $v = 0.7 c$. Angular distributions, multiplicity distributions, and correlations were analysed.

The pseudorapidity distributions of fast particles, normalized to one collision, depend only very weakly on the incoming energy and scale well with $\langle v \rangle = A\sigma_{hN}/\sigma_{hA}$. This novel result is in contradiction with most of the models proposed so far. Conclusions are drawn for those models which describe hadron-nucleus collisions in terms of multiple soft quark interactions.

As a function of the number of observed recoil protons, the multiplicity distributions of fast particles do not obey KNO scaling. We examine whether this result is consistent with the predictions of the coherent tube model. Finally, correlations in phase space of slow and fast particles are discussed and an outlook is given for future experiments.

1. INTRODUCTION -- THE FIRST 3 μ s
AFTER A HADRON-HADRON COLLISION

The subject of this paper is an experimental study of the inelastic interaction of hadrons with nuclei at high energies. In this context "high energy" is defined to be well above the threshold for pion production (incoming energies of the order of 10 GeV or higher). Indeed the most common effect of such an interaction is the creation of new particles, mainly pions. In this work a few general and simple aspects of particle production from nuclei will be examined.

In the case of the inelastic hadron-nucleon interaction, in particular the proton-proton (pp) interaction, a wealth of experimental data has been collected in the past. Seemingly almost everything which can be measured and analysed with not too great an effort has been measured up to the highest accelerator energies available at present. In addition, cosmic radiation gives us a foretaste of events at even higher energies.

A natural question to ask in view of the abundance of pp data is: what additional information can one gain if one studies particle production on nuclear targets instead of a free nucleon -- the proton target. The answer or rather a pointer to the answer may be found in Table I, where a few important events during the first 3 μ s after the start of a pp interaction are listed in chronological order.

One preparatory note to this list: most particles emerging from a pp interaction at high energy have high energies and are therefore relativistic. This is true in any reference system, but nevertheless in the following a system is assumed where the target is at rest in the laboratory for the sake of simplicity. As the particles are relativistic, characteristic times, like their lifetime, become lorentz-dilated. This has to be borne in mind. Again for simplicity, let us assume that all massive particles have a γ of 100, a value, which is typical for the energy range studied here,

$$\gamma = \frac{E}{M} = \left(1 - \frac{v}{c}\right)^{-1/2} = 100 . \quad (1)$$

So the velocity v is close to the light velocity. For pions, a γ of 100 corresponds to a laboratory energy of 14 GeV. We go backward in time. The first column of Table I contains a logarithmic time scale and the second column shows the spatial distance $z = ct$ from the interaction region.

At 3 μ s, at the end of the time interval considered, it appears that only neutrinos, muons, photons, and nucleons emerge from a strong interaction. Thus a detector at a distance of 1 km from the interaction may yield a false idea of the particles produced by hadrons as we know today. Such a device which we shall call detector No. 1 represents today's neutrino and muon detectors and has a historical significance, too. One knows of the difficulty high-energy physicists had about 30 years ago when they searched for the Yukawa mesons and found the μ mesons.

The charged Yukawa mesons decay after 780 m (if their γ is 100). Most electronic detectors are placed in the order of 1 m from the interaction region; hence charged pions appear as stable particles. Moreover, these detectors (No. 2) see photons and nucleons. We neglect the rarer particles.

The photons are the decay products of the neutral pions. Those decay after 10^{-14} s in the laboratory. From this time on, going backwards, there are only hadrons. We can descend many decades down into the past before these hadrons change again. The fact that after about 10^{-8} cm or 0.3×10^{-18} s they leave the volume of the hydrogen atom which housed the target proton disturbs the free flight of these hadrons only negligibly.

But something does happen of which we have indirect knowledge -- at a milestone of 200 fm or 0.7×10^{-21} s after the start of the interaction. Some of the pions or nucleons combine to form resonances. The typical width of strongly decaying resonances is of the order of a few hundred MeV, which corresponds to a decay time of some 10^{-23} s in the laboratory.

We know very little but have plenty of ideas about what is going on before the decay of the resonances. The size of hadrons and their strong interaction radius is about 1 fm, their characteristic interaction time is therefore $1 \text{ fm}/c = 3 \times 10^{-24}$ s. This is the interaction time in the rest system of a hadron and

it gets Lorentz-dilated for a moving hadron. Thus the interaction of a hadron with a γ of 100 extends over a distance of about 100 fm. So the undisturbed, interaction-free existence of resonances emerging from an interaction lasts hardly longer than the interaction itself. A resonance is like a short process of the final-state interaction.

Needless to say, the time interval from 10^{-24} s to the decay of the resonances is of the utmost importance for the time development of the strong interaction or, in other words, for the process of maturation of hadrons. After this time interval the end products of the strong interaction fly apart to decay eventually by electromagnetic or weak interaction into more stable particles. It is, by the way, senseless to ask what happens at even smaller times than 10^{-24} s: from the momentum and energy transfers in normal inelastic hadron interactions one knows, using the uncertainty relations, that the interaction cannot be localized to better than to 1 fm or 1 fm/c.

2. THE USE OF NUCLEAR TARGETS

2.1 A tool to study hadrons *in statu nascendi*

What we then need is a suitable detector to study the proper time interval of strong action. If we define a detector as something which causes the objects under study to interact and, being a refined detector, has a few parameters that can be varied in a controlled manner, then, with this general definition, such a detector (No. 3 in Table I) is provided by nuclei. Their size is

$$r_A = 1.2 A^{1/3} [\text{fm}] , \quad (2)$$

with variable mass number A. Detector No. 3 sees all sorts of hadrons, resonances, and maybe even bare, semibare, or semidressed quarks; in short, hadrons *in statu nascendi*.

The size alone would not make nuclei useful detectors if they were not efficient, too. They are efficient owing to their high density. The hadrons *in statu nascendi*, which were created in the first interaction of the incoming hadron with

a nucleon, will quite probably interact in the same nucleus. The absorption length or mean free path in a nucleus is

$$\lambda = \frac{1}{\rho\sigma} \approx 2 \text{ [fm]} \quad (3)$$

with ρ the density of nuclear matter ($\rho = 0.17$ nucleons/fm³) and σ the inelastic cross-section ($\sigma = 3$ fm² for a proton-nucleon interaction).

The size (2) and the mean free path (3) have to be compared with the duration of the strong interaction

$$\tau = \gamma\tau_0, \quad (4)$$

with τ_0 the characteristic time of strong interactions ($\tau_0 = 1$ fm/c) and γ defined in Eq. (1). The time evolution can be almost arbitrarily slowed down in the laboratory by increasing γ , i.e. the velocity. In nature, the hadrons created in a first interaction on a nucleon have different γ factors; however, with increasing energy of the incoming hadron their spectrum extends to higher energy, too. Thus by increasing the incoming energy one has a certain control on γ . Therefore one of the goals of the experiment to be described here was to vary the incoming energy over a large range.

The claim that nuclei are potential tools for a study of the space-time development of the strong interaction can be found in the introduction of almost every theoretical or experimental paper on hadron-nucleus interactions at high energy. Many theoretical models do not really prove this claim and so it is difficult for experiments to verify it, since experimental results depend on the interpretation by theory. For these models the specific nature of the hadrons *in statu nascendi* seems to be irrelevant, the only relevant quantity being a characteristic time which gets Lorentz-dilated corresponding to the velocity of the produced hadronic matter. Perhaps an exception is the class of models where hadrons *in statu nascendi* are identified with quarks or partons. The characteristic time of the strong interaction appears in these models as the time it takes partons to materialize or to "dress". Here nuclei may serve as a tool to study the number and energy dependence of independent parton interactions [1].

The comparison of our experimental results with these models will therefore be emphasized.

2.2 How many collisions within a nucleus?

2.2.1 The average number of collisions

The average inelastic interaction of a hadron with a single nucleon can result in a large variety of possible multiparticle final states. On a nucleus, one has, in addition, interactions with different numbers of nucleons, ranging from peripheral collisions with single surface nucleons to central collisions with many target nucleons involved.

As a measure for the mean number of inelastic interactions in a nucleus the following parameter is frequently used [2]

$$\langle \nu \rangle_{hA} = A \frac{\sigma_{hN}}{\sigma_{hA}}, \quad (5)$$

with σ_{hN} and σ_{hA} being the cross-sections for particle production on nucleons and nuclei, respectively. It is easy to see that this parameter is equal to the average number of inelastic interactions of the incoming hadron, if one assumes that the latter moves on a straight trajectory through the nucleus and that its cross-section does not change after a collision. Formula (5) yields, for example,

$$\begin{aligned} \langle \nu \rangle_{pA} &= 0.83 A^{0.28} \\ \langle \nu \rangle_{\pi A} &= 0.80 A^{0.24}, \end{aligned} \quad (6)$$

using production cross-sections on nuclear targets measured by Carroll et al. at 60 to 280 GeV [3].

2.2.2 Nuclear fragments

Instead of using an average measure for the number of collisions it would be better to have an indicator showing for the individual event how many collisions took place. Physicists working with nuclear emulsion have believed for a long time that such an indicator is provided by the grey and black tracks. They thought that these tracks, being nuclear fragments, could not only be used to tell whether an interaction occurred on a light or heavy nucleus, but more specifically would tell how many nucleons participated in the interaction [4]. As in some respect

our experiments are a continuation of emulsion experiments and we are using definitions which are customary in the emulsion technique, it may be useful to recall some of the relevant definitions.

A quantitative classification of tracks visible in an emulsion star is based on the specific ionization, i.e. the density of grains along the tracks (see, for instance, Segrè [5]). This corresponds to a classification according to the velocity or energy of the track, and hence to a relatively clear distinction of the processes leading to the emission of the particles (Table II).

The particles with low ionization are called "shower" particles; they are relativistic particles, mainly pions, and are presumably products of the primary interactions of the incoming hadron. The little drawing in Table II explains what is understood by "primary" interactions: the incoming hadron is thought to move on an almost straight trajectory through the nucleus, thereby getting excited, and only a row of nucleons in the path of the incoming hadron is hit. High-energetic secondaries produced in these interactions separate from the incoming hadron only after the nucleus has been traversed. A more thorough discussion of this classical picture of the propagation through the nucleus has been given in Ref. [1].

Tracks with intermediate ionization are called "grey". Those are mainly protons with kinetic energies between 30 and 500 MeV. They are presumably the result of a few-step intranuclear cascade as sketched in Table II. The nucleons primarily hit and large-angle secondaries produced in primary interactions can knock out further nucleons on their way through the nucleus.

Tracks with even higher grain density appear as "black" and have short ranges. These are thermal fragments with energies smaller than 25 MeV, protons, and heavier fragments, too. They are the result of a multistep intranuclear cascade where absorbed energy is thermalized.

Out of the nuclear fragments, the grey tracks are apparently more directly related to the number of primarily hit nucleons than the black tracks. Thus the aim of the experiment described below was to measure the charged outgoing particles and to have, as far as possible, the same distinction between shower and grey

tracks as in emulsion. Furthermore, the experimental study was intended for an energy range which so far had not been well explored by emulsion experiments; the one between proton-synchrotron and super-proton-synchrotron energy, i.e. between about 20 and 300 GeV. Advantages of this experiment over emulsion experiments are the use of an electronic detector, allowing higher statistics and a faster analysis, and the use of "pure" nuclear targets as opposed to a mixture of nuclei in emulsion. The disadvantages are backgrounds from secondary interactions not present, or clearly distinguishable, in emulsion.

3. THE EXPERIMENT AT THE CERN SPS

3.1 Apparatus

3.1.1 Survey

The measurements were done at the CERN SPS (Super Proton Synchrotron) using the unseparated S1 beam for incoming energies of 20 and 37.5 GeV and the H3 beam (also unseparated) for energies of 50, 100, and 150 GeV. Results of the first experiments, in the S1 beam, have been published and the list of physicists who have contributed is given elsewhere [6]. The physicists participating in the second experiment are listed in Braune et al. [7].

In short, the basic detector was non-magnetic, covered about 50% of the total solid angle, and was sufficiently subdivided in angle to measure angular distributions and multiplicities of charged particles. It could discriminate between slow and fast particles where the separation point was a velocity of $\beta = 0.7$, which corresponds to the separation between shower and grey tracks in nuclear emulsion. The lower cut-off in energy of slow particles was determined by absorbing material in front of the counters and by absorption in the target. Thus tracks corresponding to the black tracks of the emulsion were absorbed; therefore our slow tracks are essentially the same as the grey tracks.

3.1.2 Discrimination between fast and slow particles

Slow and fast particles were separated by means of "combined counters" (Fig. 1). These consisted of a CsI(Tl) crystal, 3 mm thick with a diameter of

50 mm, and the crystal was glued to a lucite light-guide, which was attached to the photomultiplier. The light signal produced in the CsI crystal is proportional to the energy loss of the particle in the crystal. The lucite light-guide acts as a Čerenkov radiator if the velocity of the particle is higher than $1/n_l = 0.7c$ (n_l is the refractive index of lucite for light). Thus the presence of a Čerenkov pulse indicates a fast particle.

Figure 2a shows the anode signal of the photomultiplier when a fast particle hit the counter. It consists of a short, high spike -- the Čerenkov signal -- followed by a long pulse from the CsI crystal with a decay time of about 1 μ s. The pulse heights are around 200 mV and 50 mV, respectively, on a 50 Ω resistor, for the chosen amplification. For a slow particle the spike at the beginning is missing.

Originally it was intended to achieve the separation by means of two discriminator levels, one set at 30 mV, below the CsI pulse height for minimum ionizing particles, and the other one at 150 mV, high enough above most CsI pulses, but still accepting all Čerenkov pulses. The lengths of the lucite cones were determined by the requirement to have high Čerenkov pulses (> 500 mV).

It was learnt, in the course of the first measurements, that a cleaner and more reliable separation between tracks with and without Čerenkov pulse could be achieved using the rise-time difference between the Čerenkov and the CsI signal (Fig. 2b). The Čerenkov signal is fast, its rise-time is determined by the intrinsic resolving times of phototube and signal cable, whereas the rise-time of the CsI signal is slower, typically 20-30 ns, owing to the light-emitting processes in the crystal. As a consequence of using the rise-time for the separation, the combined counters were rebuilt for the second run (at 50-150 GeV). The lucite cones were shortened to 3-13 cm from 13-25 cm and smaller phototubes (EMI 9813KB or AVP 56) instead of tubes with a window of 5 in. diameter were used. The gain was mainly a large reduction of material around the target, thus reducing secondary interactions outside the target, also reducing the size of the detector.

Seventy-three of these combined counters covered 53% of the total solid angle and formed 7 rings of roughly equal size in pseudorapidity η [see Section 4.2,

Eq. (11)] around the beam axis (Fig. 3a). There were no counters for $165^\circ < \theta < 180^\circ$ (θ being the polar angle with respect to the beam axis).

3.1.3 Forward hodoscope

The forward cone ($\theta < 13^\circ$) was covered by four rings of a hodoscope and one counter at $\theta = 0^\circ$. Only very few slow particles are expected in the hodoscope as they have a rather flat angular distribution and the cone $\theta < 13^\circ$ amounts to only 1% of the total solid angle. Yet an important fraction of fast particles are emitted into this cone. In the first run (20-37 GeV) the hodoscope was built from lucite Čerenkov counters, 4 cm thick in beam direction. Thus only fast particles were detected by their Čerenkov light. In the second run (50-150 GeV) the lucite counters were replaced by 5 mm thick plastic scintillators (NE 102). This was done in order to reduce the mass of the detector and to facilitate the selection of good tracks, which was based on the recorded pulse height and done off line (see below). Thus in the second run charged particles were detected in the forward hodoscope without discrimination between slow and fast.

3.1.4 Beam counters

Since the experiments were done at unseparated beams, two gas Čerenkov counters Č1 and Č2 were used to distinguish between incoming pions, kaons, and (anti)protons. The beam was defined by several counters (see Fig. 3b), beginning with counter B in front of Č1, and counter S between Č1 and Č2. Counter S provided the reference time for the event. The final definition of the beam spot on the target was accomplished in the first run by a combination of a 1 mm thick counter D ($1 \times 1 \text{ cm}^2$) followed by a veto counter AH with a hole of 8 mm in diameter to minimize unrecognized interactions upstream of the target, and in the second run by a combination of a veto counter AH with a 1 cm hole and a counter T placed directly behind the target (diameter = 5 mm, thickness = 1 mm). Large veto counters (AL, AR, AU, AD) covered the active area of the detector to reject halo particles arriving simultaneously with the beam particle. An aluminium shield towards the detector prevented vetoing of good events by backward tracks from the target hitting the large veto counters. A small counter AB ($\theta < 3 \text{ mrad}$) downstream of the target served as beam veto.

3.2 Data acquisition, reduction, and correction

3.2.1 Trigger

The interaction trigger was $\text{BEAM} \cdot \text{OR} \cdot \overline{\text{AB}}$, where "BEAM" was defined as $\text{B} \cdot \text{S} \cdot \text{T} \cdot \overline{\text{AH}} \cdot \overline{\text{AL}} \cdot \overline{\text{AR}} \cdot \overline{\text{AU}} \cdot \overline{\text{AD}} \cdot f(\check{\text{C}}1, \check{\text{C}}2)$, $f(\check{\text{C}}1, \check{\text{C}}2)$ being a combination of the gas Čerenkov counters to select the desired beam particles. The "OR" required any two of the combined or hodoscope counters, except the counter at $\theta = 0^\circ \pm 0.5^\circ$ which was not included in the trigger. By requiring only one track, the background due to accidental coincidences would have considerably increased at a negligible gain of the detected inelastic cross-section.

3.2.2 Targets

The targets used were C (4 mm thick), Cu (2 mm), Pb (2 mm) and in addition, but only for the first run at 20 and 37 GeV, Al (4 mm) and Ag (2 mm). Measurements with an empty target position were taken in order to subtract interactions outside the target: in the air, in the target counter T, or in the helium bag which was put in between the target and the hodoscope counters. In some cases measurements with different target thicknesses were done to study secondary interactions in the target. The choice of the standard target thickness corresponds to 1% of an absorption length. This is thin enough to keep secondary interactions (with other nuclei!) in the target low, but gives reasonable interaction rates at moderate beam intensities. As already mentioned, the target thickness together with the material in front of the counters is sufficient to absorb most of the "black" tracks.

3.2.3 Rates

The beam intensity was chosen to yield as high a number of triggers as could be accepted by the on-line computer, i.e. about 200 triggers per burst. If no selection of beam particles was made, this corresponded to beam intensities ($\text{B} \cdot \text{S}$) of about 40,000 per burst, yielding 20,000 "BEAM" triggers. The interaction trigger rate per "BEAM" was 1.2% at the chosen target thickness, since practically all events were "good events" from the target or the target counter D. If rare beam particles were selected, like antiprotons, the beam intensities had to be

correspondingly higher, but 10^6 particles (B·S) per second were about the practical limit, since accidental background became prohibitive at these intensities. About 100,000 (1 tape) to 400,000 events were collected for each combination of target·energy·projectile.

3.2.4 Counter electronics

For each of the about 140 counters used in the experiment (be it a combined, a hodoscope, or a beam counter) the anode signal was split between a discriminator and a charge-sensitive analog-to-digital converter (ADC). The outputs of the discriminator were fed to a pattern, a time-to-digital converter (TDC), and to the common logic (the "OR" for the combined and hodoscope counters, and the "BEAM" trigger logic for the beam counters). The TDCs and ADCs of beam counters, patterns, and scaler rates (all CAMAC) were written on tape for every event, but the TDCs and ADCs of the combined or hodoscope counters were only recorded if the corresponding pattern bit was set. Thus the amount of written data was reduced and the maximum acquisition rate was increased. The TDCs, which were started by the common reference time (beam counter S), recorded the precise trigger time of each track. Through the ADC, which converted the integrated charge of the pulse, the energy loss of tracks in scintillation counters or the amount of Čerenkov light in the case of pure Čerenkov counters was recorded. The advantage of this scheme, which may seem somewhat expensive, is apparent. Adjusting of discriminator levels and gains of phototubes was uncritical. They had to be set to guarantee full efficiency for charged tracks from the target. (Nevertheless the gains were adjusted uniformly if possible.) Only the timing of each counter had to be adjusted carefully to within 2 ns, because of common gates. The final selection of good tracks and the separation between slow and fast particles could then be done off-line, based on the recorded information.

3.2.5 Track selection

As a first step in the off-line analysis the precise calibration of each counter was determined for each tape or file separately using the ADC and TDC spectra. The calibration was provided by minimum ionizing particles which give

the reference point in time and for the energy loss. 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.

Figure 4 shows a scattergram of ADC versus TDC for one of the combined counters. One recognizes the peak of minimum ionizing particles with a Landau distribution of energy losses. About 5-10 ns later (to the right) is the mountain of slow particles, which, as expected, have higher energy losses. The separation was done by applying the cuts (vertical and inclined lines) indicated. The ADC cut below the peak of minimum ionizing particles was applied to get rid of cross talk and particles not having a proper energy loss in the CsI crystal (e.g. γ conversions in the lucite, spurious electrons not from the target). The horizontal (ADC) cut below the slow particles got rid of γ -rays absorbed in the crystal. The minimum energy loss of a slow particle traversing the CsI crystal (say a proton of 1 GeV/c momentum) is twice minimum ionizing. Smaller energy losses can only arise from particles stopped in the crystal, i.e. very-low energy particles (black tracks), or from γ -rays.

Good tracks in the hodoscope were selected by corresponding cuts in the ADC and TDC. There is only one peak of minimum ionizing particles in the TDC and ADC spectra.

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

3.2.6 Corrections

An empty target measurement, taken at identical running conditions and properly normalized, was subtracted from each measurement.

All multiplicities were corrected for acceptance as a function of the polar angle θ . The "dominance" of fast particles was taken into account. Two tracks hitting the same counter would always appear as a fast track if one of them had

a Čerenkov pulse. So the counters where a fast track was detected had to be subtracted from the active solid angle for slow particles.

It would have been difficult to correct for double or multiple hits in one counter on the basis of the measured pulse-height spectrum. (Only the very forward counters of the hodoscope show a clear double-peak structure.) Therefore it was assumed that multiple hits occurred only on a statistical basis and the true number of hits follows a Poisson distribution. For a given counter the correction was then

$$\langle \text{NPC} \rangle_{\text{true}} = -\ln \left(1 - \langle \text{NPC} \rangle_{\text{meas}} \right), \quad (7)$$

where $\langle \text{NPC} \rangle$ is the average multiplicity per counter and event for any selected sample of events.

A serious background arose from electrons produced by conversion of γ 's (from π^0 decay) in the target and the material of the detector; less important were δ -rays. To correct for γ conversions in the target it was assumed that the $\pi^0/(\pi^+ + \pi^-)$ production ratio is constant and equal to 0.5 and that the γ angular distribution is the same as that of charged pions. This latter assumption is certainly not good for large laboratory angle and thus the background subtraction will somewhat distort the η distribution around $\eta = 0$. The angle-dependent path of the γ in the target was calculated in units of γ -conversion lengths from the target centre. A γ conversion produces an e^+e^- pair, but this pair usually hits only one counter and hence was counted as one hit only.

Secondary interactions of γ 's and charged particles in the combined counters and their aluminium mount were the cause of a mismatch of the differential multiplicities found between the last ring of the combined counters and the first hodoscope ring (at $\theta = 13^\circ$). In contrast to the CsI crystals, the hodoscope counters are outside of a considerable mass of material for particles coming from the target. Just the two rings of combined counters closest to the hodoscope contain the most massive counters. After correction for δ -rays, which is also higher for the hodoscope counters than for the combined counters, the apparent mismatch amounts to about 20%, independent of incoming energy, target mass, and projectile. To

correct for this background, the average multiplicity of the hodoscope counters was correspondingly reduced.

Secondary interactions of charged particles in the target are almost negligible. They were corrected for by the formula

$$\Delta\langle N_s \rangle = -0.5d\langle N_s(E) \rangle \left(\left\langle N_s \left(\frac{E}{N_s} \right) \right\rangle - 1 \right), \quad (8)$$

where d is the target thickness in units of absorption lengths and E is the incoming energy.

4. RESULTS AND INTERPRETATION

Our observables are multiplicities of fast and slow particles, which depend *a priori* on all measurement parameters like incoming energy E_{inc} , target mass A , projectile quantum numbers, polar angle θ , or pseudorapidity η , and the azimuthal angle ϕ . Moreover, we have studied multiplicity correlations, in particular between slow and fast tracks.

In some cases the number of dependences is smaller than it could be (e.g. the slow particles do not depend on E_{inc}) or can be reduced by choosing a scaling parameter [e.g. the parameter $\langle v \rangle$ defined by Eq. (5)]. These cases deserve special attention, of course; yet more than enough dependences remain. Therefore rather than trying to be complete, the following sections on the results will be very selective. They will start with global, integrated observables and progressively deal with the more differentiated ones (this is reversed from the sequence in the actual data analysis).

In the first section (4.1) the total integrated multiplicities and their regularities are shown. At the second level of differentiation we will first look at pseudorapidity distributions of fast particles (Section 4.2) and secondly at multiplicity distributions of fast particles as a function of the number N_g of observed slow particles (Section 4.3). Finally, as an example of even higher differentiation, the pseudorapidity distributions of fast particles will be shown as a function of the number of observed slow particles (Section 4.5).

At the first level the observables are so global and insensitive that a comparison with theoretical predictions does not seem to be very meaningful. The comparison with theory will take place at the second level (Sections 4.4, 4.5). The third level is already so differentiated that all but one [8] of the theories have not been applied, so there is still room for a "free" interpretation of the results. At the beginning of most sections the corresponding results for the hadron-proton interaction from other experiments will be recalled as a basis for a better understanding of the target-mass dependence.

4.1 Regularities of total multiplicities

4.1.1 Charged-particle multiplicity in pp interactions

To start with the smallest nucleus, the energy dependence of the multiplicity of charged particles in pp interactions is displayed in Fig. 5. These data [9], extending to the highest ISR energies, show the slow increase of particle numbers, which can be described by a logarithmic expression of the form given in the figure. Here the *charged* multiplicity is plotted. In the following we will always quote multiplicities of fast and slow particles. The charged multiplicity N_{ch} is the sum of slow and fast multiplicity, N_g and N_s , and in the case of hadron-proton interactions on a stationary proton target the mean number $\langle N_g \rangle$ of slow particles is around 0.5, i.e. the target proton has in 50% of all inelastic events a recoil momentum higher than 1 GeV/c and counts as a fast particle in our definition.

4.1.2 hA collisions

Figure 6 shows the multiplicities $\langle N_s \rangle$ and $\langle N_g \rangle$ in our experiment for 50 to 150 GeV plotted versus $\langle v \rangle$. The values of $\langle N_s \rangle$ range from 5 to 15 depending on E_{inc} , A, and projectile, and range from 1 to 4 for $\langle N_g \rangle$ depending on A and projectile. The data points can be grouped into different, approximately linear, dependences, which are indicated by lines. Multiplicities of slow particles $\langle N_g \rangle$ form different groups which depend only on the projectile but do not at all depend on E_{inc} . Multiplicities of fast particles form groups, which depend on E_{inc} but not on the projectile.

4.1.3 Fast particles

Let us consider the fast particles first. The target and projectile dependences are roughly contained in one single parameter, $\langle \nu \rangle$. One can go even further and find an energy-independent quantity by dividing $\langle N_s \rangle$ by the multiplicity on a proton target or the extrapolated multiplicity at $\langle \nu \rangle = 1$. This leads to the well-known simple formula [10], which can be used as rule of thumb

$$R_A \equiv \frac{\langle N_s \rangle_{hA}}{\langle N_s \rangle_{hN}} = a + b(\langle \nu \rangle - 1) , \quad (9a)$$

where a and b depend very little on the energy E_{inc} between 20 and 200 GeV. The values we obtain for a and b are

$$\begin{aligned} a &= 1.06 \pm 0.02 \\ b &= 0.38 \pm 0.05 . \end{aligned} \quad (9b)$$

For the denominator of R_A the multiplicity $\langle N_s \rangle_{\nu=1}$ (extrapolation to $\langle \nu \rangle = 1$) was taken. This relation is so simple that one might suspect a very simple, energy-independent mechanism as being responsible for particle production on nuclei, but, as pointed out already, the total multiplicities may be too insensitive quantities. We will rather compare in the next sections the differential multiplicities (η distributions) with the predictions.

4.1.4 Slow particles

The multiplicities of slow tracks are energy independent to a remarkable precision. The differences at 50, 100, and 150 GeV are smaller than the point size in Fig. 6. The same property of energy independence has been found in our first run at 20-40 GeV; however, the cuts for the selection of slow particles were slightly different, so we do not plot the old data on the same figure. This result is not new. From emulsion experiments it has been known for a long time that the features of the grey tracks depend very weakly on E_{inc} for E_{inc} between 10 and 400 GeV. It is worth mentioning, but will not be demonstrated here, that the multiplicity and angular distributions are found to be energy independent as well, so we conclude that probably all features of the slow particles are energy independent. This is a necessary condition for N_g to be a measure of the number

of collisions. Such a measure should not depend on E_{inc} except via the cross-section which is known to depend only weakly on E_{inc} in our energy region.

The dependence on $\langle v \rangle$ is somewhat more complicated. Unlike $\langle N_s \rangle$, $\langle N_g \rangle$ does not scale with $\langle v \rangle$ but apparently depends on the projectile. If one should naïvely assume the number of slow particles to be directly related to the number $\langle v \rangle$ of collisions, then the multiplicities $\langle N_g \rangle$ would fall on one universal curve. The reality is more complicated. The multiplicities of slow particles can be described by a dependence of the form

$$\langle N_g \rangle = f(A)g(\langle v \rangle) . \quad (10)$$

According to the picture of a slow cascade sketched in Section 2.2 (see Table II) one would expect g to be linear in $\langle v \rangle$ and f to be proportional to $A^{1/3}$. The factor g contains the information on the number of primary collisions $\langle v \rangle$, while $f(A)$ is due to the cascade of nucleons and large-angle secondaries (mostly pions), so $f(A)$ is projectile independent. It is found, however, that the measured dependence of $\langle N_g \rangle$ on the projectile, i.e. on $\langle v \rangle$ is weaker than expected by such a simple model.

4.2 Pseudorapidity distributions of fast particles

4.2.1 The pseudorapidity variable η

The following two sections will deal with the inclusive pseudorapidity distribution of fast particles, their target-mass, projectile, or $\langle v \rangle$ dependence. The slow particles will be neglected altogether as if we had not measured them. At this point, an explanation concerning the use of η is in order. The pseudorapidity

$$\eta = -\ln \operatorname{tg} \frac{\theta}{2} \quad (11a)$$

is practically the same as the rapidity

$$y = 0.5 \ln \frac{E + p_\ell}{E - p_\ell} \quad (11b)$$

with θ , E , and p_ℓ being the laboratory quantities of polar angle, energy, and parallel momentum (with respect to the beam axis), if the mass m of the particle is small compared to its transverse momentum, or, more precisely, if

$$\ln \frac{E + p_\ell}{m_t} \approx \ln \frac{p + p_\ell}{p_t} \quad (12a)$$

where p_t is the transverse momentum with respect to the beam axis and $m_t = \sqrt{p_t^2 + m^2}$ is the transverse mass. The usefulness of the rapidity is due to its behaviour under a special Lorentz transformation, which adds just a constant, independent of y

$$y' = y + \ln \frac{1 + \beta}{1 - \beta}, \quad (12b)$$

where βc is the velocity of the moving reference system. Therefore rapidity distributions do not change their shape under a special Lorentz transformation, as the rapidity scale is only shifted by a constant, nor do pseudorapidity distributions since the condition (12a) is most often fulfilled by pions.

4.2.2 pp interactions and limiting fragmentation

Let us again begin with the case of pp interactions. Figure 7 shows the η distributions of charged particles for different incoming laboratory energies. With increasing energy there are more particles at high η and the particle density at low η remains constant. The width of the η distribution is equal to the rapidity difference of the two incoming protons; it is therefore proportional to $\ln E_{inc}$. The logarithmic dependence

$$\langle N_{ch} \rangle = a + b \ln E_{inc} + c (\ln E_{inc})^2 \quad (13)$$

of the total charged multiplicity (Fig. 5), which is the integral over the η distribution, is obvious from this plot, as not only the width but also the height increases proportional to $\ln E_{inc}$.

For a better understanding of the rapidity distributions the quantum number flow (the average values of quantum numbers like charge, baryon number, etc., as a function of η) has to be studied. Such experiments have led to the following picture [11]. The rapidity distribution of outgoing particles is composed of three parts: two fragmentation regions, of the target and the projectile, and a central or pionization region (Fig. 8). In the fragmentation regions, 1-2 units wide in rapidity, the quantum numbers of the incoming hadrons can be found. The

central region has the quantum numbers of the vacuum (on the average). Pions dominate and particles and antiparticles are equally frequent. In terms of the quark language: in the fragmentation regions the valence quarks are found -- confined in the leading hadrons -- while hadrons in the central region are made from sea quarks. With increasing energy the central region increases, the separation between the fragmentation regions gets wider, but content and shape of the fragmentation regions remain constant. This behaviour of the fragmentation regions is called "limiting fragmentation" [12] or "Feynman scaling" [13] and the visible, experimental proof can be seen in the constancy of the particle density $d\langle N \rangle / d\eta$ at small η -- the corresponding behaviour can of course be found at the projectile side if one plots the η distribution in the projectile rest system.

4.2.3 hA interactions

Pseudorapidity distributions of fast particles emitted in hA inelastic interactions are displayed in Fig. 9. The upper graph shows our measurements for different targets and for incoming pions of fixed energy (37.5 GeV). It can be seen that the small increase of the total multiplicity with A [cf. Eq. (9)] is due to an increase at small η only -- at the target fragmentation side. At higher η -- the projectile fragmentation side -- the changes are small and, if anything, the particle density decreases there with increasing A. It is hard to say from this plot what happens in the central region between the fragmentation regions, as the former is not sufficiently developed and the latter are not well separated yet at this energy (or at our highest energy of 150 GeV).

The dependence of E_{inc} is shown in Fig. 9b, which looks like the mirror image of the upper one. The particle density increases with E_{inc} at high η and remains constant at low η . The behaviour is very similar to the case of pp interactions. Limiting fragmentation holds for nuclear targets as well. In other words: the average energy absorbed by the target nucleus does not depend on E_{inc} if the latter is higher than 10-20 GeV. This energy independence of fast particles from the target fragmentation region is of course directly related to the energy independence of the slow particles mentioned in the previous section. Slow particles are

target fragments, too. They consist mainly of leading or spectator protons at the target side of the rapidity distribution. They do also reflect to some degree the energy absorbed by the nucleus. Moreover in emulsions one has found that the black tracks, which are a measure of the temperature of the nuclear fragments left over from the interaction, are E_{inc} independent. The connection between particles at low η and the slow tracks will be discussed in a later section. An example of the projectile dependence of the η distributions is given in Fig. 9c.

4.2.4 The normalized η distributions

A direct comparison of the η distributions with most theoretical models is not possible for the following reason. Theoretical predictions mostly refer to the increase of particles produced from a nuclear target relative to a single nucleon target as function of the rapidity y . Thus the interesting quantity is the ratio

$$R(y)_{hA} = \frac{\langle dN_s(y)/dy \rangle_{hA}}{\langle dN_s(y)/dy \rangle_{hN}} . \quad (14a)$$

We have not made measurements with a proton target, yet it is absolutely necessary to determine this ratio within one and the same experiment to have the same trigger biases, the same definition of fast particles, the same incoming energy, etc. So, to obtain the η distributions corresponding to one collision in our experiment, an extrapolation has been done. For this purpose the measured η distributions were plotted in a different way, namely versus the number of collisions $\langle \nu \rangle$ (Fig. 10). Figure 10 contains the same data points as Fig. 9a. Points which are connected by a straight line in Fig. 10 belong to the same η bin but to different targets. A linear extrapolation to $\langle \nu \rangle = 1$ was done to obtain the wanted η distribution for one collision. Examples of extrapolated η distributions at $\langle \nu \rangle = 1$ are shown in Fig. 11a for incoming pions and antiprotons at 40 GeV. It seems at first sight surprising that the extrapolated distributions for π^- and $\bar{p}$ are identical within the statistical errors, as the differences become significant with increasing target mass. However, it is known that the total multiplicities of charged particles in π^-p and $\bar{p}p$ interactions are fortuitously equal at this energy. These distributions are then our substitute for a measurement with a nuclear target.

Leaving the line of our argument for a moment, a remark may be made concerning the distributions shown in Fig. 11b. These were obtained by a more daring extrapolation to $\langle v \rangle = 0$, corresponding to an infinitely thin target of nuclear matter. This way, one expects to completely subtract the contribution from the target or, in other words, to isolate the part which is due to the projectile alone. The procedure is "daring" because a linear extrapolation over such a distance from the last data point (at $\langle v \rangle = 1.4$) is presumably not justified. However, this could be improved with some theoretical aid and there can be no doubt that in principle an extrapolation to the infinitely thin target should be possible by varying the target thickness $\langle v \rangle$.

As we have now the distributions for $\langle v \rangle = 1$ and the slope $d^2\langle N_s \rangle / d\eta dv$, we can form, for any $\langle v \rangle$, the ratio

$$R(\eta)_v = \frac{\langle dN_s(\eta)/d\eta \rangle_{\langle v \rangle}}{\langle dN_s(\eta)/d\eta \rangle_{\langle v \rangle = 1}}, \quad (14b)$$

corresponding to Eq. (14a), independently of the measured targets. Thus we can compare different projectiles and incoming energies at a fixed value of $\langle v \rangle$. In Fig. 12 the ratio $R(\eta)$ is shown at $\langle v \rangle = 3$ for different energies and projectiles; this requires a short extrapolation for pions and an interpolation for (anti)protons.

The remarkable features of $R(\eta)$ at fixed $\langle v \rangle$ are the very weak energy and projectile dependence. There is an almost perfect "differential $\langle v \rangle$ scaling". These are novel results, whereas the corresponding property of $\langle v \rangle$ scaling and energy independence of the integrated ratio R [Eq. (9)] was already noticed earlier. Note that the simultaneous energy independence of the differential ratio $R(\eta)$ and the integrated ratio R is only compatible in a limited energy range (like the one where experimental studies have been done so far, up to FNAL or CERN SPS energies). Should the energy independence of $R(\eta)$ persist up to very high energies, then one would expect the integrated R to decrease and approach 1 since the part of phase space with increased particle density [$R(\eta) > 1$] would become less and less important.

4.3 Theoretical predictions

The normalized η distributions derived in the previous section from our measurements will be compared with some theoretical predictions. A selection is

done among numerous existing models; we shall focus on the predicted energy (E_{inc}) dependence of $R(\eta)$ or, equivalently, of $R(y)$ for reasons which will become clear. First the energy flux cascade model (EFCM), then three older quark-parton models and finally a newer, quantum-chromodynamics (QCD)-inspired approach are discussed. Only some basic ideas underlying the models are sketched; for more details the reader is referred to the original papers.

4.3.1 The energy flux cascade model

The EFCM of Gottfried [14] has had an important, stimulating impact on studies of hadron-nucleus interactions. It is, however, the typical example of a model which arrives at a parameter-free prediction of $R(y)$ without specifying any dynamical properties of the hadrons *in statu nascendi*. They are represented by an energy flux which propagates through the nucleus and collides with further nucleons. The space-time expansion of the energy flux, calculated in a classical geometrical way, serves as the only criterion to decide whether the energy flux behaves as one or more hadrons in the collisions with further nucleons. The prediction is shown in Fig. 13a. The ratio $R(y)$ is equal to $\langle v \rangle$ for rapidities below the critical rapidity y_c :

$$y_c = \frac{1}{3} y_{inc} + \frac{2}{3} \ln \frac{\lambda}{2\tau_0 c} \quad (15)$$

and $R(y) = 1$ above y_c . However, it can be shown that the assumptions of the model could easily be modified such that the term $y_{inc}/3$ on the right-hand side of Eq. (15) vanishes -- so y_c would be energy independent. Alternatively, a reasoning not worse than the one leading to $y_{inc}/3$ or 0 would lead to $y_{inc}/2$ for the term containing the energy dependence of y_c [1].

4.3.2 Common properties of three older quark-parton models

The idea common to the three parton models is that hadrons consist of point-like constituents, the partons [11]. In an interaction of a hadron, the coherent bound state of partons is disturbed and partons are emitted. They are considered to be bare partons first, but not for long. After a time of the order of the characteristic time of strong interactions they "dress" or "materialize" or "hadronize",

i.e. they become hadrons by surrounding themselves with a cloud of other partons. The time of hadronization is Lorentz-dilated, corresponding to the velocity or energy of the parton

$$\tau = \frac{E}{m_t} \tau_0 \quad [\text{cf. Eq. (4)}].$$

In this context τ could be called the lifetime of a bare parton (or bare quark) in the laboratory system. We can ask ourselves how high an energy a parton has to have in order to fly 1 cm as a bare parton. With a transverse mass of 0.3 GeV and $c\tau_0 = 1$ fm one obtains

$$E = \frac{1 \text{ [cm]} \times 0.3 \text{ [GeV]}}{1 \text{ [fm]}} = 3 \times 10^{12} \text{ [GeV]}. \quad (16)$$

This is at the upper end of cosmic-ray energies, so it does not occur very often in nature that a bare quark manages to fly a path of the order of 1 cm. However, partons above a critical rapidity y_c may easily traverse the nucleus before getting dressed. The critical energy E_c or critical rapidity y_c of partons which materialize just within the nucleus is calculated in the same way as the energy of partons which fly 1 cm. Now the path at disposition is equal to the nuclear radius

$$1.2 A^{1/3} \text{ [fm]} = c\tau_0 \frac{E_c}{m_t} \approx \frac{1}{2} e^{y_c}. \quad (17)$$

The critical rapidity

$$y_c = \ln (2.4 A^{1/3}) \quad (18)$$

therefore does not depend on the incoming energy and depends only weakly on the mass number A .

Other common features of the three models are: only partons which are neighbours in y ($\Delta y < 1$) interact directly with each other. These are Feynman's "wee partons". The assumption that the interaction is of short range in y is equivalent to assuming that the momentum transfers between partons [in their centre-of-mass system (c.m.s.)] are small. The average distance in y between partons is constant, so a hadron is represented by a parton "ladder" with, on the average, equal distance between the steps. The rapidity distribution of the final-state particles formed by emitted partons becomes therefore flat at high energies (c.f. Fig. 8).

This is how far the consensus of the models goes. The opinions diverge at the question as to how many and which partons emerging from the first interaction can interact again with the following nucleons in the same nucleus.

4.3.2 The multiperipheral parton model

According to the model of Kancheli [15] and Bertocchi [16], which is based on the multiperipheral parton model (MPM) [17], only those partons can reinteract which have rapidities smaller than y_c [Eq. (18)]. In other words, only when one of the partons out of the first interaction has become a hadron by emitting a parton ladder within the nucleus can it behave as a hadron and interact again. The prediction of this model is shown in Fig. 13b. At $y > y_c$ the ratio $R(y)$ is equal to one. Below y_c the particle density $R(y)$ increases and becomes equal to $\langle v \rangle$ at rapidities which correspond to hadronization times shorter than the mean free path [Eq. (3)].

4.3.3 The additive quark model

The model of Anisovich et al. [18], Biaľas et al. [19], and Nikolaev et al. [20] is based on the additive quark model (AQM) [21]. According to this model, in a hadron there are as many hadron-like objects as there are valence quarks. Thus each valence quark has its own preformed parton cloud and can behave as a proper hadron. The interaction is multiperipheral as in the previous model, but in an interaction with a single nucleon only one valence quark of the incoming hadron interacts with one valence quark of the target nucleon; the remaining quarks are spectators. This assumption leads to the rule of additivity for the total cross-sections of different hadrons, which gave the name to the model. In an interaction with a nucleus, as many high-energy quarks can interact independently of each other as there are valence quarks in the projectile ($N_V = 2$ for mesons, $N_V = 3$ for baryons). Moreover all partons can reinteract, like in the MPM, if their rapidity is smaller than y_c [Eq. (18)]. The prediction [20] is shown in Fig. 13d. Below y_c , $R(y)$ is mainly a function of $\langle v \rangle$. In the central region, which is dominated by the decay products of the interacting valence quarks, $R(y)$ depends on the number of valence quark interactions [$1 < R(y) < N_V$]. In the

projectile fragmentation region a depletion [$R(y) < 1$] is the natural consequence of the loss of spectator quarks, as more valence quarks interact. With increasing incoming energy the central region stretches and the spectator fragments move towards higher η .

4.3.4 The independent parton model

In the model of Brodsky et al. [22], which could be called the independent parton model (IPM), the interaction and the materialization times are not equivalent as in the previous models. Rather, all partons of the projectile can interact instantaneously(!) if they find a parton close in y in the target nucleus. The interactions are assumed to be randomly distributed over the central region in rapidity where the overlap of projectile and target partons is largest. The partons between the interacting partons and the fastest or slowest parton of projectile and target hadron, respectively, are emitted. They materialize into hadrons after a (Lorentz-dilated) characteristic time. In this model the critical rapidity in the sense of Eq. (18) does not play any role, but the target fragmentation region, where partons materialize for every interaction, has about the same extent as the range below y_c in the other models, i.e. 1 to 2 units in rapidity. The prediction of the model is shown in Fig. 13c. The differential ratio $R(y)$ is equal to $\langle v \rangle$ in the target fragmentation region (0 to y_1) and equal to one in the projectile fragmentation region (y_2 to y_{inc}). There is a wedge-shaped connection between the two regions.

In summarizing the essentials of the three quark-parton models, which start from a common basis, one can conclude that the point of their divergence is the assumption of how many partons of the projectile can interact independently of each other [1]. This question should be decided by an experimental study.

4.3.5 QCD inspired model

The colour separation model (CSM) of Capella et al. [23] assumes that in an interaction each hadron splits into two coloured quark systems (quark-diquark in the case of baryons, quark-antiquark in the case of mesons) which seek to be colour-neutralized with the system of complementary colour charge of the other

hadron. The coloured quarks or diquarks fragment into hadrons in a manner described by standard fragmentation functions. Thereby two strings or chains of particles are formed; in its c.m.s. each chain corresponds to a back-to-back jet. The inclusive spectrum of particles produced is thus obtained by a convolution of quark or diquark fragmentation functions and momentum distribution functions. In hadron-nucleus collisions for each rescattering of the incoming hadron two additional chains are formed between valence quarks of the target nucleon and sea quarks of the projectile; the valence quarks can only contribute once.

The authors compare their numerical results with the data of Busza et al. [10] and do not give an explicit expression for $R(y)$. Presumably their prediction for the target fragmentation region is $R(y) = \langle v \rangle$. A weak dependence on the nucleus is caused at high rapidity, in the projectile fragmentation region, owing to energy conservation, but apart from this $R(y) \approx 1$ above the rapidity y_2 where the contributions from the chains formed by target valence quarks or diquarks and projectile sea quarks are negligible. This occurs at fixed Feynman x (independent of the energy), hence y_2 increases with the incoming energy

$$y_2 = y_{inc} - \text{const} . \quad (19)$$

Thus the resulting $R(y)$ should be very similar to that of the IPM (see Fig. 13c).

4.4 Comparison of data with predictions

4.4.1 Difficulties of the comparison

The comparison between our experimental results and the mentioned (and other) theoretical models is not straightforward. Firstly, the model predictions have to be understood as rather qualitative. Most of them neglect the possibility of cascading of produced particles, which have low energy and are emitted at large angles. This would cause $R(\eta)$ below η_c to increase beyond $\langle v \rangle$, whereas, except for Nikolaev's prediction, all models imply $R(\eta)$ to flatten out at a value $\langle v \rangle$. Energy conservation, which implies a depletion at high η , has not been taken into account except for the AQM and the CSM.

Secondly, we want to compare the expression (14b) with (14a), i.e. we use the pseudorapidity η instead of the rapidity y and an extrapolation to $\langle v \rangle = 1$ instead

of a measurement on a free nucleon target. Furthermore, we measured fast particles instead of all hadrons or instead of produced particles; this latter point will be discussed in more detail at the end of the section. Under these conditions a rather tolerant method of comparison is advised. So we focus on two properties of the data and predictions which should not be affected by these circumstances: the $\langle v \rangle$ dependence and the dependence on the incoming energy.

4.4.2 Comparison

Except for one model, the MPM of Kancheli and Bertocchi, none of the proposed models is consistent with both the differential $\langle v \rangle$ scaling and the weak-energy dependence of $R(\eta)$. Let us define for the moment as critical rapidity η_c the value of η , where $R(\eta) = 2$ in Figs. 12 and 13. Note that the definition of η_c is slightly different from that of y_c used above. The EFCM, the IPM, and the CSM, all have too strong an energy dependence of the critical rapidity. In these models η_c should move by 1/3, 1/2, 1/2, respectively, of the change Δy of the incoming rapidity [$\Delta y = y_{inc}(150 \text{ GeV}) - y_{inc}(50 \text{ GeV}) = 1.1$]. The measured changes of η_c are less than 0.2! The AQM should have both an energy and a weak projectile dependence (i.e. should violate the $\langle v \rangle$ scaling) as the central region gets longer with increasing energy and the number of interacting quarks is supposed to be higher for protons than for pions at fixed $\langle v \rangle$. Both predictions seem to be inconsistent with our data, which show a small projectile dependence, but only at small η ; $R(\eta)$ is somewhat lower for protons and antiprotons than for pions at $\eta < 2$.

4.4.3 Conclusions

One has to conclude that the simple MPM is in best agreement with the data and the other models are not. The question is then what we can learn from this observation.

It has been pointed out already that the EFCM could be modified to predict an energy-independent critical rapidity y_c . It would then be compatible with the data, as the model implies $\langle v \rangle$ scaling. The modification leading to energy independence of y_c results from a different slicing procedure. In the original model [14] the energy flux is divided into slices in rapidity space. Each slice expands

in coordinate space with time according to the different velocities of the slice components, and a slice can interact as an independent hadron when its size (in coordinate space) corresponds to the size of a real Lorentz-contracted hadron. The size of a slice was determined to be equal to the size of a Lorentz-contracted hadron moving with the average rapidity of the slice. This leads to $y_c = y_{inc}/3 + \text{const.}$ If the size of the slice is assumed to be determined by the slowest component of the slice, one obtains $y_c = \text{const.}$ [1]. From a geometrical point of view the latter choice appears to be more plausible; however it is not obvious how to infer the underlying physics from the correct slicing procedure.

To examine why some of the quark models fail is more interesting because we may learn something about the way quarks behave in soft strong interactions. The following is a suggestion to explain the failures of the AQM, the IPM, and the CSM.

The principal difference from the MPM seems to be that an increasing number of quarks or partons may interact independently of each other in the other models. So one should obviously question this independence first. In particular one may ask why in the AQM and CSM the valence quarks or diquarks of one hadron prefer to interact with the valence quarks of the other hadron; while at the same time the interactions between valence quarks belonging originally to the same hadron are neglected.

To save the basic ideas of the AQM, the possibility should be considered that a "primary" interaction indeed takes place between a pair of valence quarks belonging to different hadrons, but owing to a final-state interaction the other valence quarks get involved, too. Thus the concept of spectator quarks may need a more careful examination. If there are no spectator quarks after a single collision, multiple interactions in nuclei would lead to less drastic changes at high rapidities than predicted by present AQMs, and $\langle v \rangle$ scaling would hold.

An analogous criticism applies to the CSM. It is not clear why the colour neutralization prefers the long way in rapidity from one hadron to the other and does not, at the same time, involve the valence quarks belonging to the same hadron, or to the same nucleus in case of passage through a nucleus. Instead of

using up sea quarks of the projectile hadron the unbalanced colour of a target nucleon could interact with other target nucleons. Thus the net result after multiple interactions would be essentially two long chains as in a single collision plus some short chains.

As to the IPM and the CSM the question arises whether the partons are not taken as too real constituents. In the MPM partons are more virtual and they need a certain time τ_F to be emitted or formed, which is equivalent to their interaction time. Consequently, multiple interactions of partons are suppressed if the time τ_I between two successive interactions is smaller than τ_F .

At the end of the conclusions we are left with the question whether the agreement of the MPM with the data can give any "constructive" information about the behaviour of partons in normal (soft) strong interactions. The answer to this should be negative, if any other model not specifying the mechanism of parton interactions would lead to the same prediction as the MPM. There is indeed a candidate for such a model: replacing the "interaction time of partons" in the MPM by a purely quantum mechanical "formation time of hadrons" [1,20,24,25] should lead to predictions, which are largely equivalent to the prediction of the MPM.

4.4.4 The problem of fast recoil protons

In concluding this section, one point should be discussed which has so far been omitted. Our fast particles, like the shower tracks of the emulsion, contain an unknown amount of fast recoil nucleons ($p > 1 \text{ GeV/c}$) from the nucleus in addition to the produced pions. In the following a crude estimate of this amount is made. The number N_{recoil} of fast recoil protons will not be simply $\langle \nu \rangle$ times 0.5 (0.5 being the number in the case of a hp interaction) but rather

$$\langle N_{\text{recoil}} \rangle = 0.5 \langle \nu \rangle \frac{Z}{A} f(A) , \quad (20)$$

where Z/A is the proton to nucleon ratio and $f(A)$ is a factor which allows for multiplication of fast nucleons by an intranuclear cascade similar to the kind described for the slow recoil nucleons. However, as fast recoil particles get multiplied by the cascade, their momentum spectrum is shifted to lower momenta; hence less protons will be above 1 GeV/c . Not having done a Monte Carlo calculation for

this cascade, the best possible estimate is $f \lesssim 1$. Thus, for example, for πPb interactions one expects, on the average, less than 1 fast recoil proton among the fast particles.

Like all target fragments, the fast protons are supposedly independent of the incoming energy. So their presence tends to weaken the energy dependence of $R(\eta)$. But as long as they do not represent the dominant part of fast particles at low η the conclusions drawn from the energy independence of $R(\eta)$ should not be affected. Yet the fast protons should be kept in mind with respect to the projectile dependence at fixed $\langle v \rangle$. There may be not only less slow but also less fast recoil protons for incoming (anti)protons than for pions at fixed $\langle v \rangle$ (see Fig. 6). Therefore the weak projectile dependence predicted by the AQM for the produced particles (pions) may be partly compensated in $R(\eta)$ by the presence of the fast recoil protons.

4.5 Multiplicity distributions of fast particles versus N_g

4.5.1 KNO scaling

Owing to a scaling law it is sufficient in the hp case to know one single (universal) multiplicity distribution, which is shown in Fig. 14 [26]. The ratio of the topological cross-section σ_N to σ_{inel} (N is the multiplicity of charged particles in an event) is equal to the probability of observing a final state with N charged particles in an inelastic interaction. This ratio is multiplied by $\langle N \rangle$ and plotted versus $N/\langle N \rangle$. Thus all points fall on a universal curve, independent of the incoming energy, if the latter is above about 50 GeV. The factor $\langle N \rangle$ for the vertical axis serves to normalize the surface integral under the curve to unity. This empirical scaling rule for the multiplicity distributions has been theoretically deduced from Feynman scaling by Koba, Nielsen and Olesen [27]; hence the name KNO scaling.

4.5.2 Dispersion versus mean value $\langle N_g \rangle$

An apparent consequence of KNO scaling is that the width or the dispersion D of all multiplicity distributions in units of the mean value $\langle N \rangle$ is a constant. The linear relation between D and $\langle N_g \rangle$ was observed already a long time ago by Malhotra [28]. In the following we will be mainly concerned with the ratio

$Z = D/\langle N_s \rangle$. We will consider this ratio first for different nuclei and different energies without making use of the number of slow particles, and then for a fixed nucleus as a function of the number of observed slow particles.

In Fig. 15a the ratio is plotted versus $\langle N_s \rangle$ for incoming pions of various energies and for various targets including a H_2 target. The data points of different experiments with nuclear targets show some systematic differences. This may partly be due to different trigger biases. In addition, it has to be noted that in our case the ratio Z was calculated from the uncorrected, observed(!) multiplicity distribution. However, the value $\langle N_s \rangle$ used for the horizontal scale was corrected for solid angle and background. It is relatively easy to correct the mean values (see Section 3.2), but to obtain the true multiplicity distributions and the true dispersions D from the observed ones is not straightforward and would require a Monte Carlo simulation. The effects of the missing correction should partly cancel out in the ratio Z , but it should be kept in mind that this correction was not done and might influence our results to some extent. However, the qualitative conclusions drawn from our results will presumably not change. Similar precautions should by the way be observed for some of the other experiments, too. At any rate it can be seen that the ratio Z for nuclear targets is equal to or bigger than that for the p target. This is not surprising since there is a larger variety of reactions and final states in the case of nuclei.

4.5.3 Dispersion over $\langle N_s \rangle$ versus N_g

Figure 16 shows the frequency of events $f(N_s, N_g)$ with a given pair of observed fast and slow tracks N_s and N_g in π^-Pb interactions at 40 GeV plotted versus the number of fast tracks. The vertical scale is equal to the normalized twofold topological cross-section $\sigma(N_s N_g)/\sigma_{inel}$ (i.e. the probability to have N_s and N_g tracks in an event) times the total number of events contained in the plot. Points with an equal number of slow particles are connected by lines. Apart from their relative normalization, these curves can be considered as multiplicity distributions of fast particles at fixed numbers of observed slow tracks. The relative normalization factors which can be obtained by integrating the curves over N_s

would yield the multiplicity distribution of slow particles. It is from these curves that the ratio $Z = D/\langle N_s \rangle$ as a function of N_g is obtained.

In Fig. 15b the ratio Z is plotted versus $\langle N_s \rangle$ for the Pb target at two energies. While in Fig. 15a $\langle N_s \rangle$ was a function of energy and target mass, here $\langle N_s \rangle$ is a function of energy and N_g . [The function $\langle N_s \rangle$ versus N_g will be shown (Fig. 17) and commented in Section 4.6.] There is a significant decrease of Z with increasing N_g . This decrease is only determined by the number N_g , as can be seen in Fig. 15c where Z is plotted versus N_g and the data points for the two different energies fall approximately on the same curve. The explanation for this behaviour is possibly simple but not trivial. This decrease can be seen as an indication that the produced particles in hadron-nucleus collisions result from partly independent multiple interactions. Suppose ν collisions take place and in the nucleus every collision contributes on the average the same amount to the total multiplicity [see Eq. (9a)],

$$\langle N_s(\nu) \rangle = \text{const}_1 + \nu \langle N_s(1) \rangle . \quad (21)$$

If the collisions are statistically independent, the squared dispersion of the sum of these contributions will be the sum of the squared dispersions for the individual collisions,

$$D^2(\nu) = \text{const}_2 + \nu D^2(1) . \quad (22)$$

Therefore Z will be

$$Z \equiv \frac{D}{\langle N_s \rangle} = \frac{\sqrt{\text{const}_2 + \nu D^2(1)}}{\text{const}_1 + \nu \langle N_s(1) \rangle} \quad (23a)$$

and if the constant terms could be neglected, then

$$Z \propto \frac{1}{\sqrt{\nu}} . \quad (23b)$$

Now taking N_g as a measure for the number of collisions ν in the nucleus, the decrease of Z with N_g supports models which assume partly independent collisions to occur in the nucleus. All the models discussed in the previous section are of this kind. There is, however, at least one model, the coherent tube model (CTM) [30], which is different.

4.5.4 The coherent tube model

The CTM derives a large number of predictions for inelastic hadron-nucleus interactions from a few very simple assumptions and claims that many results of an inelastic hadron-nucleus or nucleus-nucleus interaction can be easily predicted from hadron-proton interactions. If the model would turn out to be applicable and correct in many cases, one would have to conclude that interactions with nuclei cannot teach us anything more than hadron-proton interactions and the only advantage of nuclei would then be one of economy as they provide higher c.m. energies at fixed incoming hadron energy. The basic assumptions of the model can be split into three parts. One is that the incoming hadron collides with a row or tube of nucleons having a cross-section σ_{tu} , which is in principle a free parameter but is usually taken to be equal to the cross-section of a nucleon. The effective c.m. energy squared of the particle-tube collision is

$$S_{\nu} = 2\nu m_N E_{inc} , \quad (24)$$

where ν is the number of nucleons in the tube and m_N the nucleon mass. The second assumption is that the tube recoils collectively, i.e. it acts like a single body in the interaction. The third assumption concerns the applicability. The model can only be applied to particular results which may depend on parameters like the c.m. energy but must not depend on the quantum numbers of the target. The assumptions and various predictions of the model have been discussed recently [31,32]. Our result concerns mainly the second and third assumptions. It has been predicted [30] that KNO scaling holds for a particle-tube collision. This implies a ratio Z which is independent of the number of nucleons in the tube, in clear contradiction with our result if (only if) one accepts a relation between ν and the number N_g of slow particles. Denying any relation between ν and N_g is a possibility to avoid the contradiction [32], but another way is opened up by taking the third assumption of the model at face value. The model is, strictly taken, not applicable to the target fragmentation which depends on the quantum numbers; a target with baryon number A will certainly fragment differently from a single nucleon. Indeed, one can say that a large fraction of the total fast multiplicity in collisions with

nuclear targets stems from the target fragmentation, in particular, if the number of slow particles is large (see also the next section). Discarding the target fragmentation region as a whole from the applicability of the model, the contradiction with our results (and other contradictions) can be avoided but at the cost of most of the predictive power of the model.

4.6 Pseudorapidity distributions of fast particles versus N_g

To conclude the discussion of results, an example is given for the third level of differentiation. Figure 18 shows pseudorapidity distributions of fast particles as a function of N_g . The fast particles were subject to all corrections discussed in Section 3.2; the number of slow particles N_g is the actually observed, uncorrected number in an event. Figure 18 is for one target (Pb), one sort of projectile (π^-), and two energies (20 and 37.5 GeV). This figure corresponds to Fig. 10, but now we have a fixed target and the collision parameter is N_g instead of $\langle \nu \rangle$. Points which belong to the same rapidity bin are connected by a line.

If one integrates the pseudorapidity distributions, one obtains the total multiplicity $\langle N_s \rangle$ as a function of N_g (see Fig. 17; this figure corresponds to Fig. 6 -- $\langle N_s \rangle$ versus $\langle \nu \rangle$ -- in the same way as Fig. 18 does to Fig. 10). Before discussing the differential distributions, two remarks concerning the dependence of the integrated values $\langle N_s \rangle$ on N_g should be made. Firstly, it is seen (Figs. 17a,b) how the physical range of over-all particle multiplicities is extended and events with higher number of collisions are selected if one uses N_g as collision parameter instead of $\langle \nu \rangle$. The values of $\langle N_s \rangle$ where saturation occurs is about two times higher than the average value of $\langle N_s \rangle$ for a lead target, corresponding to presumably about two times higher ν than the average $\langle \nu \rangle_{\pi\text{Pb}}$. Secondly, we find that dividing $\langle N_s(N_g) \rangle$ by the value of $\langle N_s \rangle$ at $\langle \nu \rangle = 1$ leads to a ratio

$$R(N_g) = \frac{\langle N_s(N_g) \rangle}{\langle N_s(\nu = 1) \rangle} \quad (25)$$

which is very weakly energy dependent (Fig. 17c) [33]. This may not be too surprising, because the slow tracks are energy independent and the average R [Eq. (9)] is also energy independent, but it may nevertheless be worth noticing.

Now, the pseudorapidity distributions as a function of N_g give a very nice demonstration of correlations and anticorrelations. There is a strong positive correlation (linear at small values of N_g , but saturating at high values) between fast particles at low η and the slow particles. And at high η there is an anticorrelation; fast particles decrease with increasing N_g . At intermediate η the dependence changes from a correlation to anticorrelation. Remember now the relationship between slow particles and fast particles at low η , which was discussed earlier in Section 4.2. Both sorts of particles are energy independent. There is another common property which was not mentioned so far. Slow particles and fast particles at low η have very similar dependences on A or $\langle v \rangle$: the ratio $R(\eta)$ [cf. Eq. (14b)] for fast particles at low η and the corresponding ratio for slow particles are approximately equal for the same $\langle v \rangle$. The natural explanation for all the similarities has been mentioned already. Both, the grey tracks and the pions at low η are fragments of the nucleus. Thus if we use N_g as a measure for the number of interactions in the nucleus we could as well generalize our method and add the number of fast particles at low η to N_g . In other words: our study of correlations between fast and slow particles is nothing other than a study of long- and short-range correlations in rapidity. (This subject is more familiar to high-energy physicists.) We have found strong short-range correlations.

We also see anticorrelations for larger distances in rapidity, but for the latter one cannot easily separate dynamical effects from effects of kinematical constraints like energy conservation. Missing for a study of long-range correlations in rapidity, at our energies, are long ranges in rapidity, i.e. higher energies are needed, where the central region is well developed and the distance between the fragmentation regions becomes larger.

One concluding remark: the reader has certainly noted that the subject of a quantitative relation between the two hypothetical collision parameters N_g and $\langle v \rangle$ has been avoided. [A qualitative relation can be obtained immediately from the $\langle N_g \rangle$ versus $\langle v \rangle$ plot or by a comparison between $\langle N_s \rangle$ versus $\langle v \rangle$ and $\langle N_s \rangle$ versus N_g .] Quite some work has been done on this relation in emulsion experiments [4]. We have obtained additional information by measuring the A and projectile

dependences of the grey tracks and have also worked on this subject [7]. However, there is one reserve for N_g as a collision parameter: the grey tracks are certainly correlated with the number of interactions in the nucleus, but the question is of which interactions? As a measure of the number of primary collisions in the nucleus, N_g has at least one bias, which has already been indicated in Section 4.2. The recoil protons with a momentum higher than 1 GeV/c (50% in the case of a pp interaction, probably less in the case of a hA interaction) have a good chance to be detected as fast particles if they do not lose their energy in secondary collisions. So by taking the slow recoil protons only, the softer collisions are favoured. This is the reason why the softer statement has been favoured that we have in N_g a measure for the target fragmentation here and that we study long range in y correlations.

Correlations of particle densities in phase space can give more crucial information on the mechanism of interaction than do the inclusive distributions -- the classic examples today are the studies on hard scattering events in pp interactions. However, necessary conditions for the learning process are, in addition to the experimental studies, theoretical predictions which are still scarce in the field of soft (normal) inelastic hA interactions.

5. FUTURE PLANS

The need for higher energies has been emphasized on several occasions in the previous sections. Among presently operating accelerators or storage rings, the CERN Intersecting Storage Rings (ISR) can reach the highest energy in the nucleon-nucleon c.m.s. The possibility of accelerating light ions in the CERN Proton Synchrotron (PS) and storing them in the ISR has been discussed several years ago together with the $p\bar{p}$ option. In 1976 deuterons were successfully stored for a few short test runs and led to numerous interesting publications of the experiments installed at the ISR at the time. The potential storage of α particles in the ISR was discussed again in 1979 [34] and this discussion led in 1980 to the approval of the experiment (R418) proposed for the Split Field Magnet Detector facility (SFMD). The SFMD offered the possibility to continue the studies described in this

review, by detecting and analysing the momentum of charged particles over a solid angle of almost 4π for αp and $\alpha\alpha$ interactions. Moreover the possibilities of the detector and the experiences gathered so far with it allowed the study of more special events like elastic scattering or hard (large- p_T) inelastic interactions.

With α particles in the ISR one reaches a new energy régime for collisions involving nuclei. The highest c.m. energy ($\sqrt{s}$) is 125 GeV for $\alpha\alpha$ collisions and 88 GeV for $p\alpha$ collisions. To obtain equal c.m. energies at a fixed target accelerator, one would have to accelerate α particles to 2000 GeV and protons to 1000 GeV. The "old records" were 18.5 GeV/c for α particles at the Synchrophasotron at Dubna, and 500 GeV protons at the super proton synchrotrons at FNAL and at CERN. The step in energy is therefore so large, in particular for $\alpha\alpha$ collisions, that one may even hope to discover some new phenomena, like a phase transition from hadron to quark matter. Such, and similar, ideas are at present being widely discussed by heavy-ion physicists in Europe and the United States, who want to build an accelerator reaching energies comparable to ISR energies, for heavy ions.

Heavy-ion physicists consider α particles as too light. On the other side, however, particle physicists consider α particles as too heavy and too complicated. One may therefore conclude that they are just perfect tools for improving our understanding of old phenomena, on the one hand -- old phenomena being those which are known from pp interactions and which may get somewhat amplified or distorted if one takes instead of a small piece of nuclear matter (as protons are) bigger pieces of nuclear matter (four times bigger as α particles are). On the other hand, collisions with α particles may give hints of what one should expect from collisions with heavier ions at comparable energies.

An improvement of our understanding of the old phenomena is a necessary step before one goes on to a search for new phenomena, since at present we are not even able to distinguish old from truly new phenomena if they were to occur. This was the point of view taken by the proposal for α particles in the ISR. It has been shown in this paper that even the normal (soft) inelastic interactions of hadrons with nuclei are not well understood. As to hard inelastic interactions, an "anomalous" target mass (A) dependence of the inclusive cross-section for production of

particles with transverse momenta bigger than 2 GeV/c was found some years ago at FNAL [35]; the cross-sections increase faster than linear with A. Since the SFMD and the ISR offer an almost unique chance to study the complete topology of final states (i.e. charged particle distributions and correlations over nearly 100% of the phase space) in hadronic interactions, it was hoped that a study of large- p_T events in the case of αp and $\alpha\alpha$ interactions can give a clue to the mechanism responsible for the "anomalous" enhancement. As to elastic $\alpha\alpha$ or $p\alpha$ interactions it seemed interesting to continue the study of the effect of intermediate inelastic states which was discussed for elastic $p\alpha$ and $\alpha\alpha$ collisions at the ISR [36] and for $p\alpha$ interactions at FNAL [37].

After very successful acceleration and storage of α particles, a week of data taking by R418 and other experiments installed at the time at the ISR took place in August 1980. The analysis of these data is in progress.

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Table I

The first 3 μ s after a hadron-hadron interaction

t (sec)	$z = (\tau_0 \cdot c) \gamma$	
10^{-6}	<div> <div>1000 m</div> <div>780 m</div> </div>	DETECTOR #1 (μ, ν, γ, p, n) $\pi^\pm$ decay ($\tau_0 = 2.6 \cdot 10^{-8}$ sec)
10^{-8}	<div>1 m</div>	DETECTOR #2 ($\pi^\pm, \gamma, p, n$)
10^{-10}		
10^{-12}		
10^{-14}	<div>2.5 μm</div>	π^0 decay ($\tau_0 = 8.3 \cdot 10^{-17}$ sec)
10^{-16}		$(\pi^\pm, \pi^0, p, n)$
10^{-18}	<div>1 $\text{\AA}$</div>	atomic radius
10^{-20}		
10^{-22}	<div>200 fm</div>	decay of unstable hadrons $(\hbar / \tau_0 = \Gamma \approx 100 \text{ MeV})$
10^{-24}	<div> <div>$1.3 A^{1/3} \text{ fm}$</div> <div>1 fm</div> </div>	DETECTOR #3 ($\rho, \Delta, \dots, \text{quarks}, \dots$) hadron radius

Table II

Classification of tracks in nuclear emulsion

<p><u>SHOWER PARTICLES</u></p> <p>N_s</p> <p>grain density $k < 1.4$ $\alpha)$</p> <p>$\beta = v/c < 0.7$</p> <p>pions, fast recoil protons</p> <p>$p_\pi > 140 \text{ MeV}/c$</p>	<p>"fast cascade"</p>
<p><u>GREY TRACKS</u></p> <p>N_g</p> <p>$1.4 < k < 10$ $\alpha)$</p> <p>$0.25 < \beta < 0.7$</p> <p>80% protons</p> <p>$30 < E_{\text{kin}} < 400 \text{ MeV}$</p>	<p>"slow cascade"</p>
<p><u>BLACK TRACKS</u></p> <p>N_b</p> <p>$k > 10$ $\alpha)$</p> <p>$\beta < 0.25$</p> <p>evaporation fragments $p, d, \alpha, \dots$</p> <p>$E_{\text{kin}} < 30 \text{ MeV}$</p>	<p>thermalization of absorbed energy</p>

$\alpha)$ k in units of the grain density of a minimum ionizing track.

Figure captions:

- Fig. 1 : One of the 73 combined counters.
- Fig. 2 : a) Anode signal of phototube attached to a combined counter. Horizontal scale from 0 to 1 μ s.
b) Same as a) with horizontal scale 0 to 40 ns.
- Fig. 3 : a) The detector (second version).
b) The layout of the beam counters.
- Fig. 4 : Scattergram ADC (= energy loss in CsI crystal) versus TDC (= trigger time of track with respect to the reference time of the event provided by counter S) for a combined counter.
- Fig. 5 : Charged multiplicity for pp interactions versus momentum or c.m. energy. Data are from Ref. [9].
- Fig. 6 : Total multiplicities of fast ($\langle N_s \rangle$) and slow ($\langle N_g \rangle$) tracks versus $\langle v \rangle$ for different energies and projectiles. Lines are drawn to guide the eye. The differences of slow multiplicities for different energies are smaller than the point size.
- Fig. 7 : Pseudorapidity distributions of charged particles from inelastic pp interactions at different incoming (laboratory) momenta.
- Fig. 8 : The rapidity distribution of outgoing particles at very high energy (the theorist's energy domain).
- Fig. 9 : Pseudorapidity distributions of fast particles for
a) different target nuclei, π^- at 40 GeV/c,
b) different energies, π^- Cu,
c) different projectiles (100 GeV/c) on Cu.
Lines are drawn to guide the eye.
- Fig. 10 : Pseudorapidity distributions of Fig. 9a plotted versus $\langle v \rangle$. Points which belong to the same η bin are connected by lines. These lines are extrapolated to $\langle v \rangle = 1$ and $\langle v \rangle = 3$ to get the ratio $R(\eta)$ [Eq. (14b)].

Fig. 11 : a) Extrapolated η distribution at $\langle \nu \rangle = 1$ for incoming pions and antiprotons at 37.5 GeV.

b) Extrapolation to $\langle \nu \rangle = 0$, the infinitely thin target.

Fig. 12 : Normalized η distributions [the ratio $R(\eta, \langle \nu \rangle = 3)$] for

a) incoming pions,

b) protons,

c) antiprotons.

Fig. 13 : Energy dependence of $R(\eta)$ as predicted by different models:

a) EFCM,

b) MPM,

c) IPM,

d) AQM.

The shaded areas indicate where the particle densities increase with increasing incoming energy.

Fig. 14 : KNO scaling of the multiplicity distributions of charged particles for π^-p interactions [26].

Fig. 15 : a) The ratio $Z = D/\langle N_s \rangle$ versus $\langle N_s \rangle$ for pions of different energies interacting with nuclei and protons [$\langle N_s \rangle = \langle N_s(E_{inc}, A) \rangle$].

α : Ref. [6], β : Ref. [29], γ : Ref. [10], δ : Ref. [26].

b) Z versus $\langle N_s(N_g) \rangle$ for π^- (20 and 40 GeV) on Pb and Ag.

c) Z versus N_g for π^- (20 and 40 GeV) on different nuclei.

Fig. 16 : Frequency of events $f(N_s, N_g)$ versus observed multiplicity N_s for inelastic π^-Pb interactions at 37.5 GeV. Points which belong to the same number N_g of slow particles are connected by lines.

Fig. 17 : Average $\langle N_s \rangle$ versus N_g for incoming π^- at fixed energy for different targets for

a) 37 GeV/c,

b) 20 GeV/c incoming momenta,

c) $R = \langle N_s(N_g) \rangle / \langle N_s(\nu = 1) \rangle$ versus N_g for π^-Pb at different energies.

Fig. 18 : Pseudorapidity distributions of fast particles versus N_g . Incoming π^- on Pb target.

a) 20 GeV/c,

b) 37.5 GeV/c.

Points belonging to the same η bin are connected by lines.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

Fig. 14

Fig. 15

Fig. 16

Fig. 17

Fig. 18