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Proton-Nucleus Interactions at High Energies

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Proton-nucleus interactions in nuclear emulsion at 205 GeV/c are studied. Multiplicity and pseudo-rapidity distributions are reported. In the laboratory backward hemisphere relativistic particles are emitted more abundantly than expected. Such backward particles are also studied in p-Ta interactions at 28.5 GeV/c. Energy, longitudinal momentum and angular distributions are considered to give possible explanations. It seems difficult to give satisfactory explanation by usual processes in our present knowledge.

1. Introduction. In nuclear emulsion stack (thirty-six Ilford K-5 pellicles, 150 x 75 x 0.6 mm^3 in size) exposed to 205 GeV/c proton beams at the Fermi National Accerelator Laboratory, inelastic interactions have been studied. To obtain unbiased samples of inelastic events, along-the-track scanning has been employed. Events are classified into three groups by the number of heavily ionizing tracks (N_h); namely, Nh=0 (quasi-proton-nucleon collisions), $1 \leq N_h \leq 8$ (collisions with C, N, O, and also Ag and Br), and $N_h \leq 9$ (collisions with Ag and Br). In this study, the heavily ionizing particle is the one with ionization larger than 1.4 times of the plateau ionization of extremely relativistic particles and the gray particle is the one with ionization between 1.4 and 3.0 times of the plateau value.

In Table I the number of events so far analyzed are given with other quantities. Distribution of thin particles for three groups are shown in Fig.1. For N_h=0, there are peaks at n_s=3, 5, and 7 corresponding to coherent interactions with nuclei. These coherent interactions will be discussed elsewhere(1), and

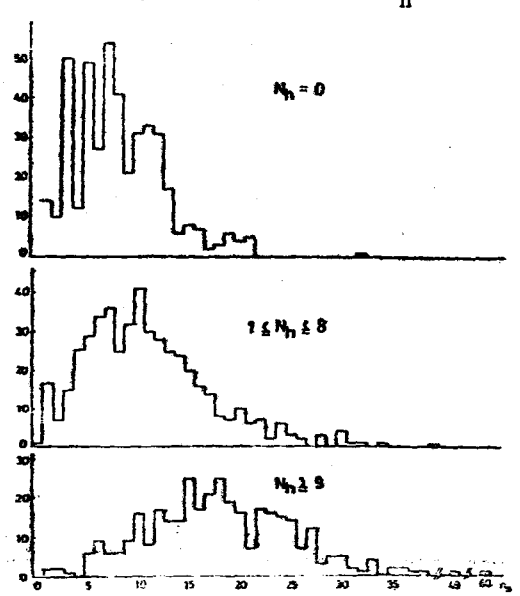

Fig.1. Multiplicity distribution in nuclear emulsion at 205 GeV/c.

N_h	0	1 8	9
No of events	436	483	348
n_s	8.1 (8.1)	10.7 (10.7)	18.0 (18.0)
No. of B-events	17(3.9%)	59(12.3%)	114(32.2%)
No. of MB-events	0	8(1.4%)	32(9.6%)
$\frac{\text{No. of B-tracks}}{\text{Total of } n_s}$	0.5%	1.2%	2.5%

Table I

possible coherent interactions are excluded in the following considerations.

Angular distributions of thin particles for three groups are shown in Fig. 2 in integral form against pseudo-rapidity η ($\eta = -\ln(\tan\frac{\theta}{2})$) on the normal probability paper, for the convenience of the following discussions.

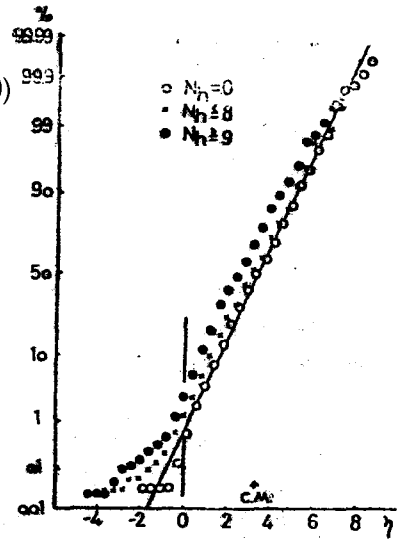

Fig. 2. Pseudo-rapidity distributions for three groups of N_h.

Detailed discussions on these general features will be given elsewhere with the consideration on models of intra-nuclear cascade, but only one point is worth to mention. The angular distribution for proton-nucleus interactions is difficult to be explained by the energy flux cascade model[2].

2. Relativistic particles emitted backward in the laboratory system.

Figure 2 shows that the η -distribution for N_h=0 is very close to Gaussian distribution. (on the normal probability paper, the straight line corresponds to the Ganssian distribution.) For p-nucleus collisions there are some discrepancies from Gaussian distribution, and tails at $\eta \leq 0$ are significant. This shows that thin particles emitted in the backward hemisphere in the laboratory system are remarkably abundant. Some features of this phenomenon has alredy been reported elsewhere[3]. The number of backward thin tracks (B-tracks), that of events with B-tracks (B-events), and of events with more than one B-tracks (MB-events) are listed in Table I. From Table I it is clear that the frquency of appearance of B-tracks and of B-events increases with N_h, and this increase is stronger than that of average multiplicity of thin particles with N_h, as seen in the last line of the Table.

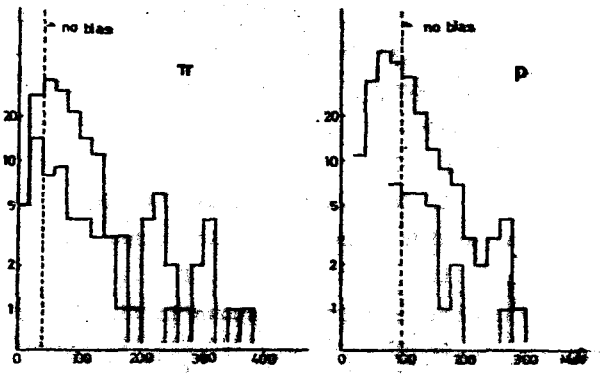

Fig. 3. The distrybution of kinetic energy of backward pions and protons.

Particle identification has been carried out for backward thin and gray tracks with projected length longer than 1 mm in the plate with multiple production events. Distributions of kinetic energy of thus identified pions and protons are shown in Fig. 3 by dotted lines. Solid lines in Fig. 3 are those of proton-tantalum interactions at 28.5 GeV/c.

Proton-Ta collisions are observed in pictures of 80 inch hydrogen bubble chamber of the Brookhaven National Laboratory. This chamber was installed one Ta plate near the downstream edge in order to raise the detection efficiency of γ-rays, and this plate has been used as the target in this experiment. In the case of p-Ta collisions, zenith angles of observed tracks are limited in the region larger than 120 degrees owing to the arrangement of Ta-plate. Also forward tracks are not measured because short available lengths do not allow the discrimination between pions and electrons. Particles are identified by the usual bubble counting method. Ionization losses in the Ta-plate are corrected for each tracks. Protons under 100 MeV and pions under 40 MeV may stop in the plate according to the depth of interaction and to the emission angle. Therfore, energies over these values are bias-free regions. The contribution to various distributions from secondary interactions in Ta-plate is estimated to be less than 10 %. Number of measured events and backward events is shown in Table II. These values should not be readily compared with those of Table I, because of the difference of measured regions of angle and energy. But the frequency of backward emission of relativistic particles is not significantly different with incident energies.

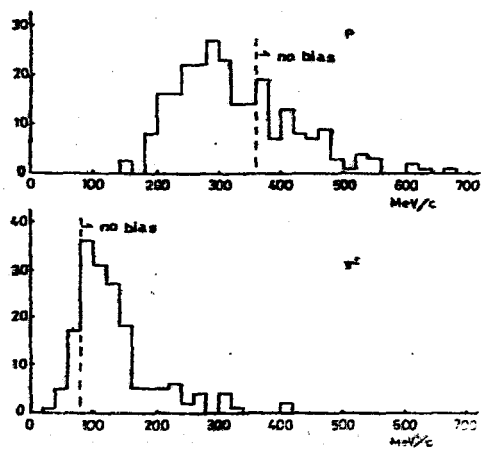

Fig. 4. ($-p_n$) spectra of pions and protons in p- Ta collisions at 28.5 GeV/c

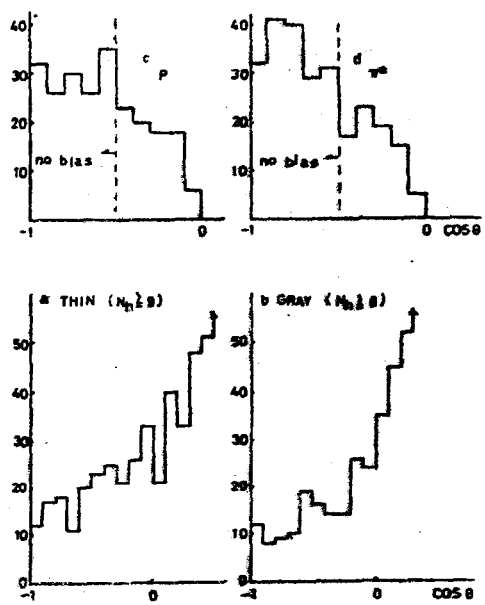

Fig. 5. Angular distributions
a, b; 205GeV/c p-(Ag,Br)
c, d; 28.5 GeV/c p-Ta.

Events with backward proton($\geq$ 100 MeV) / Observed events	$\frac{102}{894}$ = 11.4%
Events with backward pion($\geq$ 40 MeV) / Observed events	$\frac{139}{894}$ = 15.6%

Table II

Longitudinal momentum distributions of laboratory backward protons and pions in p-Ta collisions are shown in Fig. 4. Momentum regions of appearance of these two kinds of particles are shown to be entirely different.

Angular distributions are shown in Fig. 5. Abscis$a is cos$\theta$. Fig. 5 (a) and (b) give distributions of thin and gray tracks in p-(Ag,Br) collisions at 205 GeV/c. In the laboratory backward hemisphere thin and gray particles show similar angular dependence and the slow increase toward cosθ =0 is observed. Ratios of number of particles between cosθ =-1.0 and -0.5 with that between -0.5 and 0 are 1.6 for both thin and gray tracks. Fig. 5 (c) and (d) are for protons and pions in p-Ta collisions at 28.5 GeV/c. In this case only the region of backward hemisphere is shown and the scale of abscissa is different from that of p-(Ag,Br) collisions. In the narrow bias-free ranges, distributions do not differ from isotropy.

In p-Ta collisions decaying particles are found in backward particles. So far observed decaying particles with cos θ smaller than -0.5 are two K^0's, two K^+'s, and one Λ^0 in 894 events. Though the statystycs is low to give any figures of productio ratios, the frequency is certainly unexpectedly high.

3. Discussions. The probability of occurence of relativistic particles in the laboratory backward hemisphere in proton-nucleus collisions increases with mass number A of the target nucleus rather stronger than the increase of produced particles. Its energy dependence seems not so strong, but in our case A-dependence and E-dependence are combined and, therfore, the conclusion should wait more experimental data. From Table I, the probability of MB-events is nearly the square of that of B-events for three groups of N_h. This shows that the emission of multiple B-tracks in one event is a phenomenon without correlation.

As the explanation of this phenomenon, the first process to be considered is the multiple scattering inside the nucleus of recoiled nucleons and produced pions from intra-nuclear cascade multiple production. From this picture, sharp angular distri bution in the backward hemisphere is expected for particles with large longitudinal momenta and such tendency is not found experimentally. Moreover, protons with kinetic energy more than 250MeV are found in the backward hemisphere. Protons with such energy far higher than the Fermi energy inside the nucleus can not be emitted backward. Thus the superposition of elementary multiple

production processes and scattering processes, taking Fermi motion into consideration, can not give a sufficient explanation of this feature of proton- nucleus collisions.

Next, let us consider the decay of isobar produced in the nucleus. In this case, longitudinal momenta of protons and pions should be similar if the produced isobar is at rest in the nucleus. But, in general, the produced isobar has forward longitudinal momentum through the kinematic constraint and, if so, distribution of $(-p_{\parallel})$ of pions should have more particles in higher value side than that of protons, because of the difference of Lorentz transformation. Longitudinal momentum spectra of Fig. 4 show remarkably the opposite tendency and the possibility of explanation by isobar production is completely ruled out.

Ordinary processes in our present knowledge thus seem to be impossible to explain this backward emission.

Kinetic energy spectra of pions and protons of Fig. 3 show similar tendency, though the slope for pions may be a little slower. These facts may suggest that those particles come out from some states like thermal equillibrium, but to give any conclusions seem to be too early to give.

There may be a possibility that the shock wave in the nuclear matter plays a role in this phenomenon. In this case angular distributions should show some structures. It is not possible to deduce any conclusion in our limited statistics.

The reason that such an interesting phenomenon has been overlooked is perhaps that people thought the possibility of explanation by usual processes. But as shown here the problem is not so simple and the accumulation of more experimental data is urgent to clarify this aspect of proton-nucleus interactions. The study of proton-nucleus collisions at high energies may give another tool to investigate the nature of high density nuclear matter now in course of intense study and planning by nuclear physicists using heavy ion accerelators at lower energies.

References.

1) S. Konishi et al., to be published.
2) K. Gottfried, Phys. Rev. Lett. 32, 957 (1974).
3) G. Fujioka et al., J. Phys. Soc. Japan, to be published.