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200 GeV PROTON INTERACTIONS IN NUCLEAR EMULSION

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ABSTRACT

The mean-free-path for inelastic interactions of 200 GeV protons in nuclear emulsion has been measured using the techniques of along-the-track scanning and area scanning. The results obtained are, respectively, $\lambda_{inel} = 35.3 \pm 1.0$ cm and $\lambda_{inel} = 33.1 \pm 1.5$ cm. The average charged multiplicities have been found to be $\langle n_s \rangle = 8.2 \pm 0.2$ for 'white' stars and $\langle n_s \rangle = 12.9 \pm 0.15$ for all events. A plot of n_s versus N_h (where N_h is the number of black and grey tracks) shows a linear relation over the region $0 \leqslant N_h \leqslant 25$. The Castagnoli method applied to 'white' stars overestimates the C.M. energy by ∿ 40%, however, for stars with $N_h \geqslant 1$, there is good agreement.

INTRODUCTION

We present here the preliminary results of an international collaboration using nuclear emulsion exposed to the 200 GeV proton beam at the National Accelerator Laboratory, Batavia. The initial measurements were restricted to the determination of the inelastic mean-free-path and the average charged multiplicities.

Since different techniques have been used by various groups, we thought it advisable to present results from independent groups separately; thus, no particular effort has been made to combine the results at this stage.

IRRADIATION AND PROCESSING OF EMULSION STACKS

Three stacks of Ilford K5 emulsion were exposed to the NAL 200 GeV proton beam in September, 1972. The beam used had the following characteristics: a cross-sectional area of 3 cm x 8 cm and a flux of ~ 10^4 protons/pulse. The beam traversed an equivalent of 2 gm/cm^2 before entering the stacks. Two stacks (40 pellicles each), having dimensions 20 cm x 5 cm x 600μ, were exposed horizontally (beam parallel to the emulsion surface) to a flux of 2×10^4 protons/cm^2; the third stack (20 pellicles), having dimensions 5 cm x 5 cm x 600μ, was exposed vertically (beam perpendicular to the emulsion surface) to a flux of $\sim 10^6$ protons/cm^2. The density of the emulsion at the time of exposure was 3.75 gm/cm^3.

The processing of the two horizontal stacks was carried out in Strasbourg and the smaller, vertical stack was processed in Ottawa. A two-temperature development technique, using a dry hot-stage, was employed in each case.

MEASUREMENT OF THE INELASTIC MEAN-FREE-PATH

The horizontal stacks were scanned by two different methods: 1- along-the-track scanning and 2- area scanning. Only area scanning was used in the case of the vertical stack. A cut-off angle of 0.25° (relative to the beam direction) was applied to the incident protons in order to reduce the contamination by secondaries to less than 3%.

Table I. Measurement of λ_{inel} by along-the-track scanning

LAB	No. of stars	Length of track (metres)	λ inel (cm)
PARIS-STRASBOURG	513	177.66	34.1 ± 1.6
ROME	343	126.84	37.0 ± 2.0
BELGRADE	200	69.77	34.9 ± 2.5
LUND	141	47.81	33.9 ± 2.7
NANCY	92	33.17	36.0 ± 3.7
	TOTAL: 1289	455.25	$\langle 35.3 \pm 1.0 \rangle$

Table 1 summarizes the results of five groups using along-the-track scanning. 1289 inelastic interactions were observed along a total track length of 455.25 m, corresponding to a mean-free-path of $\lambda_{inel} = 35.3 \pm 1.0$ cm. Although this value of λ is not corrected for loss of events, the efficiency of the technique should be well above 90%.

Table II. Measurement of λ_{inel} by area scanning

LAB	Direction of Beam	No. of stars	λ inel (cm)
BUCHAREST	Parallel	3814	36.8 ± 1.1
CANADA	Vertical	227	32.6 ± 2.0
		132	34.4 ± 3.0
		150	32.8 ± 2.8
		TOTAL: 509	$\langle 33.1 \pm 1.5 \rangle$

Table II shows the results of the Bucharest group, who used the area-scanning technique over a well-defined region of one of the horizontally-exposed stacks. 4485 events were found in a total volume of 11.75 cm^3 of emulsion. Of these, only 3814 stars satisfied the criteria for a primary interaction, giving a value of the inelastic mean-free-path of λ_{inel} = 36.8 ± 1.1 cm.

Also shown in Table II are the results of the area scanning of the stack exposed vertically. The results tabulated refer to a second scan in which only a small field of view was examined at one time; a preliminary, more rapid scan of ~ 1 cm^2 of emulsion indicated that the efficiency of detection of events with no black tracks was low. In order to apply a correction for the loss of very small 'white' stars (2 or 3 charged shower particles only), a portion of the area was again carefully rescanned. The corrected, average value of the inelastic mean-free-path for 509 events is λ_{inel} = 33.1 ± 1.5 cm. The values of the mean-free-path obtained by the different scanning techniques agree within the limits of the statistical errors.

'White' stars having only 2 charged shower-particles ($n_s = 2$) or 3 charged shower-particles ($n_s = 3$) have been carefully studied in order to eliminate high energy δ-ray events and tridents due to direct pair formation. (A particle is classified as a shower particle if the track has a grain density $g < 1.4\ g_o$, where g_o corresponds to the grain count for the 200 GeV proton tracks). About one-half of the observed events with n_s = 2 or 3 were attributed to electromagnetic interactions.

STAR-SIZE DISTRIBUTION

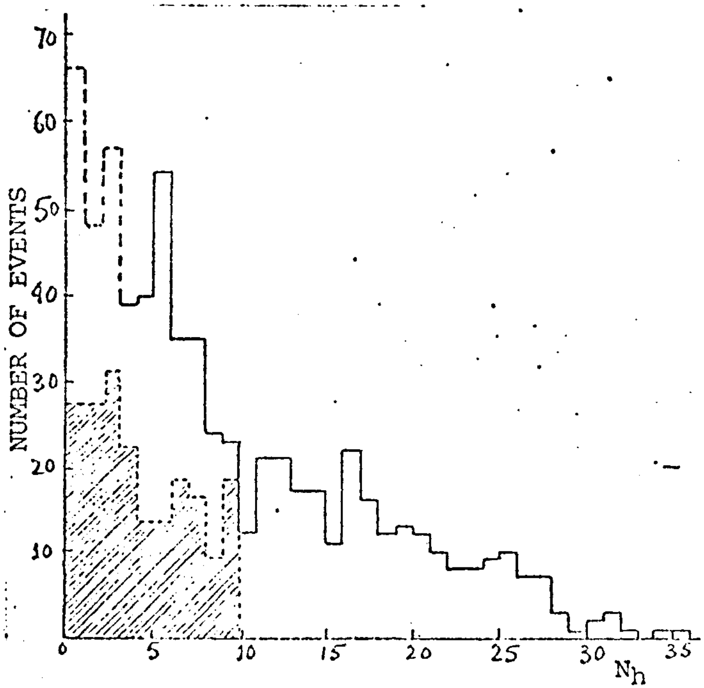

Fig. 1. Histogram of N_h distribution (corrected for loss of events) The shaded area corresponds to stars with a short recoil.

An unexpected feature of high-energy proton interactions in nuclear emulsion is the relatively high percentage (∿ 25%) of stars having $N_h \leqslant 1$. ($N_h = N_b + N_g$; N_b = number of black tracks with $g > 4\ g_o$; N_g = number of grey tracks with $1.4\ g_o < g < 4\ g_o$).

Fig. 1 shows a distribution of the number of stars (corrected for loss of stars with $N_h \leqslant 2$) as a function of N_h. In Table III, the distribution is broken down into different groups. Approximately 15% of the stars are hydrogen-type events; two-thirds of the stars fall into the group $N_h \leqslant 8$ and, therefore, the remaining one-third with $N_h > 8$ are unambiguous Ag or Br stars.

Table III. Percentage of Stars in various N_h groups

LAB	$N_h = 0$	$N_h \leq 1$	$N_h \leq 5$	$N_h \leq 6$	$N_h \leq 8$
PARIS	14.7 ± 1.7	28	56		67
LUND	15 ± 4		52		68
OTTAWA-MONTREAL	12 ± 1	19 ± 2	45	50 28 (no recoil)	60
BUCHAREST			35		

It is interesting to note at this point that from the composition of the nuclear emulsion[1], 4% of the interactions should take place in hydrogen, ∿ 25% in the C, N, O nuclei of the gelatine and ∿ 71% in Ag and Br[2]. In the vertically-exposed stack, it is possible to identify practically all of the Ag and Br stars included in the group $N_h \leq 8$ on the basis of the presence of a very short recoil (recoils as short as 1 to 2μ are usually clearly visible). Events in the group $N_h < 10$ having a short recoil are shown by the shaded area in Fig. 1. Practically all of the events with $N_h = 9$ have a recoil and are, therefore, classified correctly as Ag or Br interactions. For the stars with $N_h \leq 8$, almost exactly one-half have a short recoil. If these events are attributed to interactions in Ag or Br, the percentage of interactions in heavy nuclei is found to be about 70%, as expected from the composition of the emulsion.

AVERAGE CHARGED MULTIPLICITIES, $\langle n_s \rangle$

Figure 2 shows the observed charged multiplicity distribution for hydrogen-type events ($N_h \leq 1$) in the horizontally-exposed stacks. The average charged multiplicity for all events (solid lines) is $\langle n_s \rangle = 8.1$; for events with $N_h = 0$ (dashed lines), $\langle n_s \rangle = 7.6$.

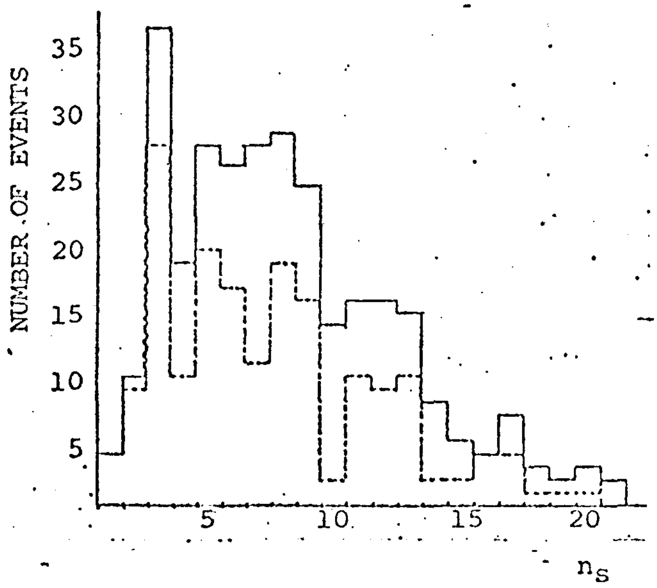

Fig. 2. Charged multiplicity distribution for stars with $N_h \leq 1$. Dashed lines: $N_h = 0$; solid lines: $N_h = 0$ or 1.

In this group of events, ~ 25% are due to interactions in hydrogen, the remainder being attributed to peripheral collisions with nuclei. The numbers of events having even and odd multiplicities are roughly equal, indicating an approximately equal number of collisions with protons and neutrons. The frequency of events with $n_s = 3$ tends to indicate a possible resonance. A similar effect has been observed in emulsion at 67 GeV/c incident proton momentum by Antonova et al[3]. The latter attributed this effect to the coherent production of particles in proton-nucleus collisions. Unfortunately, at this stage of our work, the statistics are too poor to allow a definite conclusion to be reached at 200 GeV.

In Figure 3, the charged multiplicity has been plotted as a function of the star size, N_h. The average multiplicity for all the events is 12.9 ± 0.15.

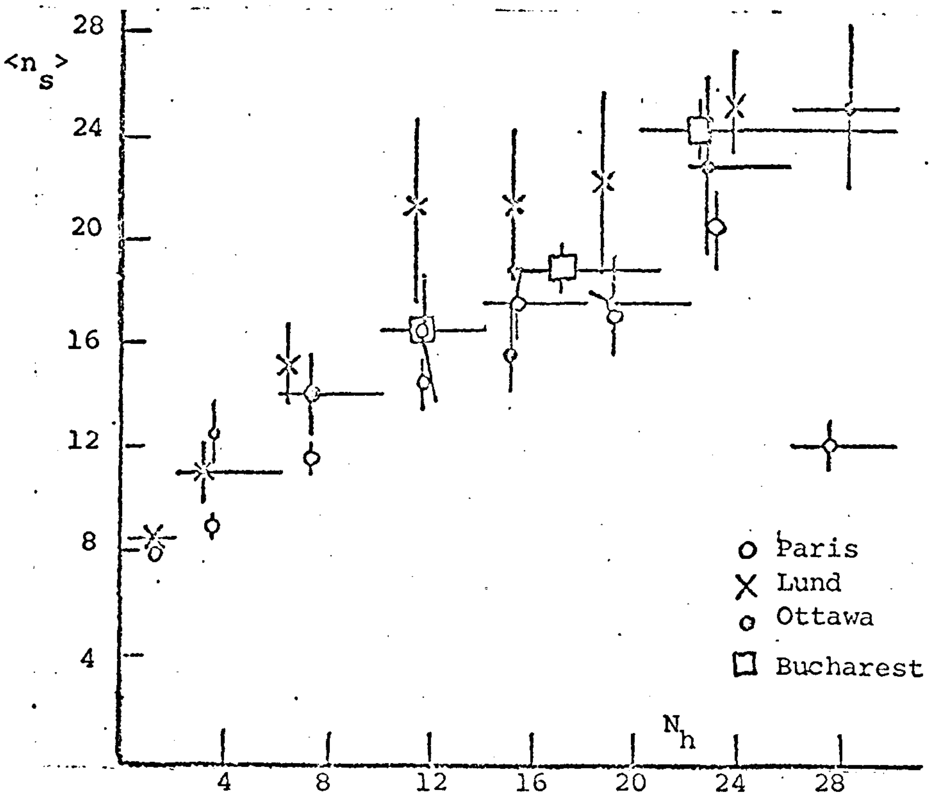

Fig. 3. Charged shower-particle multiplicity, $\langle n_s \rangle$, as a function of star size, N_h. The experimental points are plotted at the centre of gravity of the measured interval.

We observe an almost linear relationship between $\langle n_s \rangle$ and N_h. At first sight, this result appears to indicate an increase in the average charged multiplicity with increasing mass number of the target nucleus. However, it should be borne in mind that about one-half of the events with $N_h \leq 8$ should be classified as interactions in heavy nuclei. An analysis of the charged multiplicity in the vertically-exposed stack in which short recoils could be detected shows that, in fact, the average multiplicity is not appreciably different for the light (C,N,O) and the heavy (Ag,Br) nuclei. The average values found are $<n_s>_{light} = 13.1 \pm 1.0$ and $<n_s>_{heavy} = 14.1 \pm 0.6$. The increase in multiplicity with increasing N_h is, therefore, probably associated with secondary collisions inside the target nucleus.

For the hydrogen-type collisions ($N_h < 1$), the average charged multiplicity was found to be 8.2 ± 0.2. The corresponding value obtained with the hydrogen bubble chamber[4] is 7.65 ± 0.17.

Table IV shows a comparison of the results obtained at 200 GeV with previous data for incident proton energies of 6.2 and 22.5 GeV[5].

Table IV. Comparison of events at 6.2, 22.5 and 200 GeV.

E GeV	$<N_b>$	$<<N_g>$	$<n_{\pi\pm}>$
6.2	5.68 ± 0.21	3.58 ± 0.11	2.21 ± 0.04
22.5	5.22 ± 0.29	3.38 ± 0.14	5.08 ± 0.12
			$<n_s>$
200	7.0 ± 0.1	2.79 ± 0.15	12.9 ± 0.15

There seems to be little difference between the events at 6 GeV and 22 GeV, except for an increase in the average number of charged mesons produced (about a factor of 2). Between 22 and 200 GeV, there is an increase in average star size as well as an increase in charged multiplicity. The average number of grey tracks at 200 GeV has decreased by about 15% as compared with 22 GeV. This does not necessarily imply that there is any fundamental difference in the interactions at 200 GeV. The effect can be accounted for by the emission at 22 GeV of more lower-energy charged mesons, which would be classified from their ionization as grey tracks. In fact, even in the events at 200 GeV, we do observe such low-energy mesons.

ANGULAR DISTRIBUTION

Angular measurements of each shower track have been made for events of the type $N_h = 0$. Only those events with $n_s \geqslant 4$ were included in order to exclude possible high energy δ-rays and pseudo-tridents. The angular distribution of all the charged shower particles plotted in the center-of-mass (C.M.) system is shown in Figure 4.

The reason for the pronounced asymmetry in the forward-backward directions is not clear. Part of this effect could be accounted for by the fact that slightly more than half of the events (odd multiplicity) presumably correspond to collisions with a target neutron. For symmetry reasons, one would expect the struck neutron to be emitted backwards ($\cos\theta^*$ between -0.8 and -1.0) and being uncharged, the neutron is not observed amongst the shower particles.

The total energy in the C.M. system was calculated for the same 134 events by the Castagnoli method[5]. An average value of $\log \text{ctg}\, \theta_L$ was found for each of the stars. The distribution of the average values of $<\log \text{ctg}\, \theta_L>$ is plotted in Figure 5.

The mean value of the distribution corresponds to log $\gamma_{C.M.} = 1.15$, which would indicate that the Castagnoli method overestimates the energy in the C.M. system by about 40%.

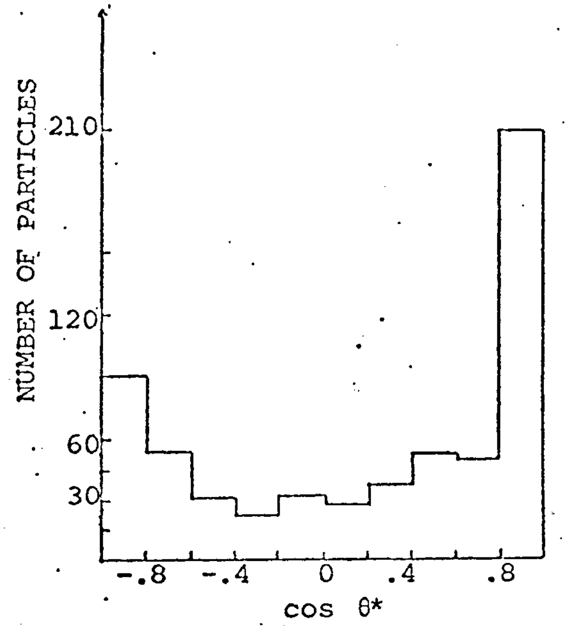

Figure 4. Angular distribution in C.M. system of charged shower particles in 'white' stars ($N_h = 0$ and $n_s \geqslant 4$)

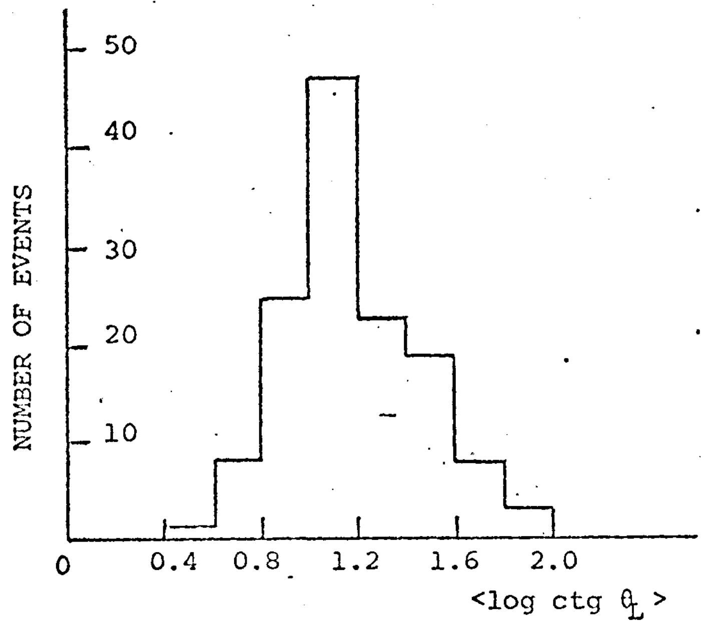

Figure 5. $\langle$Log ctg $\theta_L\rangle$ plot for stars (134) with $N_h = 0$ and $n_s \geqslant 4$

The Castagnoli method has also been tested for an unbiased sample of 53 events. In Figure 6 is shown the distribution of the values of log ctg θ_L for all the shower particles observed up to an angle of 84°. 3% of the charged shower particles in large stars were emitted at greater angles and, therefore, could not be included in the histogram. In the small stars (shaded area in Figure 6), no shower particles are observed at an angle greater than 75°. The small stars are interactions in light (C,N,O) nuclei and are those events with $N_h \leqslant 8$ and no short recoil. The remaining events are interactions in heavy (Ag,Br) nuclei.

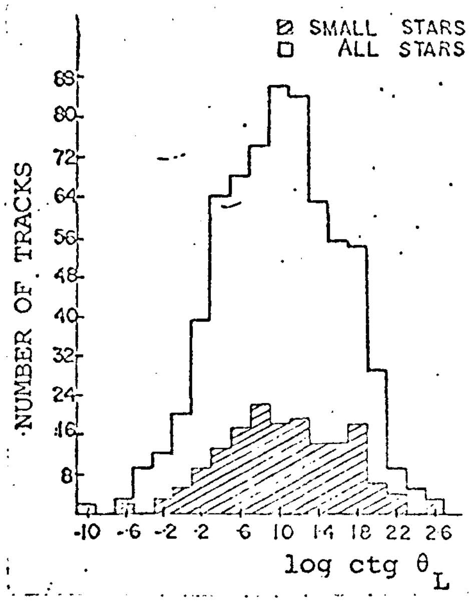

Fig. 6. Histogram of log ctg θ_L distribution for charged shower particles in 53 events. The shaded area corresponds to small stars (C,N,O group).

The average value of log ctg θ_L was calculated for each of the two groups of events and for the whole sample. The values of log $\gamma_{C.M.}$ obtained are:

C,N,O: log $\gamma_{C.M.}$ = 1.00
Ag,Br: log $\gamma_{C.M.}$ = 0.97
All events: log $\gamma_{C.M.}$ = 0.98

The values of log $\gamma_{C.M.}$, for both the light and the heavy nuclei, show a remarkable agreement with the Castagnoli method. This result would seem to indicate that the interactions involve a single nucleon in the target nucleus; however, we have observed a marked shift of $\langle \log \mathrm{ctg}\, \theta_L \rangle$ towards lower values in events of high charged multiplicity ($n_s > 20$) in both the light and the heavy groups, indicating that in these interactions more than one target nucleon appears to be involved.

CONCLUSION

The interactions of 200 GeV protons in nuclear emulsion are not basically different from lower energy proton interactions. A comparison with 22.5 GeV proton interactions shows that almost the same star-size is observed in both cases (except for the charged multiplicities); the percentage of 'white' stars (N_h = 0 or 1) is almost the same in each case (20-25%). If we compare the charged multiplicities for 'white' stars and p-p collisions at the same incident proton energies, we find the same values within the experimental errors (account being taken of showers with odd multiplicities, which are attributed to neutrons). All the evidence points to the fact that in the large majority of the 'white' stars the incident proton interacts with a proton or a neutron at the periphery of the nucleus, the latter receiving little excitation energy in the process.

Coherent production of resonances should be important at 200 GeV proton energy, but the statistics available at this time do not allow any measurement of cross-section.

An interesting feature of this preliminary study is the small difference in charged multiplicities of the (C,N,O) group and the (Ag,Br) group. A simple explanation could be given in terms of a primary proton-nucleon collision with a resulting 'fireball' travelling out of the nucleus before it disintegrates. This naive model could possibly be checked by using very heavy nuclei, such as lead, as targets.

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