# Observation of Nuclear Transparency in Proton-Nucleus Collisions at 200 GeV*

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(Received 23 May 1974)

Proton-nucleus interactions in nuclear emulsion from a 200-GeV proton beam at the National Accelerator Laboratory have been studied in terms of multiplicities and the angular distributions of shower particles. Low multiplicities observed in complex nuclei do not depend upon the size or the excitation of the target nuclei. Our experimental results are explained in terms of the energy-flux cascade model and not by intranuclear cascade models.

Recent results of rising total cross sections, large $p_t$ events, leading particle effects, and clustering of secondaries determined at the energies of the National Accelerator Laboratory and the intersecting storage rings had already been observed in earlier cosmic-ray experiments. Cosmic-ray studies had also revealed that the multiplicity, transverse momentum, and angular distribution of secondaries have weak dependence on the primary energy as well as on the size of the target nucleus, and they do not follow the predictions of the calculations of the intranuclear cascade models. Because of the revival of interest in hadron-nucleus interactions, we present here the results of 200-GeV proton-nucleus interactions in nuclear emulsion and compare them with 16-,[1] 28-,[2] 300-, and 1000-GeV[3] data from our laboratory. We feel that these studies will not only be helpful in understanding the nucleon-nucleus collisions but also they will contribute significantly in understanding better the nucleon-nucleon interactions.

The details of the exposure for this experiment were discussed earlier[4] where we presented the analysis of events with only $N_h = 0$ or 1 ($N_h$ denotes the number of heavy tracks[5] with $\beta \leq 0.7$). We scanned 713.4 m of track length by an along-the-track scanning method and observed 2293 interactions, out of which we present here the analysis of 1243 events with $N_h > 1$. In Fig. 1(a) is shown the behavior of $\langle N_h \rangle$ observed in nuclear emulsion as a function of primary energy.[6] We see that at lower energies $\langle N_h \rangle$ increases with energy, and at energy > 6 GeV there seems to be a decreasing tendency, approaching an asymptotic value of ~7.5. This is in contradiction to the intranuclear cascade mechanism. In Fig. 1(b) is shown the probability of having an emulsion star with more than $N_h$ heavy tracks for 16-GeV $\pi^-$, and 28-, 200- and 1000-GeV protons. The high-energy limit is reached very quickly, even at 16 GeV, which shows that the emission of a given number of slow protons undergoes no significant change when the incident energy is raised from 16 GeV to 1 TeV. Contradiction of the cascade mechanism is further observed in the distribution of $\langle N_h \rangle$ versus $n_s$ where $\langle N_h \rangle$ increases linearly[6] with $n_s$ (Ref. 5). The slope values at 6-, 28-, and 200-GeV proton energies are 1.2, 1.0, and 0.55, respectively. The decrease of the slope with the increase in energy is in turn further observed in the increase of $\langle n_s \rangle$ as a function of energy. At higher energies the rate of increase of $\langle n_s \rangle$ decreases. This could be explained in terms of clustering or other forms of collective behavior of secondary particles produced at high energies. In Fig. 1(c) is shown the distribution of $\langle n_s \rangle$ for a given $N_h$ at different energies: 16, 28, 200, 300, and 1000 GeV. All of these distributions show linear fits with slopes increasing monotonically with energy. The $\langle n_s \rangle$ for all events at 200 GeV is $12.7 \pm 0.2$. The 200-GeV curve when extrapolated has an intercept value at $N_h = 0$ of $\langle n_s \rangle > \sim 8.0$ which is close to $7.68 \pm 0.11$, the one observed at 200 GeV for $p$-$p$ interactions in a bubble chamber.[7] Another interesting characteristic of the multiplicity in the target nucleus $A$ is the ratio $R_A = \langle n_s \rangle_{(pA)} / \langle n_{\mathrm{ch}} \rangle_{(pp)}$, where $\langle n_{\mathrm{ch}} \rangle_{pp}$ is the mean $p$-$p$ charge multiplicity and $\langle n_s \rangle_{pA}$ is the mean $p$-nucleus multiplicity in nucleus $A$. In the nuclear emulsion $R_{\mathrm{em}}$ for 16, 28, 67,[8] 200, 300, and 1000 GeV is given by $1.24 \pm 0.12$, $1.4 \pm 0.12$, $1.53 \pm 0.4$, $1.62 \pm 0.66$, $1.65 \pm 0.10$, and $1.70 \pm 1.5$, respectively. $R_{\mathrm{em}}$ values as a function of $N_h$ in the nuclear emulsion are shown in Fig. 1(d). The linear relation at low-energy values of 16 and 28 GeV show slightly different slopes than those in 200 or in 300 GeV. It is remarkable to see that the $R_{\mathrm{em}}$ values show a very small increase with the incident energy and

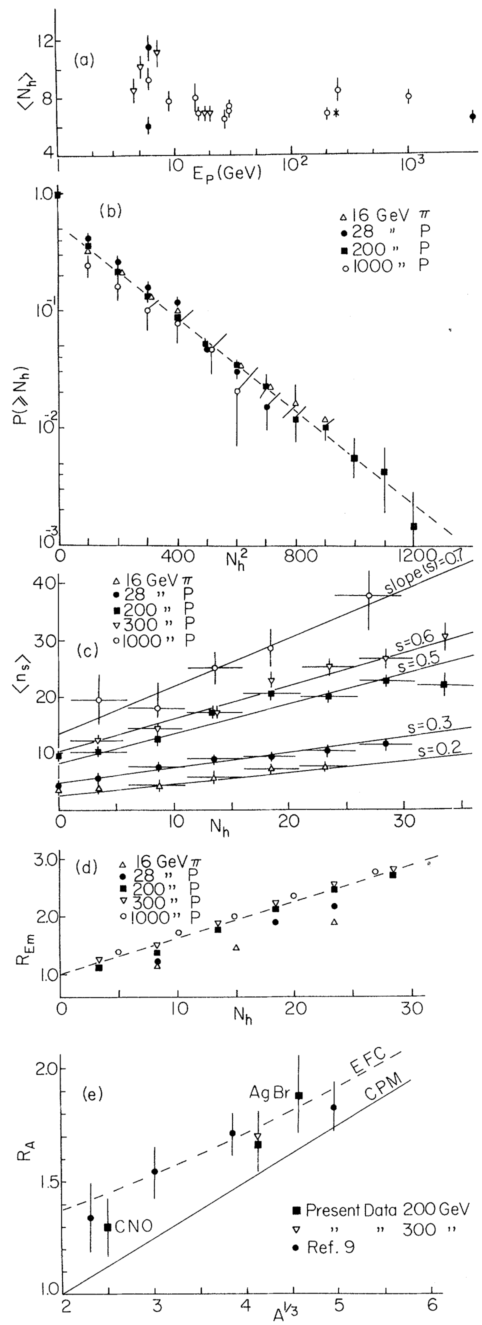


FIG. 1. (a) $\langle N_h\rangle$ produced from the interaction of pions and protons with emulsion nuclei as a function of energy. Area scanning: closed circle, proton; closed triangle, pion. Along the track scanning: open circle, proton; open triangle, pion. (b) Integral frequency distribution of $N_h^2$ for 16, 28, 200, and 1000 GeV. (c) $\langle n_s\rangle$ versus $N_h$ for 16, 28, 200, 300, and 1000 GeV. (d) $R_{\mathrm{em}}$ versus $N_h$ for 16, 28, 200, and 300 GeV. The relation for 200, 300, and 1000 GeV is given by $R_{\mathrm{em}}=1+0.06N_h$. (e) $R_A$ versus $A^{1/3}$. For EFC model, $R_A=1+\frac{1}{3}(\bar{\nu}_A-1)$, where $\bar{\nu}_A$ is average number of collisions in the nucleus. For CPM, $R_A=\frac{1}{2}(1+0.5A^{1/3})$.

with $N_h$ values. For the high energy 200-, 300-, and 1000-GeV primaries, the $R_{\mathrm{em}}$ values practically coincide for the three energies for any $N_h$ value and are given by the scaling relation $1+0.06N_h$. It is a very interesting result that we can predict an average multiplicity from nuclear targets if we know the multiplicity from $p$-$p$ collisions at the same energy or vice versa. We may add that at 200 GeV $\langle n_s\rangle_{(p\,\mathrm{AgBr})}/\langle n_s\rangle_{(p\,\mathrm{CNO})}\sim 1.5$, as found in cosmic-ray work. Constancy of $R_A$ as a function of energy has been further confirmed in a number of other targets and is shown[9] in Fig. 1(e) where the observed values of $R_A$ are plotted against $A^{1/3}$ for different nuclei. The energy-flux cascade model[10] (EFC), as compared to the coherent-production model[11] (CPM), fits the observed data very well. Our data clearly rule out cascade models which predict that $R_A$ should be independent of $A$.

In Fig. 2(a) is shown the ratio $R_E=\langle n_s\rangle_{E_1}/\langle n_s\rangle_{E_2}$ as a function of $N_h$ for 300 and 200 GeV, which is almost a constant ($\sim 1.1$), but for low-energy regions this ratio is not constant. This is very interesting, as the mean multiplicity of shower particles produced by high-energy particles on a nuclear target does not depend on either the size or the degree of the excitation of the target nucleus while at lower energies, i.e., at 16 and 28 GeV, there is a strong dependence of this kind. This is also obvious from the values of $R_{\mathrm{em}}$ for the emulsion nucleus which are $1.24\pm 0.12$ and $1.4\pm 0.12$ for 16 and 28 GeV, respectively, which are different from the scaling value of $1.65\pm 0.15$. In order to see the development of shower particles with mass $A$, we divided the shower particles $n_s$ into inner ($\tan\theta<0.1$) and outer ($\tan\theta>0.1$) cones, where each cone contains on the average one-half of the shower particles produced in the $p$-$p$ collision. This is shown in Fig. 2(b) as a function of $N_h$. One observes that the particles produced in the inner cone increase very slowly with $N_h$. If we further reduce the inner angle to $\tan\theta\leqslant 0.08$ then $\langle n_s\rangle\sim 5.5$ and is practically the same for all events, and thus the constancy of these values indicates that particles produced in the inner cone behave as if there were no nuclear matter in their way and the nucleus was apparently transparent to them. The whole increase of $\langle n_s\rangle$ with $N_h$ comes from the slow particles produced in the outer cone, which is predicted by almost all models including cascade models. However the amount of excess slow particles is a very sensitive way of distinguishing between different models.[12] The relation of angular distribution of shower particles in the inner and the outer cones as a function of $N_h$ is shown in Fig. 2(c). We notice that the $\langle x\rangle$ value [where $x=-\log_{10}(\tan\theta)$] for all angles is slowly decreasing with $N_h$. This decrease comes mainly from the inner cone; for the outer cone it is almost constant. When we further change the angle of the inner cone to $\tan\theta \leqslant 0.08$ and for the outer cone to $\tan\theta > 0.08$, the $\langle x\rangle$ values for the inner cone are practically constant for different $N_h$ values. From Figs. 2(b) and 2(c) we notice that the inner cones of angle $\tan\theta \leqslant 0.08$ give practically constant values of $\langle n_s\rangle$ and $\langle x\rangle$ for all different $N_h$ values. On the other hand, in the outer cone $\langle x\rangle$ remains constant but $\langle n_s\rangle$ increases with $N_h$.

As mentioned earlier, the existence of the leading-particle effect is determined by measuring the inelasticity $K$ which is the fraction of the incident energy carried off by secondaries. This has been calculated by the common technique used in cosmic-ray work[13] as $K=(1.5\langle p_t\rangle\sum\csc\theta_i)/200$, where $\langle p_t\rangle = 0.35$ GeV/$c$ and the innermost track has been removed. The $K$ values obtained are shown in Fig. 2(d). We notice that for $N_h<7$ ($\langle N_h\rangle \sim 7$ for 200 GeV), the $K$ values are small and are increasing, and the leading particle carries most of the energy. As $\langle N_h\rangle$ approaches 7 the leading particle becomes less energetic and the $K$ value is almost constant ($\sim 0.55$) and is insensitive to $N_h$, and this is not explained by cascade models. In Fig. 2(e) is shown the integrated and normalized rapidity distribution[14] [$=\log_{10}(\tan\theta)$] as a function of $N_h = 0$, 1, 2–5, 6–8, and $>8$. The arrows shown for $N_h=0$, 2–5, and $>8$ indicate the values of $\log_{10}(\tan\theta)$ where an equal number of tracks lie above and below $\theta$, and they are very close to one another. This shows that the angular distribution depends weakly on $N_h$; this was also concluded from Fig. 2(c). Also in this figure is shown the differential rapidity distribution for different $N_h$ values. This differential distribution is further compared with the 200-GeV $p$-$p$ normalized data from the bubble chamber.[7] We see that both the distributions for the hydrogen bubble chamber and $N_h=0$ are identical and are symmetrical about the center of mass ($C$). For $N_h>8$, the distribution is unsymmetric and the whole excess in the multiplicity appears in the target hemisphere which is not explained by the cascade models.

We thus conclude from our experiment that (i) $\langle n_s\rangle$ increases with mass $A$ and the increase observed is much smaller than predicted by intranuclear cascade models, and (ii) the multiplicity

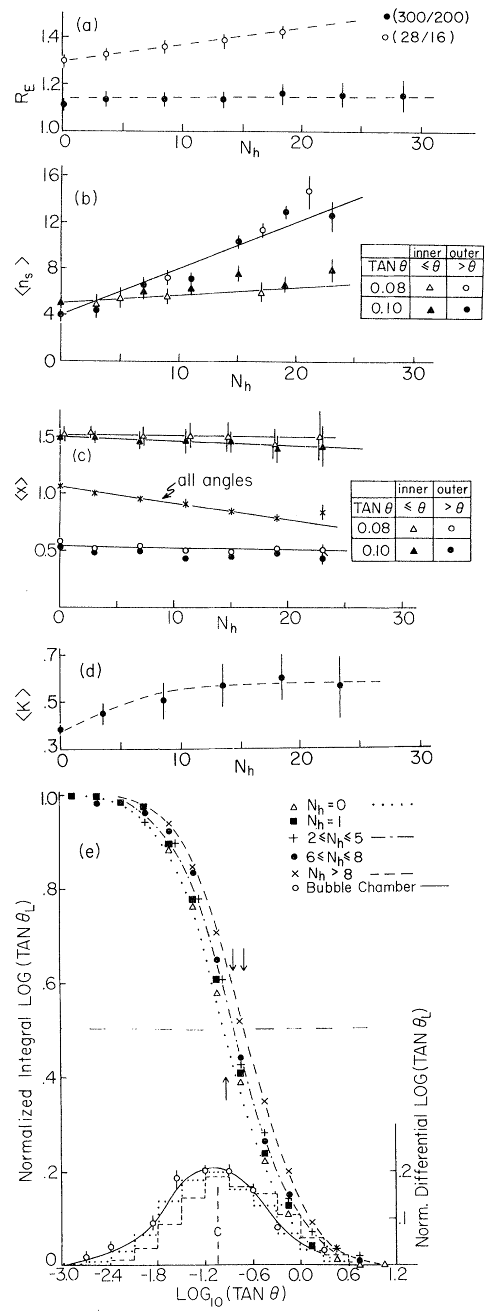


FIG. 2. (a) $R_E$ versus $N_h$ for 300 and 200 GeV, and for 28 and 16 GeV. (b) $\langle n_s\rangle$ versus $N_h$ for inner and outer cones at 200 GeV with (i) first cut $\tan\theta \lessgtr 0.1$ and (ii) (ii) second cut $\tan\theta \lessgtr 0.08$. (c) Angular distribution $\langle x\rangle$ versus $N_h$ for 200-GeV events for (i) all angles; inner and outer cone with (ii) $\tan\theta \lessgtr 0.1$ and (iii) $\tan\theta \lessgtr 0.08$. (d) Inelasticity $\langle K\rangle$ versus $N_h$ at 200 GeV. (e) Integral frequency distribution of rapidities plotted for events with $N_h = 0$, 1, 2–5, 6–8, $>8$. The center points are shown by arrows. The differential distribution of rapidities is also plotted for events with $N_h=0$ and $>8$, and this is compared with bubble chamber data at 200 GeV.

and the angular distribution in the very forward direction change very little with target size and the nuclear effects seem to come mainly from the particles produced in the backward direction but without much change in their angular distributions. Thus we see that nuclear phenomena at high energy may allow a glimpse of the underlying dynamics that cannot be seen directly in free-$p$-$p$ collisions. We are confident that nuclear studies at higher energies shall surely provide important insight into strong-interaction dynamics.

We are very grateful to Professor K. Gottfried for a useful discussion and for sending us his paper before its publication. We are also very thankful to the staff of the National Accelerator Laboratory and particularly to Dr. L. Voyvodic for their valuable help with the 200-GeV exposure.

*Work supported by the Research Corporation.

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# Observation of the Reactions $e^+e^- \to e^+e^-$, $e^+e^- \to \gamma\gamma$, and $e^+e^- \to \mu^+\mu^-$ at a Center-of-Mass Energy of 5.2 GeV*

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(Received 17 June 1974)

We report measurements of $e^+e^- \to e^+e^-$, $e^+e^- \to \gamma\gamma$, and $e^+e^- \to \mu^+\mu^-$ at angles close to 90°, relative to Bhabha scattering at 3.7°, at a center-of-mass energy equal to 5.2 GeV. The results are found to be consistent with the predictions of quantum electrodynamics.

We report here significant initial results from an experimental study of the reactions $e^+e^- \to e^+e^-$, $e^+e^- \to \gamma\gamma$, and $e^+e^- \to \mu^+\mu^-$ at the 2.6-GeV electron-positron storage ring (SPEAR) at the Stanford Linear Accelerator Center. The purpose of this experiment[1] was to test the validity of quan-