Search for Quark-Gluon Plasma in Nucleus-Nucleus Collisions at 3.2 TeV

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First results from measurements of all the shower particles produced in 191 nearly central interactions of a 200-GeV/nucleon ^{16}O beam with nuclear emulsion are presented. The lower limit of the average energy density for the events with multiplicity $n_s \geq 200$ is $\langle \epsilon \rangle \simeq 1$ GeV/fm^3.

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Recently, the interest in relativistic heavy-ion collisions has increased considerably among theoretical and experimental physicists in the fields of both nuclear and particle physics. In such collisions, the energy density in the central rapidity regions is predicted to exceed the critical value of energy density for a phase transition to occur from ordinary confined matter to an unconfined quark-gluon plasma over an extended volume. These collisions may also allow one to study the evolution of the early Universe. In order to achieve this objective, theoretically one needs nuclear events with large multiplicities and with wide rapidity ranges. These can only be produced through inelastic interactions of very-high-energy heavy-ion primary beams. However, such events are experimentally difficult to measure, especially in the very forward direction. In the present paper, we report the first results on the analysis of the central events produced in nuclear emulsion from the interactions of the highest-energy beam now available, viz., oxygen at 200 GeV/nucleon at CERN. As we are dealing with a large number of particles in the forward direction, which subtend only very small angles with respect to the primary direction, one needs a very good detector such as nuclear emulsion to analyze such events. It is well known that nuclear emulsion has the highest spatial resolution[1] among all the particle detectors.

In the present experiment we used two small stacks of Ilford G-5 emulsion 600 μm thick, and of size 12×7 cm^2. These stacks were exposed to a 200-GeV/nucleon oxygen beam at CERN with a flux density of 1×10^3 particles/cm^2, parallel to the plane of emulsion. The plates were scanned by area scanning as well as by along-the-track scanning methods. After eliminating the elastic and electromagnetic dissociated events, the mean free path was found to be $\lambda = 10.89 \pm 0.77$ cm for 23 m of track length of the oxygen beam. This is slightly less than $\lambda = 12.05$ cm ($\sigma = 1025$ mb) given by the overlapping geometrical model. During area scanning, in order to avoid the background of the secondary events produced by the outgoing particles from the primary interactions, we scanned only the first 5 cm of the plate area. Each event was further checked by following the interacting track backwards to the edge of the pellicle. This ensured that the track under consideration was the primary and not the secondary one. Furthermore, all the events were examined under a 100× oil objective in order to reject the background events having their vertices too far away from the primary beam tracks. Thus, we selected about 1500 primary interactions out of which 191 were nearly central ones. The central events are those in which the projectile and the target nuclei suffer an almost head-on collision. As a result, the target nu-

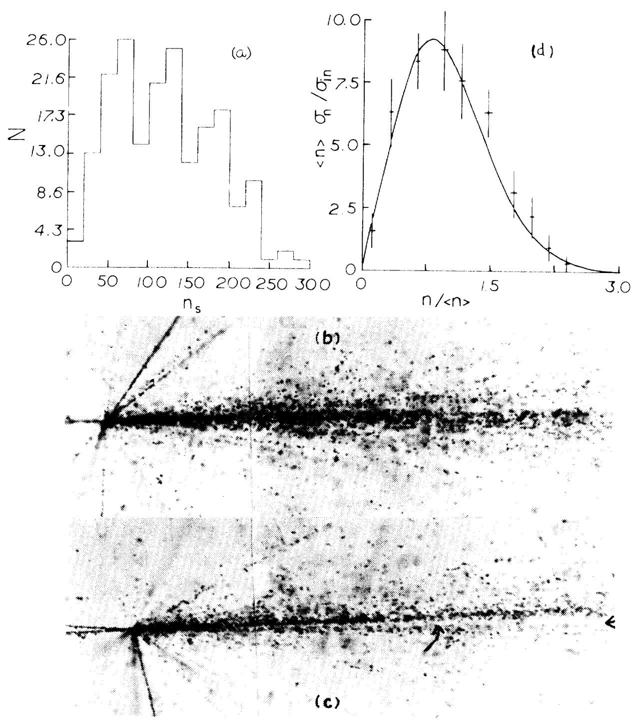

FIG. 1. (a) Frequency distribution of near central events in ^{16}O-emulsion interactions at 200 GeV/nucleon. (b),(c) Photomicrographs of two inelastic ^{16}O-AgBr interactions at 200 GeV/nucleon. (b) Event No. 45, $n_s = 264$. (c) Event No. 100, $n_s = 253$, with a narrow gap in the central zone (marked with arrow). (d) The KNO function, $\psi(z)$, plotted against $n/\langle n \rangle$ for near central events in ^{16}O-emulsion interactions (Ref. 1).

cleus is left in a highly excited state, which subsequently evaporates and low-energy fragments (N_h) are emitted. They are easily distinguished in emulsion from the minimum ionizing secondary (N_s) tracks produced in nuclear collisions. Besides, the central events, which we consider, do not have spectator fragments of the projectile with charge $Z > 1$. We present here the general results from 191 events produced by the incident oxygen beam. 143 events were with heavy (AgBr) and 36 events with light elements of emulsion, having the number of black prongs $N_h \geq 8$ and $N_h < 8$, respectively.[2] Twelve events were white stars. These results are compared with hadron beams at different energies.[1,3] The average multiplicities $\langle n_s \rangle$ for AgBr and CNO events are 139.5 ± 11.7 and 58.8 ± 9.8, respectively, and their respective $D/\langle n_s \rangle$ ratios are 0.41 and 0.44. In Fig. 1(a), the frequency of nearly central events is plotted against their multiplicities. We have divided all these events in five different multiplicity groups, viz., 0–50 (13.1%), 51–100 (27.7%), 101–150 (27.72%), 151–200 (20.9%), and 201–300 (11.0%), depending upon the different values of their impact parameters. In this paper, special emphasis is given to those events which have $n_s \geq 200$. In Figs. 1(b) and 1(c) are shown the actual photomicrographs of the central events with charged multiplicities $n_s = 264$ (event No. 45) and $n_s = 253$ (event No. 100), respectively. Most of the events with large multiplicities have the general features of the photomicrograph shown in Fig. 1(b), while the event shown in Fig. 1(c) is quite rare and distinctive in the sense that it shows a kind of narrow gap in the central zone (marked with arrow). In Fig. 1(d) is shown the Kuba-Nielsen-Olesen (KNO) scaling for nucleus-nucleus collisions of nearly central events; it is fitted with a standard curve[1] with a χ^2/degrees of freedom $= \frac{4}{12}$. This distribution is slightly narrower than that for proton-hadron interactions at 200 GeV. The sharp tail is due to a few events which are of very large multiplicities; they may be suitable candidates for the observation of the quark-gluon plasma.

There are 22 events which have $n_s \geq 200$ as shown in Fig. 1(a). For the two selected events out of these 22, we show in Fig. 2 the pseudorapidity (η_c) distributions in the center-of-mass system (c.m.s.) and the correlation of n_s with azimuthal angle (ϕ). The values of $dn/d\eta_c$ near the central region are 82.2 and 51.3 in Figs. 2(a) and 2(b), respectively. Most of these events have almost uniform azimuthal-angle distributions for produced particles over the entire pseudorapidity region, but there are some exceptions to it just as shown in Fig. 2(b), where the particles are isotropically produced in two separate clusters. The η and ϕ distributions of all the 22 individual events differ from one another. However, there is one common feature: The particle density in the central and target fragmentation regions of pseudorapidity is high in every case. The normalized pseudorapidity distribution for the 22 events having $n_s > 200$ is shown in Fig. 2(c),

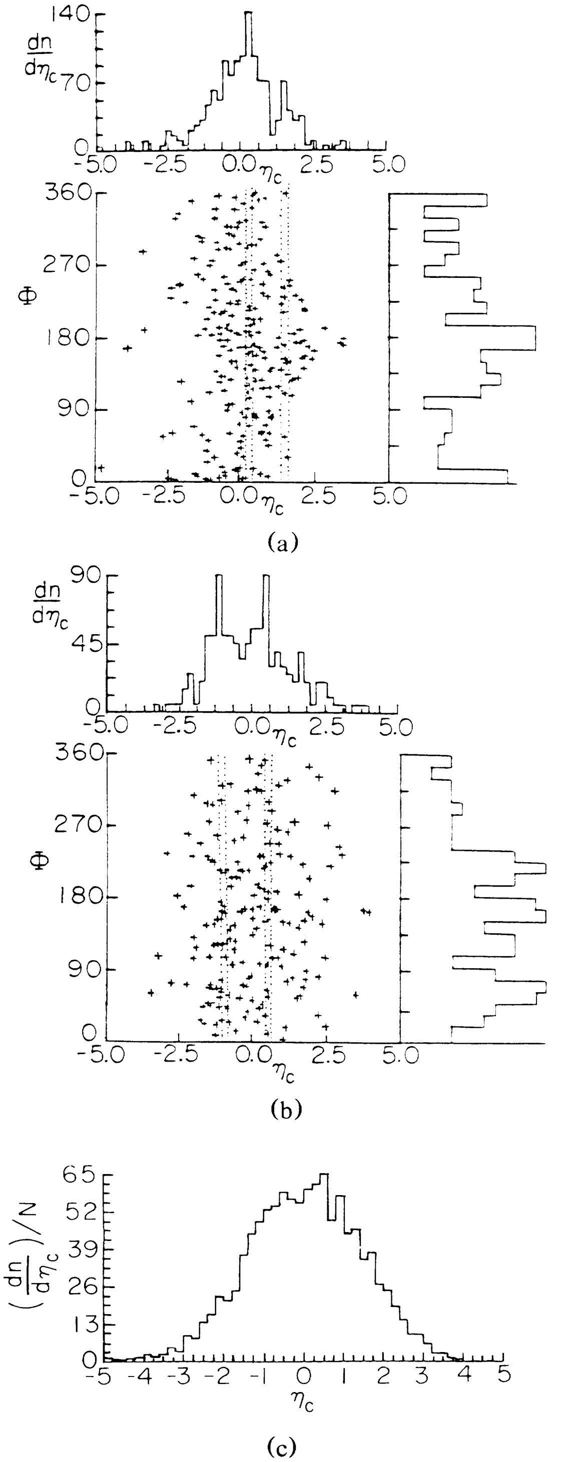

FIG. 2. The c.m.s.-pseudorapidity (η_c) and azimuthal-angle (ϕ) distributions for two selected ^{16}O-AgBr events: (a) Event No. 45, $n_s = 264$, and (b) event No. 51, $n_s = 203$. Dotted lines represent the isotropic ϕ distributions in individual peaks. (c) The normalized pseudorapidity distribution $(1/N)(dn/d\eta_c)$ for $N = 22$ central events with $n_s > 200$.

where the particle density in the central region is 50.7 ± 2.3.

In Fig. 3(a) is shown particle density per unit of pseudorapidity distribution in the c.m. system for the "central" and for the "fragmentation" regions of the target and the projectile as a function of the multiplicity n_s. We find that the slope for the central region is higher than that for the target region. In the projectile region the particle densities are almost constant (i.e., 1.69). If we calculate for the oxygen beam the nucleon density per unit of rapidity per charge unit (i.e., 1.69/8=0.2), then this value is the same as that for 200-GeV proton beam[3] with any of the targets (H, CNO, and AgBr) in the projectile region (for $\eta_c \geq 3$). The particle densities produced in the central regions with proton beam of energies 200, 300, 400, and 800 GeV interacting with different targets (e.g., p-p, p-CNO, and p-AgBr) are shown in Fig. 3(b). The density values are too small as compared with Fig. 3(a) for oxygen beam. We know that in nucleus-nucleus collisions at a particular energy, the multiplicity depends upon the number of collisions among the nucleons, which subsequently depends upon the values of the impact parameters. It is also known from the previous studies with grey tracks[4] (mostly protons with energy between 40–400 MeV) that their number (N_g) may be treated as an experimental parameter representing the number of collisions, which in turn depends upon the impact parameter for the production of n_s. In Fig. 3(c) is shown the value of $\sqrt{N_g}$ for four different groups of the multiplicity n_s, which increases with n_s. The low multiplicity events are always dominated by the large value of the impact parameter. In the central region, the growth of the charged-particle density $\langle (dn/d\eta_c) \rangle$ for p-p, ^{16}O-CNO, and ^{16}O-AgBr as a function of $A^{1/3}$ is shown in Fig. 3(d) at 200 GeV, indicating that at high energy, the multiplicity in the central region grows as $A^{1/3}$. In order to test the current theoretical prediction[5] of QCD that strongly interacting hadronic matter may dissolve into a weakly interacting quark-gluon plasma at $\epsilon > 1$ GeV/fm^3, we estimated the energy density ϵ for 22 events with $n_s \geq 200$ by using the simple formula proposed by Bjorken.[5] His formula is based upon the inside-outside cascade picture for the space-time development of the hadrons created in the ultrarelativistic nucleus-nucleus collisions. It is given by

$$\epsilon_{\min} = (p_t^2 + m_\pi^2)^{1/2} \tfrac{3}{2} (dn/d\eta_c)/(2\pi\tau_0 A_{\min}^{2/3}), \qquad (1)$$

where $A_{\min}$ is the oxygen nucleus, $\tau_0 \simeq 1$, and $\langle p_t \rangle = 300$ MeV, although individual values for p_t will be much higher than 300 MeV. By making use of Eq. (1), we show in Fig. 3(e) the $\epsilon_{\min}$ values for 22 events with $n_s \geq 200$. The average value of $\langle \epsilon_{\min} \rangle \simeq 1$ GeV/fm^3, which is much greater than any ϵ value achieved by the highest-energy hadron beam.

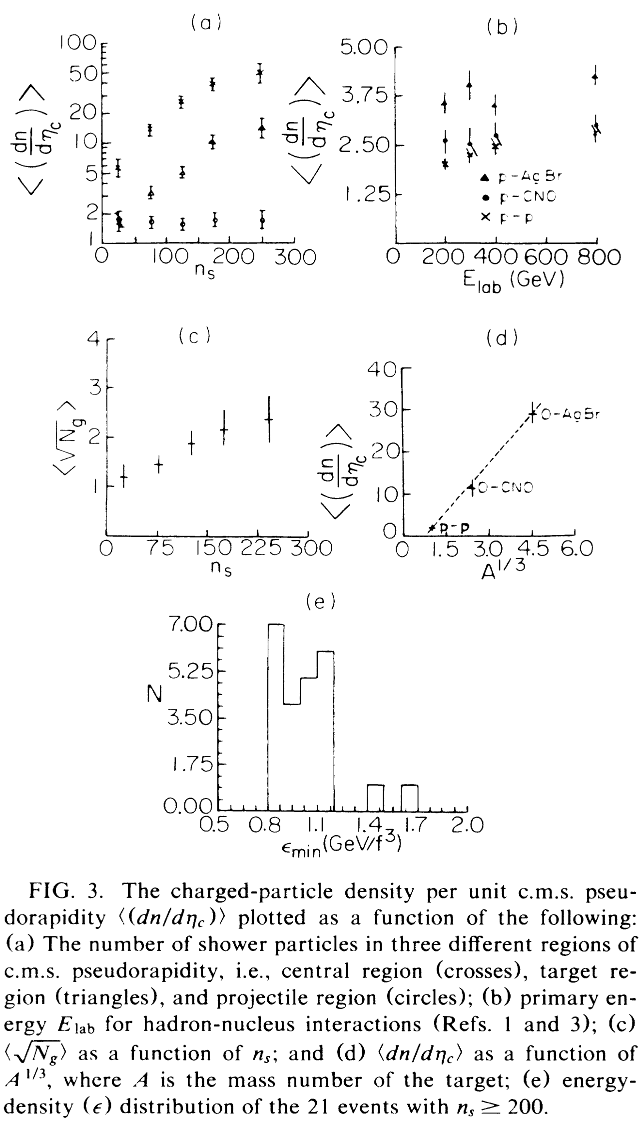

FIG. 3. The charged-particle density per unit c.m.s. pseudorapidity $\langle (dn/d\eta_c) \rangle$ plotted as a function of the following: (a) The number of shower particles in three different regions of c.m.s. pseudorapidity, i.e., central region (crosses), target region (triangles), and projectile region (circles); (b) primary energy E_{lab} for hadron-nucleus interactions (Refs. 1 and 3); (c) $\langle \sqrt{N_g} \rangle$ as a function of n_s; and (d) $\langle dn/d\eta_c \rangle$ as a function of $A^{1/3}$, where A is the mass number of the target; (e) energy-density (ϵ) distribution of the 21 events with $n_s \geq 200$.

In conclusion, we feel that data on the average multiplicities and the angular distributions of secondary particles presented here for the first time in central collisions of oxygen at 200 GeV/nucleon with emulsion will enhance the existing state of knowledge in the quest for quark-gluon plasma.

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[1]P. L. Jain, K. Sengupta, and G. Singh, Phys. Lett. B **187**,

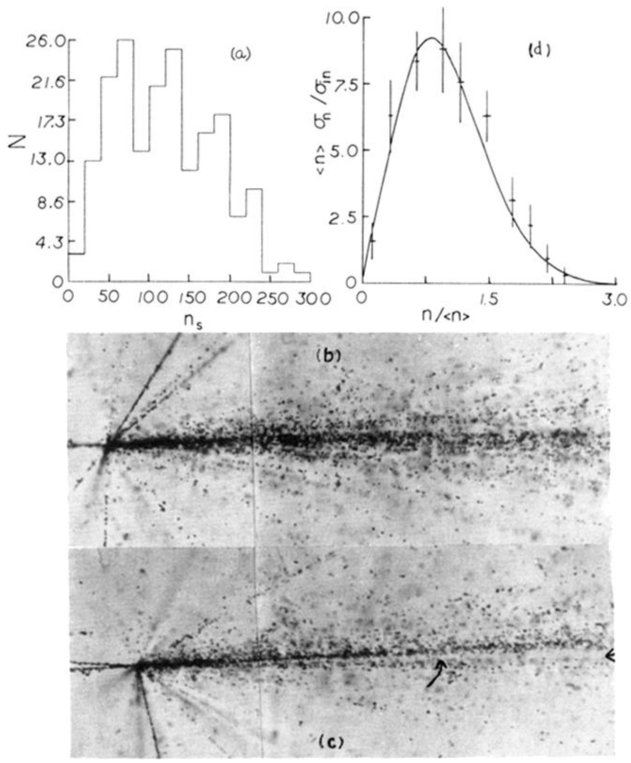
175 (1987).

[2]There is a probability that a small fraction of events assigned to light target (CNO) with $N_h < 8$ may actually belong to a heavy target (AgBr). For distinctive separation, see P. L. Jain *et al.*, Phys. Lett. **154B**, 252 (1985).

[3]P. L. Jain *et al.*, Phys. Rev. Lett. **34**, 972 (1977).

[4]M. K. Hegab *et al.*, Phys. Lett.**105B**, 103 (1981); W. Q. Chao *et al.*, Nucl. Phys. **A395**, 482 (1983); M. K. Hegab *et al.*, Nucl. Phys. **A384**, 353 (1982); B. Anderson *et al.*, Phys. Lett. **73B**, 343 (1978); P. L. Jain *et al.*, to be published.

[5]J. D. Bjorken, Phys. Rev. D **27**, 140 (1983); L. Van Hove, Z. Phys. C **27**, 135 (1985); Larry McLerran Fermilab Report No. Conf. 86/164-T, 1986 (unpublished); H. Satz, in *Proceedings of the Twenty-Third International Conference on High Energy Physics, Berkeley, California, 1986,* edited by S. Loken (World Scientific, Singapore, 1987).



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