Central Collisions of 14.6, 60, and 200 GeV/Nucleon ^{16}O Nuclei in Nuclear Emulsion

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Central collisions of ^{16}O nuclei with the ^{107}Ag and ^{80}Br nuclei in nuclear emulsion at 14.6, 60, and 200 GeV/nucleon are compared with proton-emulsion data at equivalent energies. The multiplicities of produced charged secondaries are consistent with the predictions of superposition models. At 200 GeV/nucleon the central particle pseudorapidity density is 58 ± 2 for those events with multiplicities exceeding 200 particles.

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The recent surge of interest in relativistic nucleus-nucleus (A-A) collisions has been driven by the possibility of observing a new state of matter,[1] a quark-gluon plasma. The critical energy density for quark-gluon plasma formation, $\epsilon \gtrsim 2$ GeV/fm^3, may be reached in central A-A collisions. In contrast, the conservative view is that A-A interactions can be explained as the superposition of many nucleon-nucleon (N-N) interactions in which a nucleus can be approximated as a cluster of free nucleons.[2,3] This view has evolved from the study of p-A collisions, for which superposition models have been shown to provide an adequate explanation of the experimental data.[4]

The acceleration of beams of heavy ions up to 200 GeV/nucleon allows this question to be addressed experimentally. Here we present results on particle production in central collisions of ^{16}O with Ag/Br nuclei, O-Ag/Br interactions, compare them to central collisions of protons with Ag/Br and to inclusive proton-emulsion (p-emul) interactions at similar energies,[5] and examine the consequences of interpreting these data in terms of models that describe A-A collisions as the superposition of N-N collisions.

Stacks of BR-2 emulsion pellicles with dimensions 5×10 cm$^2 \times 600$ μm were exposed horizontally at the Brookhaven National Laboratory to the 14.6-GeV/nucleon ^{16}O beam and at CERN to 60- and 200-GeV/nucleon ^{16}O beams. The emulsions were developed and then scanned with optical microscopes. An along-the-track scan located 1855 inelastic events, giving an interaction mean free path of 12.0 ± 0.3 cm, which corresponds to a total inelastic cross section of 1052 ± 26 mb. This is in good agreement with the calculated value of 12.2 cm ($\sigma = 1040$ mb),[6] indicating the high efficiency of the scanning.

Only events accompanied by a high excitation of the target nucleus were analyzed. An excited target nucleus evaporates low-energy fragments which produce heavily ionizing tracks (N_h) that are easily distinguished from the n_s relativistic secondaries, for which $I \leq 1.4 I_{min}$, corresponding to pion energies above 70 MeV and proton energies above 400 MeV. To provide a sample of small impact parameter, or "central," interactions occurring with the Ag or Br nuclei in emulsion, events with $N_h > 15$ and no $Z \geq 2$ fragments from the incident nucleus ($N_F = 0$) were selected. These central collisions represent $(17 \pm 2)\%$ of the total inelastic cross section and $(31 \pm 3)\%$ of the interactions with Ag and Br.

TABLE I. Central O-Ag/Br interactions with $N_h > 15$ and $N_F = 0$.

Energy (GeV/nucleon)	Number of events, N_{ev}	$\bar{n}_s$	$D(n_s)$	$\bar{N}_m$
14.6	75	49.3 ± 1.6	13.4 ± 1.1	41.3 ± 1.6
60	123	107.1 ± 3.2	35.3 ± 2.2	99.1 ± 3.2
200	120	171.8 ± 4.2	45.8 ± 3.0	163.8 ± 4.2

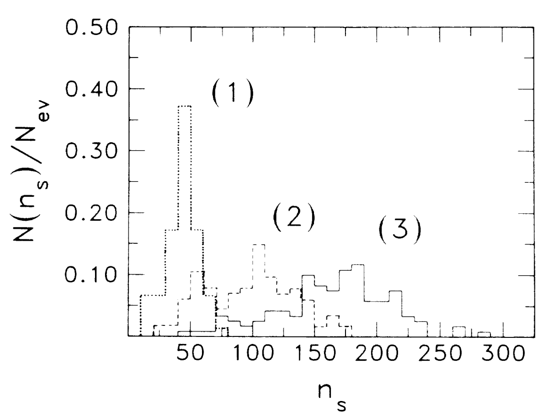

FIG. 1. Normalized shower-particle multiplicity distributions for O-Ag/Br central collisions at (1) 14.6, (2) 60, and (3) 200 GeV/nucleon.

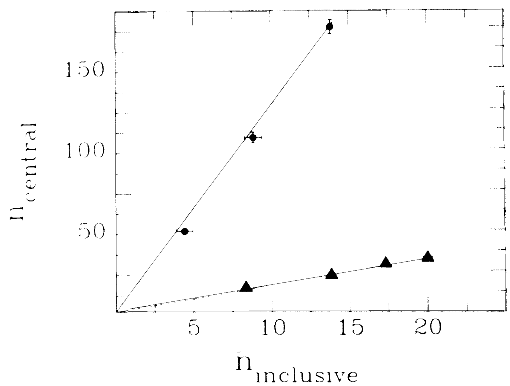

FIG. 2. Average multiplicities, $\bar{n}_{\text{central}}$, in central interactions of ^{16}O (circles) and p (triangles) on Ag/Br nuclei vs the average multiplicities, $\bar{n}_{\text{inclusive}}$, in inclusive p-emul collisions at the same energy. Lines are fits by $\bar{n}_{\text{central}} = A\bar{n}_{\text{inclusive}}$, where A is the ratio of the corresponding average numbers of interacting nucleons.

Table I gives the number of central collisions analyzed, the mean shower-particle multiplicity, $\bar{n}_s$, the dispersion of n_s, $D(n_s) = [\overline{n_s^2} - \bar{n}_s^2]^{1/2}$, and the mean meson multiplicity, $\bar{N}_m$ ($\bar{N}_m = \bar{n}_s - 8$, i.e., subtracting the eight projectile protons) at each energy. The n_s distributions are shown in Fig. 1. The dispersions of the multiplicity distributions are smaller than $\bar{n}_s$ due to the limited range of impact parameters for the central collisions. This leads to much smaller dispersions than observed for inclusive collisions (averaged over all impact parameters) for which $D \approx \bar{n}_s$.[3]

In order to compare the results with superposition models, we use the average number of interacting nucleons, $\bar{w} = (A\sigma_{pB} + B\sigma_{pA})/\sigma_{AB}$, where A and B are atomic masses of the colliding nuclei and σ_{pA}, σ_{pB}, and σ_{AB} are corresponding inelastic cross sections. For proton interactions, the average number of interacting nucleons is 3.5 ± 0.2 for inclusive p-emul and 5.9 ± 0.5 for central p-Ag/Br collisions.

The average multiplicities in central collisions of oxygen and proton projectiles are proportional to the average multiplicity in inclusive p-emul interactions as shown in Fig. 2, where the slopes of the lines represent the ratios $\bar{w}_{\text{cent}}/\bar{w}_{\text{incl}}$. From one-parameter linear fits in Fig. 2, ratios of 12.8 ± 0.6 and 1.65 ± 0.02 are obtained for central O-Ag/Br and p-Ag/Br collisions, respectively. With use of $\bar{w} = 3.5 \pm 0.2$ for inclusive p-emul interactions, the average number of interacting nucleons is 44.1 ± 3.2 for O-Ag/Br and 5.7 ± 0.3 for p-Ag/Br collisions.

The average number of interacting nucleons for ^{16}O collisions can be estimated independently[7] by applying the Glauber model. The maximum impact parameter corresponding to the data selection, calculated from the relative cross sections, is $b_{\max} = 4.0$–4.5 fm. This yields $\bar{w} = 41.5 \pm 2.0$ in good agreement with the previous estimate. Hence, we adopt $\bar{w} = 43 \pm 3$ for O-Ag/Br collisions.

Figure 3(a) shows the energy dependence of the average meson multiplicity per interacting nucleon compared to the energy dependence of the mean meson multiplicity in (p,p) collisions (dashed line), obtained from fits to charged pion and kaon data.[8] $\bar{N}_m/\bar{w}$ increases somewhat faster with energy than would be expected from the energy dependence of p-p multiplicities for both the A-A and

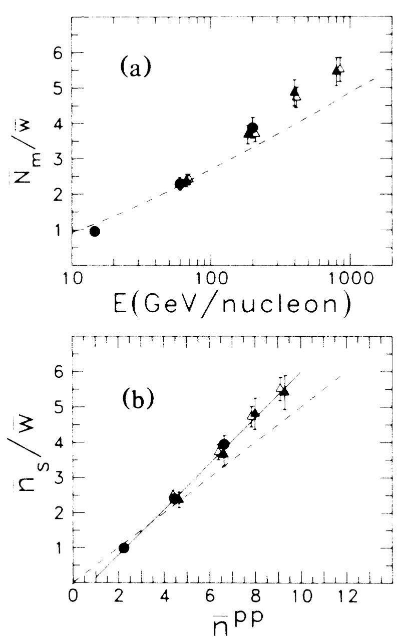

FIG. 3. Experimental results: circles, O-Ag/Br; open triangles, p-Ag/Br; and filled triangles, p-emul interactions compared to predictions of superposition models (dashed lines). (a) Energy dependence of the mean meson multiplicity per interacting nucleon, and (b) relates the mean shower-particle multiplicity per interacting nucleon to $\bar{n}^{pp}$, the produced charged-particle multiplicity $(\bar{n}_{\text{ch}}^{pp} - 1)$ measured in p-p collisions. (Note: Data points at the same energy have been shifted slightly for clarity.)

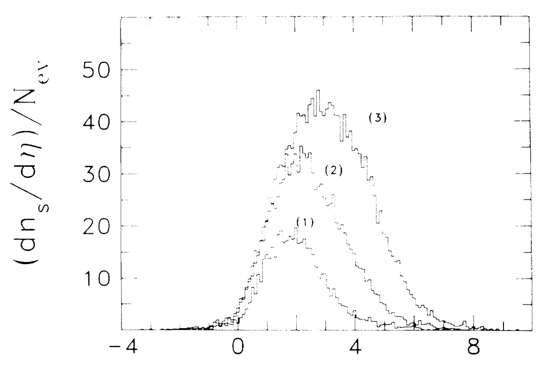

FIG. 4. Normalized pseudorapidity distributions in O-Ag/Br interactions at three energies: (1) 14.6, (2) 60, and (3) 200 GeV/nucleon.

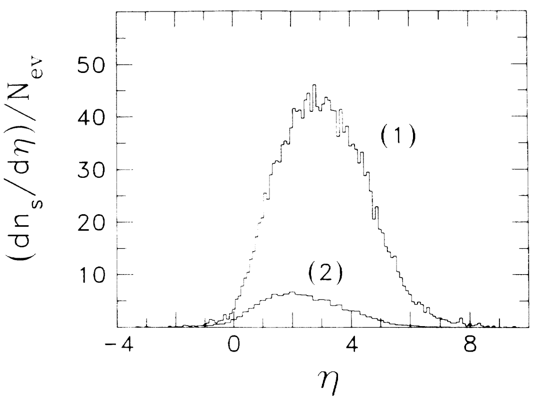

FIG. 5. Pseudorapidity distributions at 200 GeV/nucleon for (1) O-Ag/Br and (2) *p*-Ag/Br collisions.

p-*A* results.

To illustrate this point further, Fig. 3(b) shows the dependence of the average shower multiplicity per interacting nucleon on the proton-proton average multiplicity $\bar{n}^{pp}$. The fit to the experimental data shows that $\bar{n}_s/\bar{w}$ is a linear function of $\bar{n}^{pp}$, but increases faster than simple superposition models would predict (dashed curve). This behavior is indicative of some cascading within the nucleus, which is not observed in *p*-*p* results. However, the agreement of the *A*-*A* and *p*-*A* results in Fig. 3 suggests that O-Ag/Br collisions can be explained by the superposition picture.

The normalized pseudorapidity ($\eta = -\ln\tan\theta/2$) distribution for the secondary particles produced in the O-Ag/Br interactions are shown in Fig. 4. There is approximate scaling in the target fragmentation region, but the distributions shift toward larger η with increasing primary energy. The forward part of the η distributions contains both mesons and proton projectile fragments because they cannot be distinguished. Figure 5 compares the η distributions for particles produced in central O-Ag/Br collisions with *p*-Ag/Br data at 200 GeV/nucleon. The increase in particle production by heavy ions is evident over almost the entire range of η.

The highest-multiplicity events ($N_s > 200$) at 200 GeV/nucleon have a central pseudorapidity density of 58 ± 2. Assuming a normal average transverse momentum of 350 MeV/*c*, the energy density we calculated from Bjorken's formula[9] is still less than the estimated energy density required for a transition to a quark-gluon plasma phase.

Preliminary results from the analysis of small-impact-parameter (central) collisions of ^{16}O nuclei with Ag and Br in nuclear emulsion do not provide evidence for any unusual phenomena in the energy range 14.6–200 GeV/nucleon. A similar conclusion has been reported from a study of central O-Pb collisions by Bamberger *et al.* (NA35 Collaboration).[10] Our data on the average multiplicities, the dispersion of the multiplicity distributions, and the angular distributions of secondary particles can be adequately explained by the conservative picture of a nucleus-nucleus collision as a superposition of elementary interactions, providing allowance is made for some cascading within the nucleus. However, the average multiplicities and the single-particle angular distribution are rather insensitive to the dynamics of the collision process. In order to study whether new phenomena do occur in this mass-energy regime, it will be necessary both to obtain larger statistical samples and to make detailed analyses of individual events, searching for multiple-particle correlations and anomalous signatures.

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[1]E. V. Shuryak, Phys. Rep. **115**, 151 (1984); H. Satz, Annu. Rev. Nucl. Part. Sci. **35**, 245 (1985); J. Cleymans, R. V. Gavai, and E. Suhonen, Phys. Rep. **130**, 217 (1986).

[2]K. Kinoshita, A. Minaka, and H. Sumiyoshi, Prog. Theor. Phys. **61**, 165 (1975); A. Capella, C. Pajares, and A. V. Ramallo, Nucl. Phys. **B241**, 75 (1985).

[3]A. Bialas, M. Bleszynski, and W. Czyz, Nucl. Phys. **B111**, 461 (1977).

[4]J. E. Elias *et al.*, Phys. Rev. D **22**, 13 (1980); J. Babecki *et al.*, Phys. Lett. **52B**, 274 (1974); I. Otterlund, Nucl. Phys. **A418**, 87c (1984).

[5]J. Babecki *et al.*, Phys. Lett. **47B**, 268 (1973); J. Babecki *et al.*, Acta Phys. Pol. B **5**, 315 (1974); Alma-Ata–Leningrad–Moscow–Tashkent Collaboration, Yad. Fiz. **22**, 736 (1975) [Sov. J. Nucl. Phys. **22**, 380 (1975)]; E. G. Boos *et al.* (Alma-Ata–Gatchina–Moscow–Tashkent Collaboration) Nucl. Phys. **B143**, 232 (1978); J. Babecki *et al.*, Acta Phys. Pol. B **9**, 495 (1978); A. Abduzhamilov *et al.*, Phys. Rev. D **35**, 3537 (1987).

[6]F. Hagen, Ph.D. thesis, University of Maryland, 1976 (unpublished).

[7]T. W. Atwater, Ph.D. thesis, University of Minnesota, 1986 (unpublished).

[8]A. M. Rossi *et al.*, Nucl. Phys. **B84**, 269 (1975). [The fits for $\langle n_{\pi^+}\rangle$, $\langle n_{\pi^-}\rangle$, $\langle n_{K^+}\rangle$, and $\langle n_{K^-}\rangle$ in *pp* collisions are added to obtain $\langle n_\pi\rangle_{pp}$. Here $\bar{n}_{\rm ch}^{pp}$ is not used since it contains the interacting nucleon.]

[9]J. D. Bjorken, Phys. Rev. D **27**, 140 (1983).

[10]A. Bamberger *et al.* (NA35 Collaboration), Phys. Lett. B **184**, 271 (1987).