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Multiplicity and rapidity density in central collisions of 4.1 A GeV c^{-1} ^{22}Ne nuclei in nuclear emulsions

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Abstract. The multiplicity and pseudo-rapidity distributions of hadrons produced in central collisions of 4.1 A GeV c^{-1} ^{22}Ne nuclei in nuclear emulsion are studied. The KNO scaled multiplicity distribution of the produced hadrons is compared with the predicted distributions according to the Lund model, dual parton model (DPM) and the negative binomial law. The negative binomial method seems to offer a better representation of the experimental data at 4.1 A GeV c^{-1}. The energy density is calculated according to the Bjorken model and found to be less than the estimated energy density required for the transformation into the quark–gluon plasma phase.

1. Introduction

The recent surge of interest in relativistic nucleus–nucleus collisions has been driven by the possibility of observing a new state of matter (Shuryak 1984, Satz 1983, Cleymans *et al* 1986). Developments of theoretical models (Chin 1978, Shuryak 1980, Satz 1983) demonstrate the formation of new states of hadronic matter at extreme conditions which have been out of the domain of the traditional nuclear and particle physics. Most of these theoretical works commonly predict phase transitions of nuclear matter of confined hadrons into a quark–gluon plasma (QGP) at sufficiently high temperature (200–220 MeV), high energy density ($\geqslant$2 GeV fm^{-3}) and/or high baryon density (>0.5 fm^3), which may be reached in central nucleus–nucleus collisions. In contrast, the conservative view is that nucleus–nucleus interactions can be explained as a superposition of many nucleon–nucleon interactions in which a nucleus can be approximated as a cluster of free nucleons (Kinoshita *et al* 1975, Bialas *et al* 1977, Capella *et al* 1985). Since the formation and space-time evolution of a dynamical hadronic/nucleonic systems are commonly unclear for hadronic and QGP ensembles, experimental tests are vital not only to find clues of new states of matter, but also to understand dynamical aspects of high-density hadronization processes.

2. Experimental details

A stack of NIK-F1-Br-2 emulsion pellicles with dimensions 10×20 cm^2 $\times$ 600 μm was exposed horizontally to 4.1 A GeV c^{-1} ^{22}Ne beam of the Dubna synchrophasatron. Along the track scanning was carried out for the emulsions. The mean free path 'λ'

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† Deceased.

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for inelastic ^{22}Ne–Em interactions was calculated: $\lambda = 9.92 \pm 0.29$ cm. This value is very near to the mean-free-path value ($\lambda = 10.21$ cm) calculated according to Bardt–Peters' formula (Bradt and Peters 1950, Daniel and Durgaprusad 1962, Cleghorn *et al* 1972). For each event, the number of heavily ionizing particles N_h and relativistic charged shower particles n_s were carefully counted. Events accompanied by a high excitation of the target nucleus were analysed. Events with $N_h \geqslant 28$ were selected to provide a sample of small impact parameter, or 'central', interactions occurring with the Ag or Br nuclei in emulsion. These central-collision events represent $(7.33 \pm 0.99)\%$ of the total inelastic cross section and $(9.91 \pm 1.39)\%$ of the interactions with Ag and Br nuclei.

3. Results and discussion

Table 1 gives the mean shower particle multiplicity, $\langle n_s \rangle$, and the mean heavily ionizing particle multiplicity, $\langle N_h \rangle$, emitted in the central collision events of ^{22}Ne. For comparison we present the corresponding mean multiplicities for other incident nuclei (^{4}He, ^{12}C and ^{24}Mg) (Tolostov *et al* 1974, Mansy 1982, Hamed 1990) at nearly the same momentum/nucleon. The dependence of these average multiplicities on the projectile mass number, A_p, are presented in figures 1 and 2. From table 1 and figures 1 and 2, it is found that $\langle n_s \rangle$ is characterized by a relatively strong dependence on A_p, ($\langle n_s \rangle = 2.29 A_p^{0.81}$) while $\langle N_h \rangle$ appears to be, within the statistical errors, independent of A_p. The n_s multiplicity for central collisions of 4.1 A GeV c^{-1} ^{22}Ne–AgBr is Gaussian, as shown in figure 3. Figure 4 shows the multiplicity distribution of the produced hadrons on a KNO-scaling graph (Koba *et al* 1972). The dual parton model (DPM) (Capella *et al* 1987) and the Lund-model (Otterlund 1987) calculations for the case of 200 A GeV ^{16}O–^{202}Pb and 60 A GeV ^{16}O–Au, respectively, are shown on the same figure. One may notice that there is a deviation between the experimental data and the theoretical distributions. This observed deviation may be due the fact that the Lund and the dual parton models are constructed only for ultrarelativistic reactions and hence they do not offer a true representation of the presented data, since the energy of this work is not high enough. On the other hand, it may be noticed (in figure 5) that a better representation of the experimental data is offered by the negative binomial distribution curve (Hegab *et al* 1990).

The dispersion of n_s, $D(n_s) = [\langle n_s^2 \rangle - \langle n_s \rangle^2]^{1/2}$, is 7.1, from which the mean negative pion multiplicity $\langle N_{\pi^-} \rangle$ is deduced: $\langle N_{\pi^-} \rangle = 12.6$, $\langle N_{\pi^-} \rangle \simeq D_-^2$ (Aksineskov *et al* 1980). D_- is the dispersion of negative pion multiplicity related to $D(n_s)$ through

Table 1 The average multiplicities of shower particles, $\langle n_s \rangle$, and the heavily ionizing particles, $\langle N_h \rangle$, for the central collisions of different projectiles with Ag and Br nuclei at nearly the same momentum/nucleon.

Projectile	Momentum (A GeV c^{-1})	$\langle n_s \rangle$	$\langle N_h \rangle$	Reference
^{4}He	4.5	6.90 ± 0.30	32.00 ± 0.70	Tolostov (1974)
^{12}C	4.5	18.60 ± 0.70	33.40 ± 1.30	Mansy (1982)
^{22}Ne	4.1	26.85 ± 2.25	30.20 ± 1.08	This work
^{24}Mg	4.5	30.56 ± 1.76	34.00 ± 1.02	Hamed (1990)

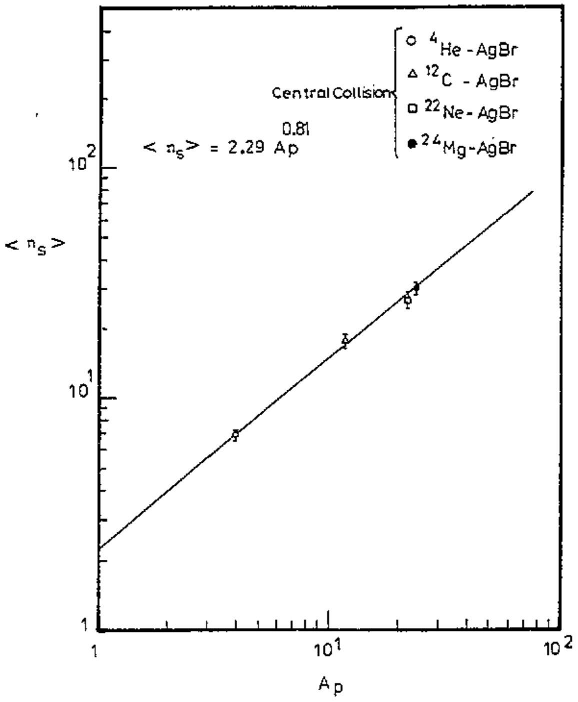

Figure 1. The dependence of the average multiplicity of shower particles, $\langle n_s \rangle$, on the projectile mass number, A_p, for the central collisions of different projectiles with Ag and Br target nuclei at nearly the same momentum per nucleon.

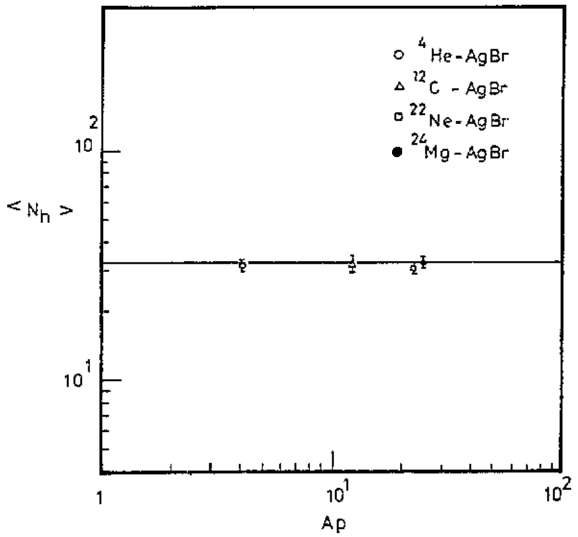

Figure 2. The dependence of the average multiplicity of heavily ionizing particles, $\langle N_h \rangle$, on the projectile mass number, A_p, for the central collisions of different projectiles with Ag and Br target nuclei at nearly the same momentum per nucleon.

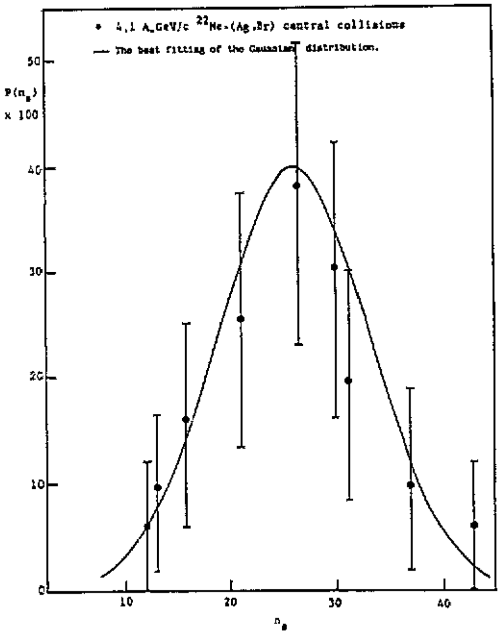

Figure 3. The multiplicity distribution of shower particles per event produced in 4.1 A GeV c^{-1} ^{22}Ne–Ag, Br central collisions. The solid curve is the best fitting of the Gaussian distribution.

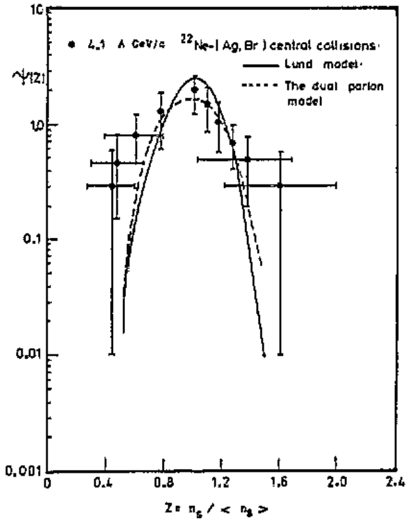

Figure 4. The KNO scaled multiplicity distribution of shower particles produced in 4.1 A GeV c^{-1} ^{22}Ne–Ag, Br central collisions. The solid and dashed curves are the corresponding distributions for 60 A GeV ^{16}O–Au and 200 A GeV ^{16}O–Pb central collisions predicted by the Lund model and the dual parton model calculations respectively.

the relation, $D_- = D(n_s)/2$ (Golokhvastov 1978). Our experimental value of D_- is compatible with the value deduced from the relation for central collision (Grin 1980),

$$D_- = [1.01\langle N_{\pi^-}\rangle_{A_1A_2} + \tfrac{1}{48}\langle N_{\pi^-}\rangle^2_{A_1A_2}]^{1/2}$$

where A_1 and A_2 represent the incident and target nuclei, respectively. Figure 6 shows the linear relationship found by Aksineskov *et al* (1980) between the values of D_-^2 and $\langle N_{\pi^-}\rangle$ produced in central collisions of ^{4}He, ^{12}C and ^{16}O projectiles with different target nuclei at 4.5 A GeV c^{-1} together with the corresponding present result for 4.1 A GeV c^{-1} ^{22}Ne–Ag, Br. Our experimental point nearly coincides with the straight line found by Aksineskov *et al* (1980).

The normalized pseudo-rapidity distribution ($\eta = -\ln\tan(\theta/2)$, θ = space angle) for the shower particles produced in ^{22}Ne–Ag, Br central collisions with $N_h \geqslant 28$ (dashed histogram) and $N_h \geqslant 35$ (solid histogram) are shown in figure 7. From this figure it can be shown that, within the statistical errors, $dn_s/d\eta$ for the $N_h \geqslant 35$ distribution is higher than the corresponding value for the $N_h \geqslant 28$ distribution in the spike bin. This means that the rapidity density increases as the centrality of the reaction increases. Also the $N_h \geqslant 35$ distribution ends before the distribution of events having $N_h \geqslant 28$, which indicates that the amount of energy transferred from ^{22}Ne to Ag, Br nuclei in the former distribution is greater than that in the latter one, i.e. the stopping power of the ^{22}Ne projectile in Ag, Br target nuclei for events with

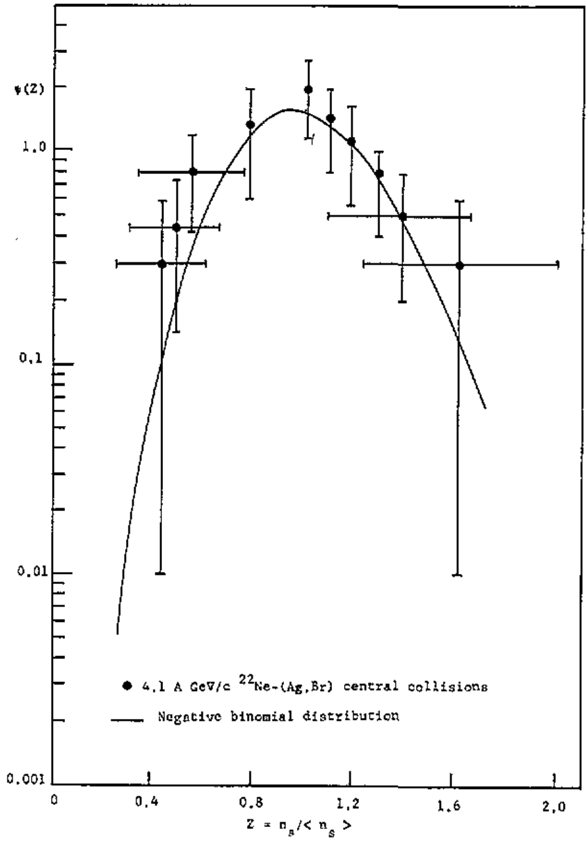

Figure 5. The KNO scaled multiplicity distribution of shower particles produced in 4.1 *A* GeV c^{-1} ^{22}Ne–Ag, Br central collisions. The solid curve is the prediction of the negative binomial distribution pertaining to the present ^{22}Ne projectile.

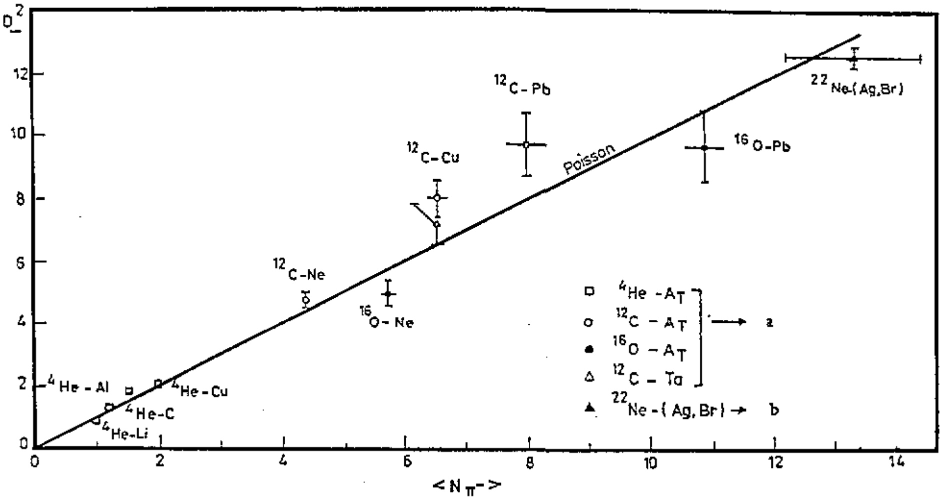

Figure 6. The dependence of D_- on $\langle N_{\pi^-}\rangle$ for the central collisions of ^{4}He, ^{12}C, ^{16}O with different target nuclei and ^{22}Ne with Ag, Br at nearly the same momentum/nucleon (4.5 *A* GeV c^{-1}): (a) Aksineskov (1980); (b) this work.

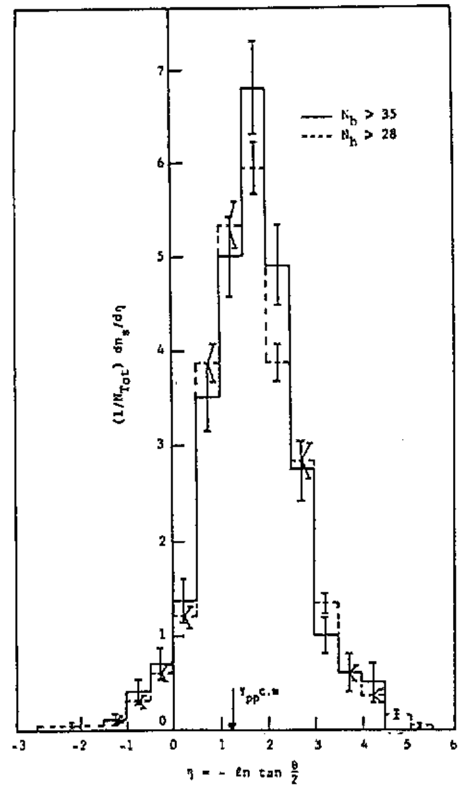

Figure 7. The pseudo-rapidity distribution, η, of the shower particles produced in $4.1\,A\,\mathrm{GeV}\,c^{-1}$ ^{22}Ne–Ag, Br central collisions.

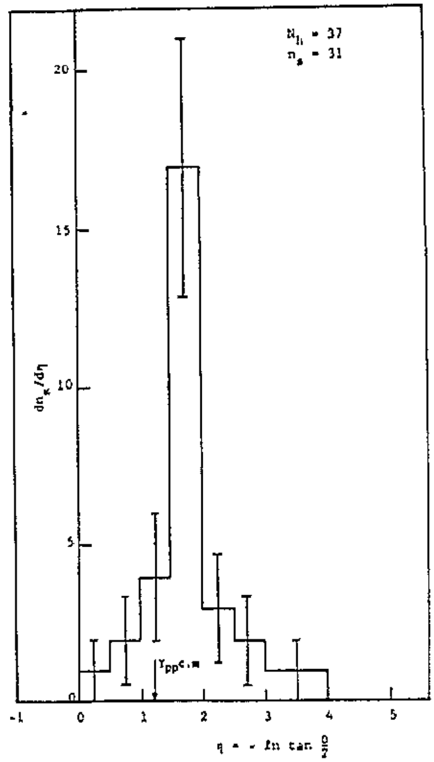

Figure 8. The pseudo-rapidity distribution, η, of the shower particles produced in one event with $N_h = 37$ and $n_s = 31$.

$N_h \geqslant 35$ is greater than the corresponding value for events with $N_h \geqslant 28$. This result is consistent with the nuclear stopping power discussed by Buza and Goldhaber (1984). Using Bjorken's formula for the energy density 'ε' (Bjorken 1983):

$$\varepsilon = \tfrac{3}{2}(\langle p_T\rangle^2 + m^2)^{1/2}\left(\frac{dn_s}{d\eta}\right)_{\eta_{cm}=0} / V$$

and taking $\langle p_T\rangle = 0.350\,\mathrm{GeV}\,c^{-1}$, and the volume $V = \pi A_p^{2/3}(1.18)^2\,\mathrm{fm}^3$ (A_p is the mass number of the projectile); our data gave $\varepsilon = 1.3\varepsilon_0$ and $1.44\varepsilon_0$ for events having $N_h \geqslant 28$ and $N_h \geqslant 35$, respectively (ε_0 is the cold nuclear density and equal to $0.145\,\mathrm{GeV\,fm}^{-3}$) (Gyulassy 1982). On an event-by-event basis, the highest-multiplicity event ($n_s = 31$, $N_h = 37$), having the narrower pseudorapidity distribution (figure 8), has a central pseudo-rapidity density = 22. Assuming a normal average transverse momentum = $0.350\,\mathrm{GeV}\,c^{-1}$, the energy density we calculated from Bjorken's formula ($\varepsilon = 2.5\varepsilon_0$) is still less than the estimated energy density required for a transition to a quark–gluon plasma phase ($\varepsilon = 5\varepsilon_0$).

The results obtained by Bjorken's model at the present energy may be somewhat surprising, since the model was constructed for much higher energies. Previous results (Barbier 1988) from the analysis of small impact parameter (central) collisions of ^{16}O nuclei with Ag, Br in nuclear emulsion do not provide evidence for any unusual phenomena. A similar conclusion has been reported from the study of central O–Pb collisions by Bamberger *et al* (1987).

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References

Aksineskov V D *et al* 1980 *Nucl. Phys.* A **348** 518
Bamberger A *et al* 1987 *Phys. Lett.* **184B** 271
Barbier L M *et al* 1988 *Phys. Rev. Lett.* **60** 405
Bialas A, Bleszynski, M and Cryz W 1977 *Nucl. Phys.* B **111** 461
Bjorken, J D 1983 *Phys. Rev.* D **27** 140
Bradt H L and Peters B 1950 *Phys. Rev.* **77** 54
Buza W and Goldhaber A S 1984 *Phys. Lett.* **139B** 235
Capella A *et al* 1987 *Phys. Rev.* D **35** 2921
Capella A, Pajares C and Ramallo A V 1985 *Nucl. Phys.* B **241** 75
Chin S A 1978 *Phys. Lett.* **78B** 552
Cleghorn T F, Freier P S and Waddington G J 1972 *Can. J. Phys. Soc.* **179** 488
Cleymans J, Gavai R V and Suhonen E 1986 *Phys. Rep.* **130** 217
Daniel R R and Durgaprusad N 1962 *Nuovo Cimento* **23S** 82
Golokhvastov A I 1978 *Sov. J. Nucl. Phys.* **27** 387
Grin Yu T 1980 *Sov. J. Nucl. Phys.* **32** 719
Gyulassy M 1982 *Nucl. Phys.* A **400** 31
Hamed A A 1990 *PhD Thesis* Faculty of Science, Cairo University
Hegab M K, Hussien M T and Hassan J 1990 *J. Phys. G. Nucl. Part Phys.* **16** 607 and references therein
Kinoshita K, Minaka A and Sumiyoshi H 1975 *Prog. Theor. Phys.* **61** 165
Koba Z, Nielsen H B and Olesen P 1972 *Nucl. Phys.* B **40** 317
Mansy M M 1982 *MSc Thesis* Faculty of Science, Cairo University
Otterlund I 1987 *Nucl. Phys.* A **461** 113C
Satz H 1983 *Nucl. Phys.* A **400** 541
Shuryak E V 1980 *Phys. Rep.* **61** 72 and references therein
Shuryak E V 1984 *Phys. Rep.* **115** 151
Tolostov K D *et al* 1974 *Communication of JINR Dubna* P1-8313