Evidence of multiplicity scaling of medium energy protons emitted in relativistic heavy ion collisions and antiproton annihilation in nuclei

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This paper presents an interesting observation, i.e., Koba-Neilsen-Olesen-type scaling in the multiplicity distribution of medium energy protons emitted as a result of ^{12}C-AgBr (emulsion) and central ^{24}Mg-AgBr (emulsion) interactions at 4.5A GeV/c and $\bar{\text{p}}$-AgBr (emulsion) reactions at 1.4 GeV/c. In all cases, the experimental points lie on the universal curve which can be fitted with a Koba-Neilsen-Olesen-type scaling function $\psi(Z=n_p/\langle n_p\rangle)=(4Z+34Z^3-5Z^5+0.35Z^7)\exp(-2.957Z)$.

Particular interest in the investigation of relativistic heavy ion collisions results from the expectation of collective phenomena, such as particle correlations, shock waves, or phase transitions, as characteristic features of nuclear matter beyond the production of excited baryonic and mesonic states by individual nucleon-nucleon collisions.

In the past, there had been a considerable amount of study on the characteristics of medium energy grey hadrons for hadron-mass A (h-A) interactions at relativistic energies.[1–3] It is generally believed that they are the low energy part of the internuclear cascade and leave the nucleus during or shortly after the passage of the incident nucleus (10^{-22} sec) and are collimated in the direction of motion of the primary beam. Due to the fact that they are emitted during or shortly after the passage of the leading projectile, they are expected to remember part of the history of the relation;[2] the studies of the behavior of the grey hadrons gained special attention. The validity of scaling for the multiplicity distribution of the grey hadrons was also tested, with a negative result, in the case of h-A interactions at accelerator energies.[3]

There has been considerable speculation on the types of exotic matter which may be formed in heavy ion collisions at high energies, where novel phenomena of the transient highly excited nuclear state may occur, being manifested through the emission of complex nuclear fragments during the expansion of an initially heated zone.[4] Furthermore, in the case of antiproton annihilation, it has been suggested by Rafleski[5] that data on $\bar{\text{p}}$ plus complex nucleus interactions may yield valuable information on the behavior of very hot nuclear matter. The exciting aspect of such interactions is the possibility of phase transition from (locally) very hot nuclear matter to a quark gluon plasma.

In this paper we have made an attempt to test whether protons emitted in the ^{12}C-AgBr, ^{24}Mg-AgBr, and $\bar{\text{p}}$-AgBr interactions obey any Koba-Neilsen-Olesen (KNO) type of scaling.

KNO scaling is a well-established empirical law for multiparticle production in high energy nondiffractive p-p collisions, and can be compared with the experimental data on the multiplicity distribution of target protons to see whether it favors the universal scaling law.

The probability distribution for the production of n charged particles in h-h collisions is observed to exhibit a universal behavior; hence one may expect

$$\langle n\rangle P_n=\gamma(n/\langle n\rangle)\ ,$$

where P_n is the probability of producing n charged particles, $\langle n\rangle$ represents the average number of charged particles, and ψ is some function variable $Z\ (=n/\langle n\rangle)$. This behavior of multiplicity distribution as a function of the variable Z is referred to as KNO scaling after Koba, Neilsen, and Olesen.[6]

Thus,

$$P_n=\frac{\sigma_n}{\sigma_{\text{inel}}}=\langle n\rangle^{-1}\psi(Z)\ , \tag{1}$$

independent of the energy of the incoming hadron and the atomic mass number A of the target nucleus. σ_n denotes the partial cross section for producing n charged particles, and σ_{inel} denotes the total inelastic cross section.

In terms of moments of the multiplicity distribution,

$$C_q=\langle n^q\rangle/\langle n\rangle^q=\text{constant}\ . \tag{2}$$

The constant C_q is independent of energy, where

$$\langle n^q\rangle=\sum_{n=2}^{\infty}n^q\sigma_n/\sigma_{\text{inel}}$$

is the qth moment of the multiplicity distribution (for $n=2$ we exclude the elastic contribution).

KNO scaling relates the experimental multiplicity distribution at different energies to one another, and it may also reflect specific properties of the hadronization phenomena.[7] Irrespective of the specific form of the scaling function ψ, KNO scaling leads to a linear relation between the dispersion D and the mean number $\langle n\rangle$

$$D(E)=[\langle n^2\rangle-\langle n\rangle^2]^{1/2}=\alpha\langle n\rangle(E)\ , \tag{3}$$

where α is some numerical constant. This equation has been well tested experimentally.[8] Jain *et al.*[9] have shown the scaling behavior in the multiplicity distribution of showers emitted in h-A and A-A interactions from 2–1000 GeV.

TABLE I. Values for $\langle n_p \rangle$, $D=[\langle n_p^2 \rangle - \langle n_p \rangle^2]^{1/2}$, $\langle n_p \rangle /D$, and C_2 and C_3 for ^{12}C-AgBr, ^{24}Mg-AgBr, and $\bar{p}$-AgBr interactions at 4.5 (GeV/c)/nucleon and 1.4 GeV/c.

Interactions	No. of events	$\langle n_p \rangle$	D	$\frac{\langle n_p \rangle}{D}$	C_2	C_3
^{12}C-AgBr at 4.5 (GeV/c)/nucleon	1000	3.09±0.07	2.21±0.07	1.36±0.07	1.51±0.026	2.34±0.062
$\bar{p}$-AgBr at 1.4 GeV/c	1205	2.29±0.05	1.80±0.05	1.27±0.05	1.62±0.021	2.19±0.044
^{24}Mg-AgBr at 4.5 (GeV/c)/nucleon	1000	19.20±0.35	11.30±0.35	1.69±0.35	1.49±0.20	2.029±0.26

The experimental data on ^{12}C-AgBr and ^{24}Mg-AgBr interactions have been obtained from the stacks of photoemulsion plates (NIKFI-BR 2) with dimensions 10 cm$\times$20 cm$\times$600 μm, irradiated by ^{12}C and ^{12}Mg beams of 4.5 GeV/c per nucleon initial momentum from the Dubna Synchrophasotron. Plates were scanned with the aid of a Leitz ortholux microscopic utilizing 100$\times$ oil emulsion objective and 20$\times$ ocular lens. The ^{12}C and ^{24}Mg events were chosen utilizing the following criteria:

(a) The beam track should be $<3°$ to the beam direction of the beam as observed in the pellicle.

(b) The interaction should not be within (top or bottom) 20 μm thickness of the pellicle.

Furthermore, all primary beam tracks were followed back to be sure that the events chosen did not include interactions from the secondary tracks of the other interactions. The grey tracks were selected for which $b^* \geq 1.4$, $g^* \leq 6$, where b^* is the normalized blob density and g^* is the normalized grain density. The tracks of such particles were followed to their end points and only those tracks were taken which did not show any signs of interaction or decay, to eliminate the grey tracks which are not due to protons. Furthermore, to eliminate those proton tracks which are the projectile fragments, only those tracks were considered which were in an angle greater than 5° with respect to the incident beam direction, i.e., with an emission angle $>5°$. Tracks due to deuterons and tritons were carefully eliminated from the sample of target protons. Each event was scanned by three independent observers to increase the scanning efficiency, which turned out to be 98%. In the above process 1000 events each were taken for analysis in the cases of ^{12}C-AgBr and ^{24}Mg-AgBr interactions. In the case of the ^{24}Mg-AgBr interaction, a bias was made to select only central collisions ($n_h > 25$, where n_h is the number of heavy tracks) to study the dependence of scaling behavior on central and noncentral AgBr collisions. The data (1205 events) for the $\bar{p}$-AgBr interaction at 1.4 GeV/c have been taken from the works of Breivik *et al.*[10]

It was found that the total multiplicity distribution of the target protons in $\bar{p}$-AgBr, ^{12}C-AgBr, and ^{24}Mg-AgBr interactions strongly deviated from the Poisson form.

Table I shows the values for the mean multiplicity distribution $\langle n_p \rangle$, the dispersion

$$D=(\langle n_p^2 \rangle - \langle n_p \rangle^2)^{1/2} ,$$

and $\langle n_p \rangle /D$, the ratio of the values of the qth multiplicity moment and qth power of the average multiplicity of the protons, for the ^{12}C-AgBr, ^{24}Mg-AgBr, and $\bar{p}$-AgBr interactions. The C_2 and C_3 values for $\bar{p}$-AgBr, ^{12}C-AgBr, and ^{24}Mg-AgBr are consistent with being constant within their statistical limits for target protons. It is interesting to note that the C_2 and C_3 values are in near agreement with the work of Areti *et al.* for p-emulsion interactions between 6.2 and 300 GeV, in the case of

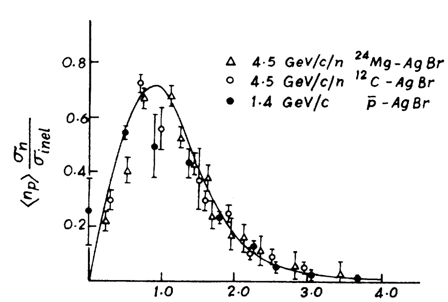

FIG. 1. Plot of n_p ($\sigma_n/\sigma_{\rm inel}$) and $n_p/\langle n_p \rangle$ for 4.5 (GeV/c)/nucleon ^{12}C-AgBr and ^{24}Mg-AgBr and 1.4 GeV/c $\bar{p}$-AgBr interactions.

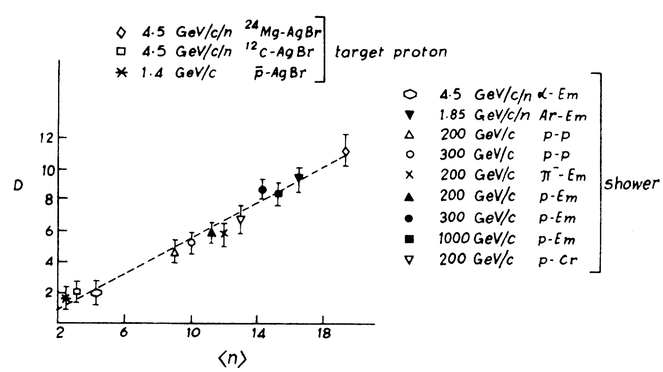

FIG. 2. Plot of D as a function of $\langle n \rangle$ for showers in the cases of 1.85 GeV/nucleon Ar emulsion, 200 GeV p-p, 300 GeV p-p, 200 GeV p emulsion, 300 GeV p emulsion, 200 GeV π^- emulsion, 200 GeV p-Cr, 4.5 GeV/c α emulsion, and for target protons in the cases of $\bar{p}$-AgBr at 1.4 GeV/c and ^{12}C-AgBr and ^{24}Mg-AgBr at 4.5 (GeV/c)/nucleon.

shower tracks.[11] The result is also in agreement with the work of Jain *et al.*[9] for ^{40}Ar emulsion at 1.85 GeV/nucleon, in the case of shower tracks.

In Fig. 1 we plot $\langle n_p \rangle (n/N)$ vs $n_p/\langle n_p \rangle$, i.e., $\langle n_p \rangle (\sigma_n/\sigma_{\rm inel})$ vs $n_p/\langle n_p \rangle$, where $\langle n_p \rangle$ denotes the average proton multiplicity, n denotes the total number of events with the same proton multiplicity $\propto \sigma_n$, N denotes the total number of events $\propto \sigma_{\rm inel}$ and n_p denotes the proton multiplicity for 4.5 GeV/c per nucleon ^{12}C-AgBr and ^{24}Mg-AgBr and 1.4 GeV/c $\bar{\rm p}$-AgBr interactions. The experimental points lie on the universal curve which can be fitted with the KNO type of scaling function

$$\psi(Z=n_p/\langle n_p \rangle)=(4Z+34Z^3-5Z^5+0.35Z^7)\times\exp(-2.957Z)\;. \quad (4)$$

The value of χ^2 between Eq. (4) and the experimental data points is 0.11/(degrees of freedom).

Figure 2 shows a plot of D as a function of $\langle n \rangle$ for showers in the cases of 1.85 GeV/nucleon Ar emulsion, 200 GeV/c p-p, 300 GeV/c p-p, 200 GeV/c p emulsion, 300 GeV/c p emulsion, 1000 GeV/c p emulsion (data taken from Ref. 9), 200 GeV/c π^- emulsion, 200 GeV/c p-Cr (author's data), 4.5 GeV/c α emulsion (data taken from Ref. 12), and for target protons in the cases of $\bar{\rm p}$-AgBr reactions at 1.4 GeV/c and in the cases of ^{12}C-AgBr and ^{24}Mg-AgBr interactions at 4.5 GeV/c per nucleon (the present work). A linear dependence for D is observed on $\langle n \rangle$ all cases.

From the above experiment we conclude that the KNO type of scaling behavior of the multiplicity distribution is well satisfied by all target protons produced due to ^{12}C-AgBr, ^{24}Mg-AgBr, and $\bar{\rm p}$-AgBr interactions at 4.5 (GeV/c)/nucleon and 1.4 GeV/c.

This KNO type of scaling behavior in the target proton multiplicity distribution might be a reflection of some unexpected or unknown phenomenon which occurs exclusively in relativistic nucleus-nucleus interactions or antiproton annihilation reactions.

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