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Characteristics of Pseudorapidity Distributions of Shower Particles Emitted in Interactions of silicon Nuclei with Nuclear Emulsion at 4.5 A GeV/c

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Key words

Heavy-ion collisions, hadronic phase, nuclear emulsion, pseudorapidity, quark-gluon plasma state (QGP).

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Abstract

The present study is based on the interactions caused by silicon nuclei with emulsion nuclei at 4.5 A GeV/c. The main aim is to study the characteristics of pseudorapidity distributions of shower particles emitted in the interactions. The pseudorapidity distributions of shower particles produced in the interactions was well fitted to the Gaussian distribution. The dependence of the pseudorapidity distributions on the projectile mass have been studied. Also, the dependence of the distributions on the target nuclei (AgBr and CNO) has been studied. The variations of the average of pseudorapidity with the average of shower multiplicity have been investigated. The energy density resulting from the interaction was estimated according to the Bjorken model. It was an insufficient energy density for the phase transition to the QGP state to occur.

1. Introduction

Nucleus-nucleus collisions are distinguished from hadron-hadron or hadron-nucleus collisions by the large amount of energy produced due to the multiple nucleon collisions within nuclear dimensions [1]. High-energy nucleus-nucleus collisions also provide extremely intense conditions of energy density and temperature. Therefore, the study of high-energy heavy-ion collisions has attracted the attention of scientists in recent years to investigate the behavior of matter under such conditions, particularly its transition from the normal state to the quark-gluon plasma state (QGP). The study of QGP has mainly

focused on two directions. The first direction focuses on studying heavy ion interactions at high temperatures and low baryon densities [2–6]. The second direction is focused on the study for the critical point of the phase transition of hadronic matter into the QGP state. For quark-gluon plasma state, the energy range is predicted to be between several GeV and several tens of GeV [7].Theoretical predictions show that a mixed phase of excited hadronic matter, consisting of free quarks and gluons, as well as protons and neutrons, forms at energies ranging from 4 to 11 GeV per nucleon [8-10].

Also the theoretical calculations have shown that quark matter can be formed when the temperature reaches the critical point $\approx 200Mev/c$ and energy density $\varepsilon \approx 15 - 25\ \varepsilon_0$ (where $\varepsilon_0 = 0.13GeV/fm^3$ is the energy density of normal nucleus) [11, 12].The study of multi-particle and pseudorapidity distributions in secondary particles is often used to search for quark-gluon plasma state, because the secondary particles are formed from a fireball of nuclear matter [13]. The pseudo-rapidity distribution of charged shower particles is a significant experimental observable. The investigation of this observable may enhance understanding of the characteristics of particles generated in collisions and the mechanisms of particle generation [14].
The aim of our analysis is to study the properties of pseudorapidity distributions of shower particles produced by high-energy nucleus-nucleus collisions, and their dependence on projectile and target mass. As well as in this study, the estimation of the energy density resulting from the collision of silicon nuclei with heavy elements (Ag, Br) in the nuclear emulsion has been investigated.

1- 1 Rapidity variable:
Rapidity variable is used to describe the motion of a particle and is defined by the energy (E) and longitudinal momentum (P_L) [15] :

$$Y = \frac{1}{2}\ln\left(\frac{E+P_L}{E-P_L}\right) \qquad (1)$$

1- 2 Pseudorapidity variable:
In several experiments, only the emission angle of the observed particle relative to the beam axis direction can be measured (θ). In this case, it is suitable to use this data by utilizing the pseudorapidity variable to describe the properties of the observed particle.
[15].

$$Y = \frac{1}{2}\ln\left(\frac{E+P_L}{E-P_L}\right) = \frac{1}{2}\ln\left(\frac{\sqrt{m^2+P^2}+P\cos\theta}{\sqrt{m^2+P^2}-P\cos\theta}\right) \qquad (2)$$

Where m, P are the mass and the momentum of the particle. At very high energy, $P >> m$ and it is:

$$Y = \frac{1}{2}\ln\left(\frac{P+P\cos\theta}{P-P\cos\theta}\right) = \frac{1}{2}\ln\left(\frac{1+\cos\theta}{1-\cos\theta}\right) = \frac{1}{2}\ln\left(\frac{2\cos^2(\theta/2)}{2\sin^2(\theta/2)}\right) \qquad (3)$$

$$Y \approx \ln(\tan(\theta/2)) \qquad (4)$$

The function ($Y \approx \ln(\tan(\theta/2))$) is called the pseudorapidity variable and it is usually denoted by η. At extremely high energy, the rapidity and pseudorapidity are nearly equal.

$$Y \approx \eta = \ln(\tan(\theta/2)) \qquad (5)$$

If the rapidity distribution of the particles is dN/dY, then the distribution of the pseudo-acceleration of these particles is $dN/d\eta$:

$$dN/d\eta = \sqrt{1 - \frac{m^2}{m_T^2\cosh^2 Y}}\,dN/dY \qquad (6)$$

Where m_T is the transverse mass of the particle.

2- Experimental Techniques:

The experimental data used in this study were obtained from exposing two stacks of the nuclear emulsions of type NIKFI-BR2. The first stack has dimensions (16.9 × 9.6 × 0.06) cm³, was exposed to a beam of silicon ions at 4.5A GeV/c, while the second stack has dimensions (18.6 × 9.5 × 0.06) cm³, and was exposed to a beam of carbon ions at the same energy at the Dubna Synchrophasotron in Russia. By using a Nikon microscope with 40× objectives and 15 × eye-piece, the traces were captured at 3 mm from the edge of the entry to the pile. In the observed collisions, all the charged secondary particles have been classified according to the relative speed β, the range L in the emulsion, and the relative ionization g^* into the following groups [16]:

- Shower tracks producing (s-particles) having a relative ionization $g^* \le 1.4$, with a relative speed of $\beta \ge 0.7$ and its multiplicity is denoted by N_s .
- Grey tracks producing (g-particles) having ($1.4 < g^* < 10$),($0.3 < \beta < 0.7$), and $R > 3mm$ and its multiplicity is denoted by N_g .
- Black tracks producing (b-particles) having ($g^* \ge 10$),($\beta \le 0.3$), and $R \le 3mm$ and its multiplicity is denoted by N_b .
- Heavily ionizing tracks producing (h-particles) are defined as the sum of gray and black tracks, and its multiplicity is denoted by N_h ,where $N_h = N_g + N_b$.

The emulsion nuclei have been classified according to the value of N_h into two groups of target nuclei [17]: light nuclei (CNO) with ($0 < N_h < 8$) and heavy nuclei (AgBr) with ($N_h \ge 8$). In this study, the experimental data for 700 interactions from Si^{28}-emulsion and 500 interactions from C^{12}-emulsion have been analyzed.

3- Results and Discussions

3-1 Pseudorapidity distribution of shower particles

The pseudorapidity distributions (η) of shower particles N_s resulting from the nuclear interactions (^{12}C,^{28}Si) with the nuclear emulsion at 4.5A GeV/c are shown in Fig. 1(a) and Fig. 1(b). The data was well fitted to the Gaussian distribution given by the following formula:

$$\rho(\eta) = \rho_{max} e^{-(\eta-\eta_{peak})/2\sigma^2} \qquad (7)$$

Where $(\sigma, \eta_{peak},, \rho_{max})$ are the distribution parameters, the standard deviation, peak position and highest density of the distribution respectively.

$\rho(\eta)$ is the pseudorapidity density and satisfies the normalization condition:

$$\int \rho(\eta) d\eta = \langle N_s \rangle \qquad (8)$$

The values of the distribution parameters which are calculated from equation (7) are presented in Table (1). The figures show that there is an excess of the particles above $\eta > 2.4$ in case of ^{12}C and in the case of ^{28}Si this excess of particles decreases with increasing projectile mass. The increase in the number of shower particles can be explained by the emission of fast protons from light nuclei, which appear in the emulsion as shower particles. Also it can be seen from Table (1) that there is a slight increase in the values of the parameters $(\sigma, \eta_{peak},, \rho_{max})$ with projectile masses.

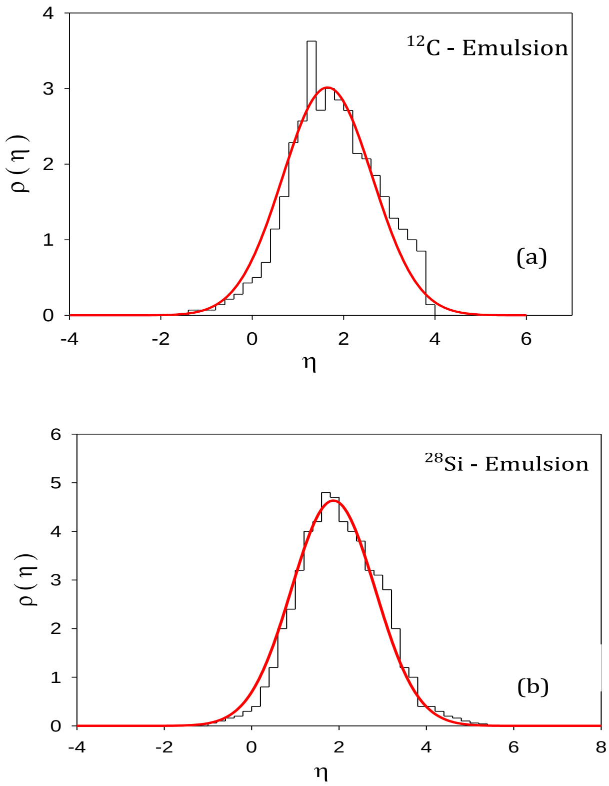

Fig. 1 (a, b): The pseudorapidity distributions of shower particles produced in interactions of (^{12}C, ^{28}Si) nuclei with emulsion at 4.5 A GeV/c.

Table 1: Values of the distribution parameters $(\sigma, \eta_{peak},, \rho_{max})$

The interaction	σ	η_{peak}	ρ_{max}
^{12}C-Emulsion	0.94	1.35	3.00
^{28}Si-Emulsion	1.02	1.87	4.64

To investigate the dependency of the pseudorapidity distributions on the target mass, the experimental results of shower particles emitted in the interactions of ^{12}C and ^{28}Si with target nuclei, AgBr and CNO, are presented in Fig. 2(a) and Fig. 2(b), respectively. For both interactions, the pseudorapidity distributions are seen to scale with the projectile mass in the target fragmentation region ($\eta < 1$). In the projectile fragmentation region ($\eta > 2$), the number of particles increase with the projectile mass.

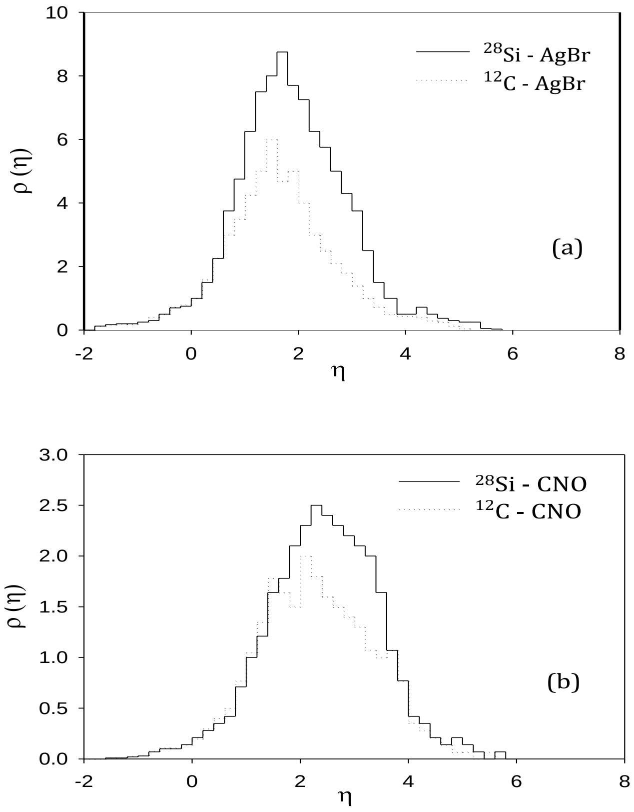

Fig. 2 (a,b): The pseudorapidity distributions of shower particles produced in interactions of (^{12}C, ^{28}Si) nuclei with target nuclei, AgBr and CNO at 4.5 A GeV/c.

Fig. (3) shows a comparison between the pseudorapidity distributions of shower particles emitted in interactions of ^{28}Si-AgBr and ^{28}Si-CNO.

It is clear from this figure that the peak distribution in the case of ^{28}Si-AgBr is higher than the peak distribution in the case of ^{28}Si-CNO. This is evidence that the interactions of the projectile with AgBr are more than the interactions with CNO. It is also noticed that the number of particles increases in the target fragment area. The same previous behavior was observed in Au interactions with the nuclear emulsion at 10.6 A GeV/c [18].

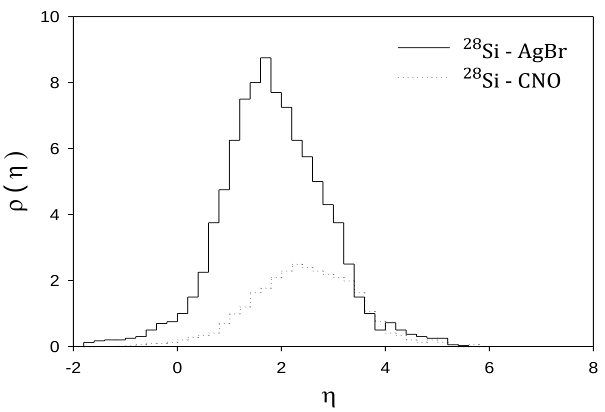

Fig. 3: The pseudorapidity distributions of shower particles produced in interactions of ^{28}Si nuclei with target nuclei, AgBr and CNO at 4.5 A GeV/c.

The relation between the mean of the pseudorapidity $\langle\eta\rangle$ and the mean of the shower particles $\langle N_s \rangle$ is presented in Figure (4), and it is clear from the figure that $\langle\eta\rangle$ decreases with an increase in $\langle N_s \rangle$. A linear fit of the experimental data has been made with the equation: $\langle \eta \rangle = a + b\langle N_s \rangle$ (9)

The values of constant (a, b) were calculated as follow: $a = 2.29 \pm 0.02$ *and* $b = -0.016 \pm 0.003$.

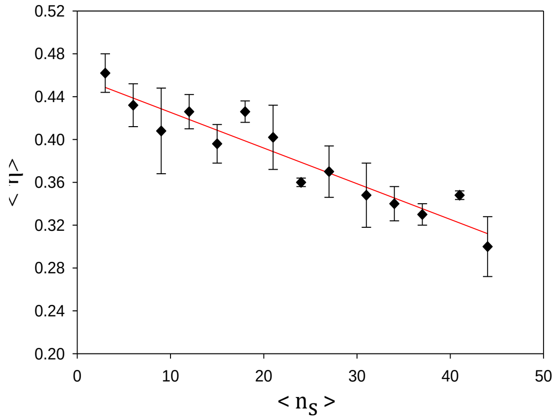

Fig. 4: The Variations of $\langle \eta \rangle$ with $\langle N_s \rangle$ in interactions of ^{28}Si -emulsion at 4.5 A GeV/c.

Also the dependence of shower width, $R(\eta)$ (the difference between the highest and lowest values of the pseudorapidity of the shower particles resulting from the interaction) on the average of multiplicity of shower particles, $\langle N_s \rangle$ has been investigated. Fig.5 shows the relation between $\langle R(\eta) \rangle$ and $\langle N_s \rangle$ and it was observed that this relation is not linear, but it has been shown to be well fitted by the equation: $\langle R(\eta) \rangle = c \ln\langle N_s \rangle + \mathrm{d}$ (10)
Where $c = 1.05$ *and* $d = 1.64$. This behavior has been observed by other researchers [19].

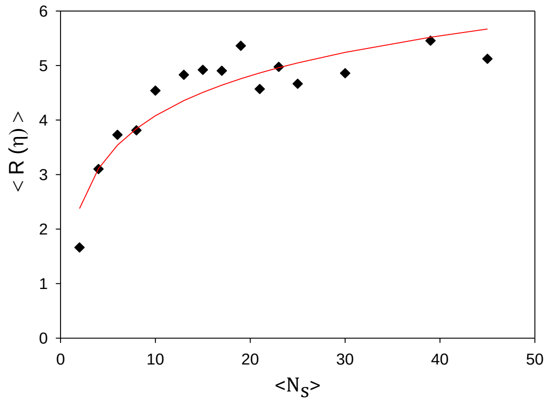

Fig. 5: the relation between $\langle R(\eta) \rangle$ and $\langle N_s \rangle$ in interactions of ^{28}Si -emulsion at 4.5 A GeV/c.

3-2 The search for the new phase of matter

To search for the new phase of matter (transition from hadronic state to quark-gluon plasma state (QGP)), the knowledge of energy density generated in intense collisions is essential for this particular investigation. The energy density (ε) resulting from highly relativistic nucleus – nucleus collisions is estimated using Bjorken's model [20]:

$$\varepsilon = \frac{3}{2}\sqrt{\langle P_T \rangle^2 + m_\pi^2}\left(\frac{dN_s}{d\eta}\right)V^{-1} \quad (11)$$

Where P_T is the transverse momentum $(\langle P_T \rangle = 0.350\ GeV/c)$, m_π is the mass of meson (π) and V is the volume of the smaller nuclei involved in the interaction $(V = \pi A^{\frac{2}{3}}(1.18)^2)$.

For this investigation the collisions of ^{28}Si ions with the nuclear emulsion at a momentum of 4.5A GeV/c have been used and the highest multiplicity, where the pseudorapidity distribution shows peak higher than the overall distribution, have been chosen. These conditions were obtained in the interactions having $N_s = 61$, $N_h = 34$ and $\left(\frac{dN_s}{d\eta}\right)_{max} = 30$ as shown in Fig. 6, where η is the normalized pseudorapidity.
$\eta = (\eta - \eta_{min})/(\eta_{max} - \eta_{min})$, where η_{max}, η_{min} are the maximum and the minimum pseudorapidities. From the value of maximum pseudorapidity density, the energy density is calculated using equation (11): $\varepsilon = 2.9\varepsilon_0$, it is an insufficient energy density for the phase transition to the QGP state to occur.
Table (2) presents a comparison of this value with some energy density values obtained by other researchers for different projectile-

target collisions.

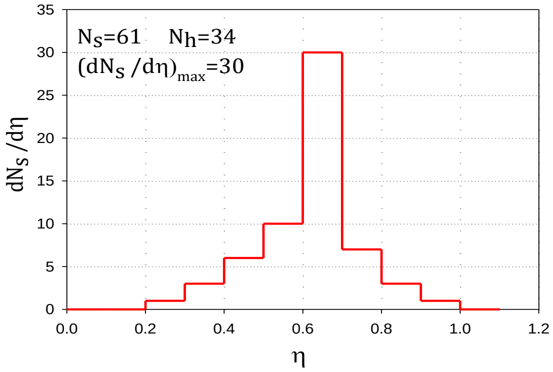

Fig 6: the normalized pseudorapidity distribution of shower particles produced in single event having $N_s = 61$, $N_h = 34$ in the interactions of ^{28}Si - AgBr at 4.5 A GeV/c.

Table 2: The energy density resulting from the collision of different projectiles with emulsion at similar momentum.

The interaction	momentum A GeV/c	energy density	Reference
^{22}Ne-emulsion	4.1	$\varepsilon = 2.5\varepsilon_0$	[21]
^{24}Mg-emulsion	4.5	$\varepsilon = 2.25\varepsilon_0$	[22]
^{28}Si-emulsion	4.5	$\varepsilon = 3.2\varepsilon_0$	[23]
^{28}Si-emulsion	4.5	$\varepsilon = 2.9\varepsilon_0$	Present work

4- Conclusion

To conclude, the investigation of characteristics of pseudorapidity distributions of shower particles emitted in interactions of silicon nuclei with emulsion nuclei at 4.5 A GeV/c found that the pseudorapidity distributions of shower particles can be well-fitted with a Gaussian distribution and the average of pseudorapidity decreases linearly with the increase in the average multiplicity of the shower particles.

The energy density (ε) resulting from the collisions of silicon nuclei with heavy nuclei (AgBr) in the nuclear emulsion was estimated using the Bjorken model, where it was found to be equal to $\varepsilon = 2.9\varepsilon_0$, which is not sufficient density for the transition from the hadronic phase to the QGP.

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خصائص توزيع الاسراع الزائف للجسيمات الر ذاذية المنبعثه من تفاعلات انويه السيلكون مع المستحلب النووي عند 4.5 AGeV/c

سليمه صالح ابوعزوم مصطفى عبدالسلام بن نصر فاطمه ابوزقيه حليمه الجمل
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الكلمات المفتاحية:
تصادمات الانويه الثقيله ، الطور الهادروني ، المستحلب النووي ، الاسراع الزائف ، حاله الكوارك قليون بلازما QGP.

الملخص

الدراسة الحالية تركزت على التفاعلات الناتجة عن انويه السيليكون مع انويه المستحلب النووي عند 4.5 AGeV/c. الهدف الرئيسي من هذه الورقة هو دراسة خصائص توزيعات الإسراع الزائف للجسيمات الرذاذية التي تنبعث في التفاعلات. البيانات على توزيعات الاسراع الزائف للجسيمات الرداديه المنبعثه في هده التفاعلات تم ملائمتها بشكل جيد مع توزيع جاوس. اعتماد توزيعات الإسراع الزائف على كتلة القديفه تمت دراستها. كدلك اعتماد هده التوزيعات على كتله انويه الهدف (AgBr وCNO) تمت دراسته. تم أيضاً في هذا العمل دراسة العلاقة بين متوسط الإسراع الزائف ومتوسط تعددية الجسيمات الرذاذية الناتجة من هذه التفاعلات. كما تم حساب كثافة الطاقة الناتجة من تفاعل أنوية السيلكون مع أنوية المستحلب عند الطاقات العاليه طبقا لنموذج Bjorken و كانت كثافة الطاقة غير كافية لحدوث الانتقال الطوري إلى حالة كوارك قليون بلازما.