Indication of Shock-wave in ^{12}C + Emulsion Interactions at 4.5 GeV per Nucleon

Dipak Ghosh, Jaya Roy*, and Ranjan Sengupta

High Energy Physics Division, Department of Physics,
Jadavpur University, Calcutta – 700032, India

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This paper presents a study of the angular distribution and two-particle angular correlation among 'black' and 'grey' particles produced in the interaction of ^{12}C nuclei with a photoemulsion at 4.5 GeV per nucleon. Experimental data are compared with Monte Carlo simulated values assuming independent emission. The observation of some short-range correlation among the target fragments may indicate shock-wave formation.

1. Introduction

Relativistic nuclear collisions may demonstrate interesting and exotic nuclear phenomena involving abnormally dense nuclear matter [1], meson condensation [2] or a phase transition to a quark gluon plasma [3]. For these nuclear effects to occur, some degree of equilibrium or collective interactions among the colliding nucleons must take place. With the increasing overlap volume of the nuclei, the reaction process becomes more complex. Experiments on the cumulative production of mesons [4] and the fragmentation of relativistic nuclei [5], and also on the hypotheses of the production of nuclear density isomers and the formation of nuclear shock-waves [6] indicates that the study of collisions of relativistic nuclei is extremely attractive from the point of view of obtaining new important information on the dynamics of strong interactions. Hydrodynamic calculations predict the formation and propagation of shock-waves when the nuclear sound velocity ($v \approx 0.2\,c$) is exceeded. The density perturbation causes the emission of particles from the nuclear surface having a velocity corresponding to the shock-wave propagation velocity. The idea that a nuclear shock-wave could be produced when a high energy particle moves through the nucleus was proposed by Glassgold et al. [7]. After that, many models were proposed and the common prediction of all the models is the preferential emission of target fragments perpendicular to the Mach shock front [8].

The predicted angular distribution of nuclear matter is different in different shock-wave models. Some models predict comparatively narrow peaks closely perpendicular to the conical shock front [9], whereas other models predict broad forward peaked distributions [10]. It is therefore important to investigate the correlations not only among the relativistic particles but also among particles resulting from the disintegration of the target nuclei. In the ideal case, when the well defined Mach Cone is developed, one may observe directions of preferential emission of nuclear matter, and such emission must lead to a "short-range" angular correlations among secondaries.

Here we present the angular distribution and two particle correlations among the slow particles produced in the interaction of relativistic ^{12}C nuclei with photoemulsion at 4.5 GeV per nucleon by comparing experimental data with those obtained by Monte Carlo simulation assuming independent emission.

2. Experimental

In our experiment the photoemulsion layers of NIKFI BR2 plates with dimensions 10 cm · 20 cm · 600 μm were irradiated in the High Energy Laboratory of JINR at Dubna by a ^{12}C beam with a momentum of 4.5 GeV per nucleon from the JINR Synchrophasotron. By double, fast and slow "along

* Present address: Regional Computer Centre, Jadavpur University Campus, Calcutta – 700032, India.

Reprint requests to Dr. Dipak Ghosh, 60/7 M.T. Road, Calcutta 700031, India.

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the track" scanning 1850 inelastic carbon interactions were recorded, from which 1000 ^{12}C + emulsion events were selected without any discrimination as to angular measurements and further analysis. The plates were scanned by Leitz-Ortholux microscopes provided with a Brower travelling stage, utilising the following optics: 100× oil immersion objective and 20× occular lens. The events were chosen utilising the criteria:

a) the beam track should be at $< 3°$ to the beam direction of the beam as observed in the pellicle;
b) the interaction should not fall within a top or bottom layer of 20 μm thickness of the pellicle.

In accordance with the conventional emulsion terminology, the charged secondary particles were classified into the following types:

i) black track or short range particles (B) with range $l < 3$ mm;
ii) grey track particles (G) with $l > 3$ mm and ionization $g > 1.4\,g^0$, where g^0 is the plateau grain density for singly charged particles, except particles of type (iv). The tracks due to projectile fragments (iv) were eliminated from the sample after their identification.
iii) relativistic (S) particles with $g < 1.4\,g^0$;
iv) doubly charged projectile fragments, with a constant $g \approx 4\,g^0$ along the track length of 2 cm ionization, and $\theta < 5°$ (θ is the emission angle in the lab. frame).

3. Method of Analysis

In this investigation we make a search for shock-wave formation based on

a) the angular distribution and angular correlation of black and grey particles,
b) the two-particle correlation among black and grey particles.

3.1. Two Particles Correlation

We investigate the two particle correlation by using the standard correlation function

$$C(z_1, z_2) = \frac{1}{\sigma_{in}} \frac{d^2\sigma}{dz_1\, dz_2} - \frac{1}{\sigma_{in}^2} \frac{d\sigma}{dz_1} \cdot \frac{d\sigma}{dz_2}, \quad (1)$$

where

$$\sigma_{in}, \quad \frac{d\sigma}{dz} \quad \text{and} \quad \frac{d^2\sigma}{dz_1\, dz_2}$$

are the inelastic cross section, the single and the two particle distributions, respectively.

For the black and grey particles we take $\cos\theta$ as the variable z, so that (1) becomes

$$C(\cos\theta_1, \cos\theta_2) = \frac{1}{\sigma_{in}} \frac{d^2\sigma}{d(\cos\theta_1)\, d(\cos\theta_2)} - \frac{1}{\sigma_{in}^2} \frac{d\sigma}{d(\cos\theta_1)} \frac{d\sigma}{d(\cos\theta_2)} = \frac{N_2(\cos\theta_1, \cos\theta_2)}{N} - \frac{N_1(\cos\theta_1)\, N_1(\cos\theta_2)}{N^2},$$

where $N_1(\cos\theta)$ is the number of black or grey particles with $\cos\theta$ between $\cos\theta$ and $\cos\theta + d(\cos\theta)$, $N_2(\cos\theta_1, \cos\theta_2)$ is the number of pairs of black and grey particles with $\cos\theta$ between $\cos\theta_1$, $\cos\theta_1 + d(\cos\theta_1)$ and $\cos\theta_2$, $\cos\theta_2 + d(\cos\theta_2)$ in the same event, and N is the total number of inelastic interactions in the sample.

The normalised correlation function can be defined as

$$R(z_1, z_2) = \frac{\dfrac{1}{\sigma_{in}} \dfrac{d^2\sigma}{dz_1\, dz_2} - \dfrac{1}{\sigma_{in}^2} \dfrac{d\sigma}{dz_1} \cdot \dfrac{d\sigma}{dz_2}}{\dfrac{1}{\sigma_{in}^2} \dfrac{d\sigma}{dz_1} \dfrac{d\sigma}{dz_2}}. \quad (2)$$

For black and grey particles with $z = \cos\theta$:

$$R(\cos\theta_1, \cos\theta_2) = \frac{\dfrac{1}{\sigma_{in}} \dfrac{d^2\sigma}{d\cos\theta_1\, d\cos\theta_2} - \dfrac{1}{\sigma_{in}^2} \dfrac{d\sigma}{d\cos\theta_1} \cdot \dfrac{d\sigma}{d\cos\theta_2}}{\dfrac{1}{\sigma_{in}^2} \dfrac{d\sigma}{d\cos\theta_1} \dfrac{d\sigma}{d\cos\theta_2}} = \frac{N\, N_2(\cos\theta_1, \cos\theta_2)}{N_1(\cos\theta_1)\, N_2(\cos\theta_2)} - 1, \quad \text{as before.}$$

3.2. Monte-Carlo Simulation

In studies of correlation functions, pseudocorrelations arise from the broad multiplicity (n) distribution, the dependence of the one particle spectrum on the multiplicity and the trivial correlations due to kinematical constraints in the individual events. In the framework of an independent emission model $^{12}C + A$ interactions were simulated by the Monte-Carlo method and the correlation function was generated for the simulated events.

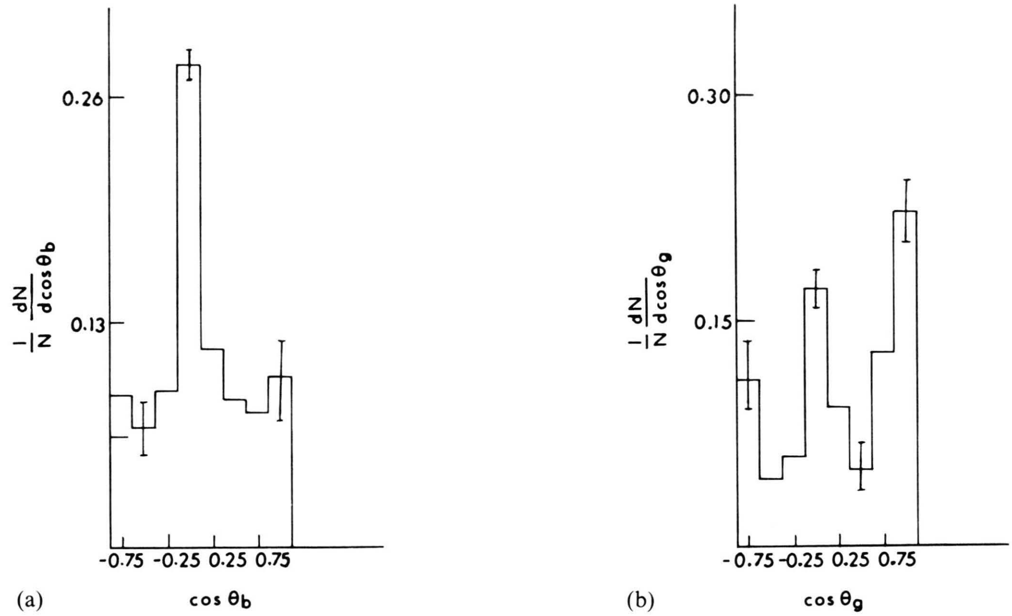


Fig. 1. Angular distribution of a) black particles, b) grey particles.

The simulation was based on the following assumptions:

a) particles of all types are emitted independently of each other;
b) the multiplicity distribution in each ensemble of Monte Carlo events reproduces the empirical multiplicity spectrum of the real ensemble;
c) the angular distribution of all types of particles coincides with the empirical 'semi inclusive' (i.e. at fixed n_s, n_b and n_g) one particle distribution.

Due to the lack of precise knowledge of the energy and momentum of the system, in our case of ^{12}C + Emulsion interactions there is no other way but to use a random sampling method on the corresponding experimental distribution to generate Monte-Carlo events. It may be noted that this method has been successfully applied for hardron + nucleus and nucleus + nucleus interaction before [11].

Gulamov et al. [12] have compared correlation functions C calculated from inclusive ensembles of random events generated according to the method adopted here, i.e. the Independent Emission Model (IEM), with the correlation function C generated according to the Cylindrical Phase Space Model (CPSM) [which gives the contribution of correlations due to kinematics] and observed that the conservation laws led to an increase of long-range and a decrease of short-range correlations. Therefore any observation of an excess of short range correlations over the predictions of the IEM will indicate the presence of dynamical effects which cannot be explained by the conservation laws. Moreover, the differences between the experimental results and model predictions will increase if we take into account the conservation laws in the form dictated by the statistical theory of multiple production.

By comparing the correlation function (C) and the normalised correlation function (R) obtained from experiment (separately for black and grey particles) with C_M and R_M obtained from the Monte-Carlo simulated events, one can search for the dynamical contribution to the correlation. The differences $C_D = C - C_M$ and $R_D = R - R_M$ (dynamical surplus) can be interpreted as a manifestation of dynamical correlations.

4. Results and Discussion

Figure 1 shows the single particle inclusive distributions with respect to $\cos\theta$ for a) black, b) grey tracks.

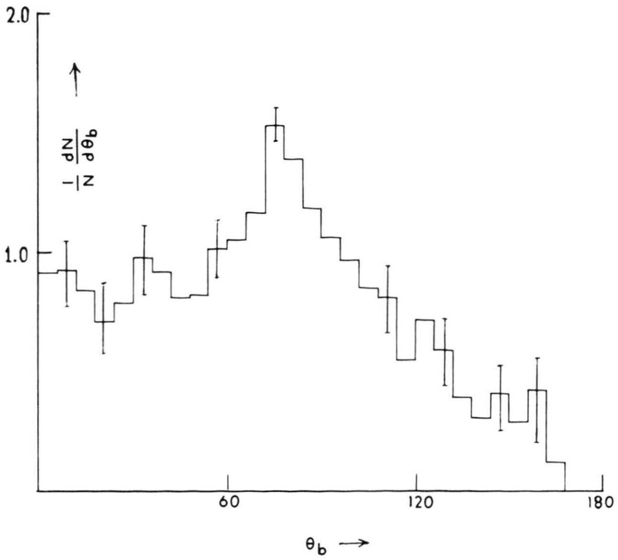


Fig. 2. Distribution of the angle between the black tracks.

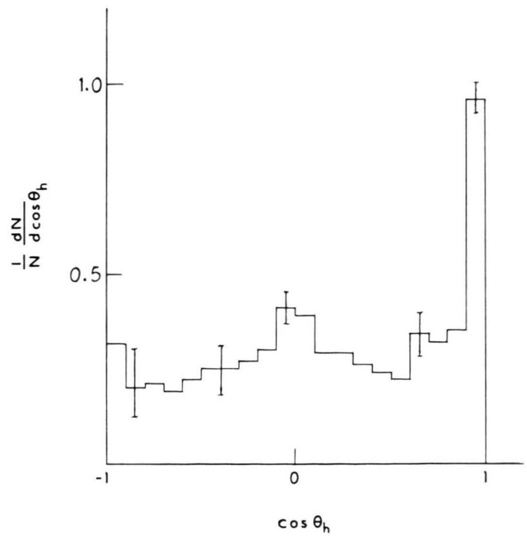


Fig. 4. Distribution of the angle between the heavy tracks.

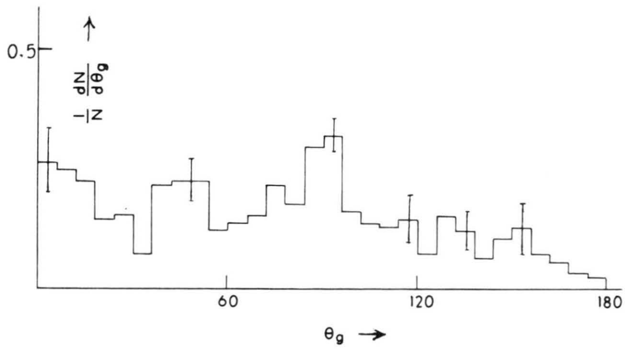


Fig. 3. Distribution of the angle between the grey tracks.

The angular distribution for the black particles has an F/B ratio (F is the total number of particles with emission angle $\leqq 90°$, and B is the total number of particles with emission angle $> 90°$, both in the laboratory frame) of about 1.94, which is smaller than the corresponding ratio for grey particles ($F/B_{grey} \approx 2.01$). The obtained ratio is not in good agreement with an estimated F/B ratio based upon the assumption of evaporation theory for isotropic emission in the system of the excited target nuclei. The distribution shows a marked anisotropy due to a high peak in the region $\cos\theta = 0$.

Similarly, in the angular distribution of the grey particles, three enhancements are observed, a large one in the region of $\cos\theta = 1$ and the other two in the region $\cos\theta = 0$ and $\cos\theta = -0.75$. This infers that the emission of some grey particles is anisotropic. The F/B ratio (≈ 2.01) is also high for a slowly moving excited nucleus. Both distributions reflect 'forward collimation'.

Figures 2, 3 and 4 show the distributions of the angle between the black, grey and heavy (grey + black) tracks. It is a test where each observed event contributes as many time to an angular distribution as given by the number of charged secondary particles of the event. The first contribution is the angular distribution with respect to the track No. 1 (arbitrarily assigned), the second contribution is the angular distribution with respect to track No. 2, and so on. Since by means of this procedure an angle θ between two tracks is repeated as an angle $360 - \theta$, the distributions have been folded at 180 degrees. The angular correlations of the black, grey and heavy tracks were measured and it was observed that each secondary track has more partners in the forward direction, i.e. within $0° - 90°$.

The distribution of the angle between the black tracks shows an enhancement in the region of $66° - 90°$. The other enhancement, which is not so appreciable, appears in the region of $30° - 42°$. This reveals that a track has more partners in the regions of $66° - 90°$ and fewer partners at greater angles.

In the distribution of the angle between the grey tracks there is a large enhancement in the region of

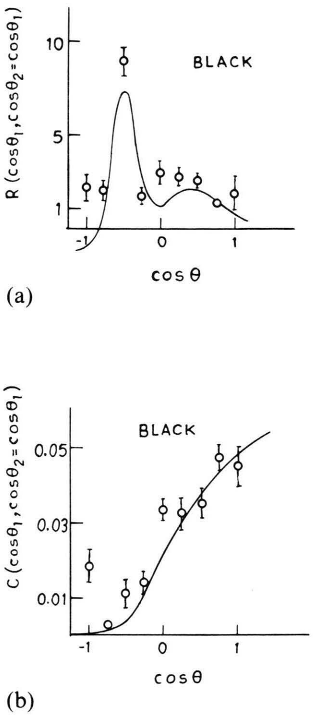


Fig. 5 (a, b). Two particle correlation function of black particles (R and C).

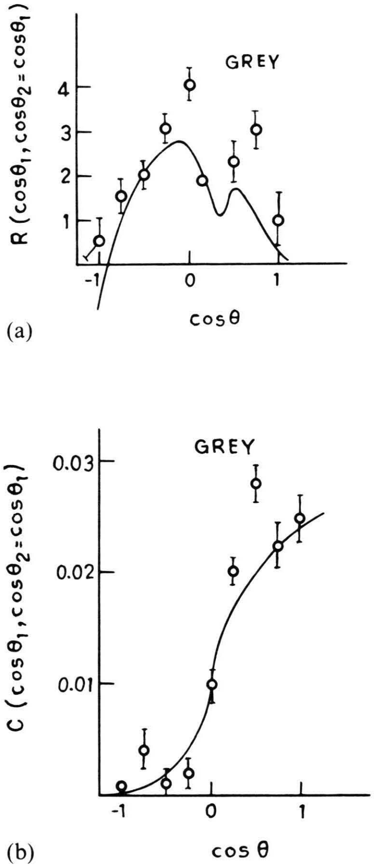


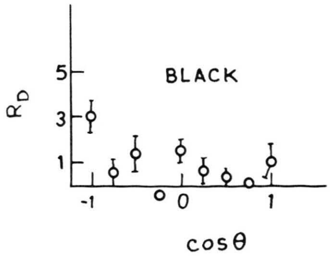
Fig. 6 (a, b). Two particles correlation function of grey particles (R and C).

84° − 96°; other enhancements, which are small, occur in the regions 0° − 18° and 36° − 54°. The distribution shows no peak in the region above 96°, indicating the presence of more partners of a track in the forward hemisphere.

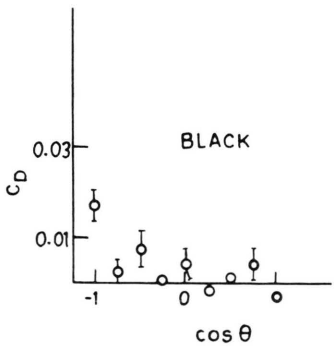
The distribution of the angle between heavy tracks shows a major enhancement in the region of $\cos\theta = 1$ and a small enhancement in the region of $\cos\theta = 0$. This indicates that there exists a small angle correlation between the heavy tracks. There is also a correlation in the region of 90°, which is not so prominent. This kind of anisotropic distribution indicates that the evaporation theory fails.

A similar analysis has been performed by Breivik et al. [13] to search for shock-waves in case of the $\bar{p}$ + AgBr reaction at 1.4 GeV per nucleon. From the angular distribution, they have also observed indications of some anisotropic process in the nuclear matter, possibly shock-waves.

The two particle correlations (both R and C) of black and grey tracks, along with the Monte-Carlo simulated values, are shown in Figs. 5 (a, b) and 6 (a, b). It can be observed that the values of the diagonal elements of the correlation matrices for black and grey tracks for the real events are not in agreement with those for the simulated ones. The corresponding values for the 'dynamical surplus' (C_D and R_D) are shown in Figs. 7 (a, b) and 8 (a, b). This indicates that the experimental data do not agree with the hypothesis of independent emission of these particles. The observed excess correlation over the Monte-Carlo background is statistically significant. This result is in agreement with our previous work on ^{16}O + Emulsion interaction at 2.1 GeV per nucleon [11], where such a short-range correlation was found to exist and contradicts the work of Chernov et al. [14] on ^{14}N − Emulsion interaction at 2.1 GeV per nucleon.

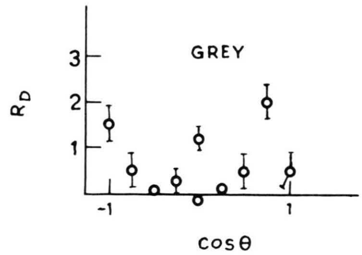


(a)

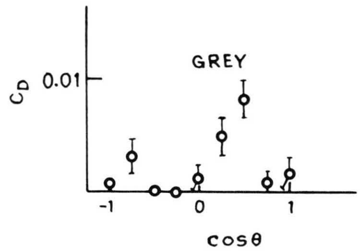


(b)

Fig. 7 (a, b). "Dynamical surplus" (C_D and R_D) of black particles for the cases shown in Figure 5 (a, b).



(a)



(b)

Fig. 8 (a, b). "Dynamical surplus" (C_D and R_D) of grey particles for the cases shown in Figure 6 (a, b).

5. Conclusion

The overall forward collimation due to some anisotropic fast process in the emission of the charged non relativistic target fragments and the existence of a short-range correlation between the slow particles from the excited target nuclei may indicate the presence of nuclear shock-waves in nucleus-nucleus interactions.

Although more data at different energies and a more comprehensive analysis in terms of models of the reaction dynamics are required to arrive at a definite conclusion, this analysis of the ^{12}C + Emulsion interaction data at 4.5 GeV per nucleon presents a positive indication of the presence of the shock-wave phenomenon in relativistic heavy ion interactions.

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