Search for Ring and Jet-like Structures in Particle Emission from High-energy Nucleus-nucleus Collisions

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ABSTRACT

In this paper, we investigate the ring like and jet like structures in the distribution of secondary charged hadrons coming out of ^{16}O-Ag/Br and ^{32}S-Ag/Br interactions at an incident momentum of 200A GeV/c each. Nuclear photographic emulsion technique has been used to collect the experimental data. Results from the experiment were compared with Monte Carlo simulations. The investigation shows presence of jet-like structures in the distributions of secondary charged hadrons.

1. INTRODUCTION

The central objective of studying high-energy nucleus-nucleus (*AB*) collision is to squeeze and heat two nuclei so hard as to create a color deconfined Quark-gluon Plasma (QGP) like state of matter under the controlled conditions of a laboratory [1]. It is speculated that the universe might have been filled up with such a state of matter right after (within a few μsec) its birth, and one may still be able to find it out at the core of a very dense compact star. The space-time evolution of an *AB* collision can be broadly divided into three sub-stages namely, (i) a very short lived pre-equilibrium stage, (ii) a comparatively longer lived thermally equilibrated fireball stage during which depending on the initial conditions a deconfinement may or may not take place, and (iii) the longest lived freeze-out stage during which the final state particles come out of the collision debris. A probable phase transition from the QGP like state to the final state of hadronic matter may manifest itself in the form of large local density fluctuations of produced particles.

One hypothesis behind observing such high density of particles in narrow intervals of phase space is the emission of conical gluonic radiation, which is an outcome of a partonic jet travelling through the nuclear medium. The phenomenon is similar to the emission of Cherenkov electromagnetic radiation [2]. An alternative approach however, may be to consider the formation of a Mach shock wave travelling through the nuclear medium that may also result in preferential emission of final state hadrons [3,4]. In either case, the emission pattern is characterized by a conical structure defined through a semi-vertex angle (α) as,

$$\cos\alpha = \frac{c_{med}}{v} = \frac{c}{nv} \tag{1}$$

where, depending on the case c_{med} is either the velocity of the gluons, or it is the velocity of sound wave, v is the velocity of the partonic jet that triggers Cherenkov gluon / shock wave emission, and n is the refractive index – all values pertaining to the nuclear medium. Under favorable circumstances this original conical structure may be preserved withstanding the impact of collision. If the initial / triggering parton direction is same as the incident beam direction, and if the number of gluons – each emitting a minijet is large, then under the above condition one may observe ring like structures in the distribution of particles that are clustered within a narrow region of pseudorapidity (η), but distributed more or less uniformly over the azimuthal angle (φ). On the other hand, if the number of jet emitting gluons is small, then it is more likely that several jets, each restricted to narrow intervals in both η and φ directions, will be formed, thereby resulting in jet structures in the distribution of final state hadrons. Ring like structures were first studied in a cosmic ray experiment [5]. Later in several accelerator based experiments involving high-energy *AB* interactions ring and/or jet like structures were further investigated [6-10]. In the present study we investigate the presence of such substructures in the distributions of final state charged hadrons in ^{16}O-Ag/Br and ^{32}S-Ag/Br interactions at 200A GeV/c. The organization of the paper goes as, section 2 – the experimental aspects, section 3 – the statistical and computational methods adopted, section 4 – a description of our results, and section 5 – a critical discussion of the outcome of the investigation.

2. EXPERIMENT

The experimental data used in the present analysis have been obtained from the stacks of Illford G5 nuclear photo-emulsion pellicles of size 18cm × 7cm × 600μm, that were horizontally irradiated by the ^{16}O and ^{32}S beams, each with an incident momentum 200A GeV/c from the super-proton synchrotron (SPS) of CERN. Leitz microscopes with total magnification 300× have been used to scan the plates along the projectile tracks to find out primary interactions. Angle measurement and counting of tracks were performed under a total magnification 1500× with the help of Koristka microscopes. According to the emulsion terminology, tracks emitted from an interaction (called a star) are classified into four categories namely, shower, grey, black tracks, and projectile fragments. The shower tracks are due to singly charged produced particles moving with relativistic speed (> 0.7*c*, *c* is the velocity of light) caused by the charged mesons, mostly pions. Total number of such tracks in an event is denoted by 'n_s'. Our analysis is confined only to the shower tracks, and we have considered only a sample of central events with small impact parameters, imposed by the condition $n_s > 150$ for the ^{16}O events and

$n_s > 250$ for the [32]S events. The sample size respectively, are $N_{ev} = 88$ and 74, while the average shower multiplicities are $< n_s > = 192.86 \pm 3.25$ and 312.83 ± 3.98, respectively. Total fragmentation of the projectile nuclei has taken place in each event of the considered samples. At the present incident energy scale (≈200A GeV), care should be taken regarding the contribution coming from γ-conversion into e^+e^- pairs, which may lead to strong unwarranted correlations, thereby causing inflation in the values of parameters sensitive to such correlations. Following the methods and arguments given in [11] we may infer that such contribution is kept at the minimum. In an emulsion experiment η together with φ of a track constitutes a convenient pair of basic variables in terms of which the particle emission data can be analyzed. η is an approximation of the dimensionless boost parameter rapidity (y) of a particle, and it is related to the emission angle (θ) of the corresponding track as, $\eta = -\ln\left(\tan\frac{\theta}{2}\right)$. An accuracy of $\delta\eta = 0.1$ unit and $\delta\varphi = 1$mrad could be achieved through the reference primary method of angle measurement. Nuclear emulsion experiments in spite of its many limitations are superior to other big budget experiments in one respect, that they offer a very high angular resolution. When distributions of particles within small phase space regions are to be examined, this certainly is an important advantage. The details of an emulsion experiment including the event and track selection criteria can be found in [12, 13]. The single particle density functions denoted by, $\rho(\eta) = \frac{1}{N_{ev}}\left(\frac{dn_s}{d\eta}\right)$ and $\rho(\varphi) = \frac{1}{N_{ev}}\left(\frac{dn_s}{d\varphi}\right)$ were obtained.

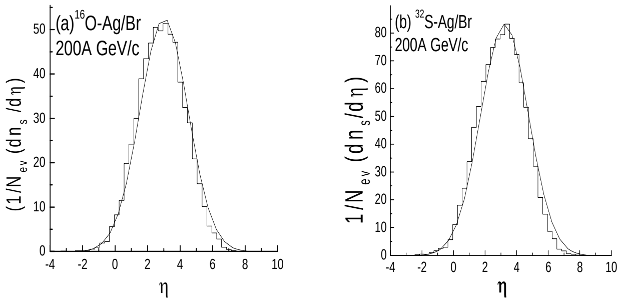

Figure 1. Pseudorapidity distribution of shower tracks (a) in [16]O-Ag/Br and (b) in [32]S-Ag/Br interactions at 200A GeV/c. The histograms represent experiment and the continuous curves are the respective Gaussian fits to data.

For each set of experimental data while a Gaussian function like $\rho = \rho_0 \exp\left[-\frac{(\eta - \eta_0)^2}{2\sigma_\eta^2}\right]$ represents the η-distribution well (see Figure 1), the φ-density within statistical uncertainties, is found to be uniformly distributed between $\varphi = 0$ and 2π. Values of the Gaussian fit parameters for the [16]O-sample are, the peak density $\rho_0 = 52.62$, the central value $\eta_0 = 3.01$, and the distribution width $\sigma_\eta = 2.97$ whereas, for the [32]S-sample $\rho_0 = 83.40$, $\eta_0 = 3.24$, and $\sigma_\eta = 3.05$. At same incident energy per nucleon a lower η_0 value indicates more stopping in [16]O induced interactions than in the [32]S induced interactions.

3. METHODOLOGY

In literature there exist several methods by which dense clusters of particles in an event can be characterized. While distributing over a suitable (or a set of) phase space variable(s), they appear in the form of rapidly fluctuating density functions. In the resultant distribution, often trivial statistical noise is combined with one or more dynamical effect(s), and it is not always an easy task to separate out one from the other. One way to do so is to generate random values of η and φ, and assign them to an event according to its shower track multiplicity. The random data set can serve the purpose of the statistical background, as neither any ring nor a jet structure is present as an input to generate these numbers. In the present investigation we adopt the method prescribed in [6], and start with a fixed number n_d of particles (shower tracks). Each n_d-tuple of particles put consecutively along the η-axis, is then characterized by a size $\Delta\eta_d = \left|\eta_{i+n_d-1} - \eta_i\right| : 1 \le i \le (n_s - n_d + 1)$, a mean $\eta_m = \sum \eta_i / n_d$ and a density $\rho_d = n_d / \Delta\eta_d$. Thus each subgroup of particles, dense or dilute, has the same multiplicity and hence can be easily compared with each other. The azimuthal structure of a particular subgroup can now be parametrized in terms of the following quantities,

$$S_1 = -\sum \ln(\Delta\varphi_i) \quad \text{and} \quad S_2 = \sum (\Delta\varphi_i)^2. \tag{2}$$

Here $\Delta\varphi$ is the φ-difference of two neighboring particles belonging to a subgroup (starting from first and second, and ending at n_d-th and first). One can, for example, measure $\Delta\varphi$ in units of a complete revolution (2π). Note that both S_1 and S_2 are small $(S_1 \to n_d \ln n_d$ and $S_2 \to 1/n_d)$ for ring-like structures and are large $(S_1 \to \infty$ and $S_2 \to 1)$ for jet-like structures. While S_1 is sensitive to small gaps, S_2 is sensitive only to large gaps. The expectation values of these parameters under a purely stochastic scenario, where particles are emitted independently without any correlation are,

$$\langle S_1 \rangle = n_d \sum_{k=1}^{n_d-1} \frac{1}{k} \quad \text{and} \quad \langle S_2 \rangle = \frac{2}{n_d + 1}. \tag{3}$$

Corresponding distributions would be peaked around these expectation values. Presence of jet-like substructures would result in bulging and small local peaks in the distribution to the right side of the mean, whereas ring-like substructures would do the same to the left. A direct comparison between the experimental data and that representing an independent emission can be made by computer simulations. Experimental φ-distribution being uniform between 0 and 2π one can generate its stochastic equivalent by generating (pseudo) random numbers between 0 and 2π. This was done with the help of a simple recursive linear congruential sequence [14],

$$X_{n+1} = (a * X_n + C) * \mathrm{mod}(m): \; n \ge 0. \tag{4}$$

Here X_n is the sequence of random numbers, m is called the modulus, a $(0 < a < m)$ is the multiplier, C $(0 \le C < m)$ is the increment, and X_0 is the seed/initial value. Similarly, the η density is normally distributed. Following the inverse of integral method the Gaussian distributed random numbers were generated, where a variable transformation from Cartesian (x, y) to Polar (r, ϑ) became necessary. The Gaussian distributed random numbers had the same centroid, peak density and width as the corresponding experimental set. Each pair of randomly generated (η, φ) will now represent a particle/track, and all such doublets, equal in number as the corresponding experimental set, was assigned to individual events according to their multiplicity n_s. The data analysis, simulation, documentation and drawing of graphs were all done in HP and IBM (P-IV) Desktop and Laptop Computers using the Lahey-Fujitsu95 FORTRAN compiler, and software packages like Microsoft Excel-2007 and Microcal Origin 7.0.

4. RESULTS

For the ^{16}O events our ring-jet analysis is confined to events samples having $n_s > 150$ with the choice of $n_d = 20$ and $n_s > 250$ with $n_d = 30$ for the ^{32}S events. For two different choices of n_d values, the expected stochastic mean values are $\langle S_1 \rangle \approx$ 71 and 119, and $\langle S_2 \rangle \approx$ 0.095 and 0.065, respectively. Distributions of $S_1/\langle S_1 \rangle$ and $S_2/\langle S_2 \rangle$ are for the ^{16}O events given in Figure 2 for the ^{16}O-data, where the experimental and stochastic results are shown together. The same graphical plots for the ^{32}S-data can be found in Figure 3.

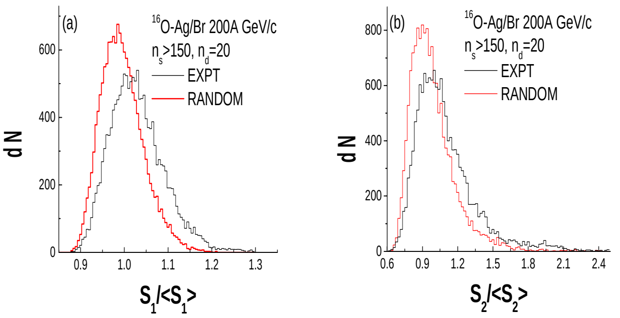

Figure 2. Distributions of (a) $S_1/\langle S_1 \rangle$ and (b) $S_2/\langle S_2 \rangle$ in ^{16}O-Ag/Br interactions at 200A GeV/c.

As expected and as can be seen from these diagrams, the stochastic distributions are peaked around unity, and in comparison with experiment they are more smoothly varying. In all cases the peaks of the randomly generated distributions are taller than the experimental one, and each experimental distribution is broader than the respective random number generated distribution. With a sharp rise and a slow fall, the distributions are asymmetric (left skewed), and the asymmetry is more pronounced in the experimental distributions. In each case, for the random distribution the rising part left to the peak is higher and the falling part right to the peak position is lower than those of the corresponding experimental distributions. Thus the large S_1 and S_2 values which correspond to jet like structures, cannot be generated by a random number based stochastic model as abundantly as in the experiment. In the right side of the respective experimental peaks, one can find bulging and/or smaller peaks that are more pronounced than the random number prediction.

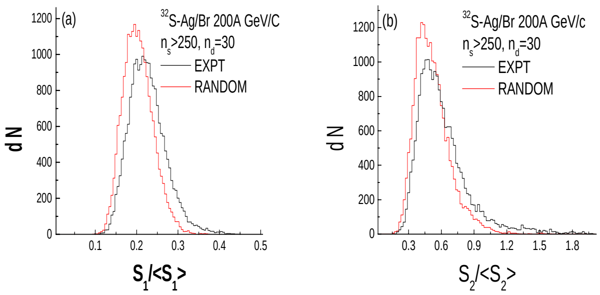

Figure 3. Distributions of (a) $S_1/\langle S_1 \rangle$ and (b) $S_2/\langle S_2 \rangle$ in ^{32}S-Ag/Br interactions at 200A GeV/c.

In Figure 4, graphical plots of average S_1 and S_2 against the cluster size $\Delta\eta_d$ for both types of interactions have been made, where the stochastic expectation represented by a solid line in each graph, the random number generated values, and the experimental values are plotted together. One can see that, the random number generated values lie more or less along the stochastic expectation line, whereas, the experimental values lie consistently above of both of them. Once again the inadequacy of independent emission to replicate the experimental observation can be seen.

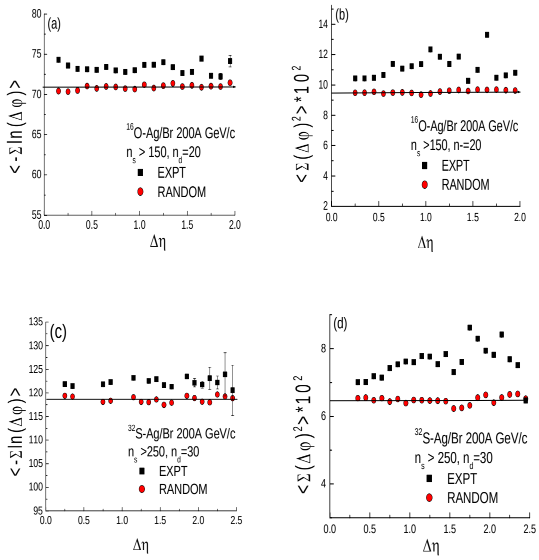

Figure 4. Plot of $\left\langle -\sum \ln(\Delta\varphi) \right\rangle$ and $\left\langle \sum (\Delta\varphi)^2 \right\rangle$ vs. $\Delta\eta$.

The size of the jet / ring like substructures (if there is any) can be investigated by the $\Delta\eta_d$ distributions. For both types of interactions under consideration, these distributions are graphically plotted in Figure 5 and 6. A distinction between the ring and jet structure has been made by separately plotting $S_2/\langle S_2\rangle < 1$ and $S_2/\langle S_2\rangle > 1$ regions. These distributions are once again left skewed, having a sharp rise and a comparatively long falling region to the right hand side of the peak. The width of experimental distribution in each case is more or less same as that of the random number generated distribution. For the ^{16}O-data one can however, see that the clusters of small size have an experimental surplus over the statistical noise, whereas, clusters of large size are more or less reproducible by the random numbers. On the other hand, in ^{32}S-data the distributions except for a very narrow region near the peak for the $S_2/\langle S_2\rangle < 1$ case are always very close to the random number prediction.

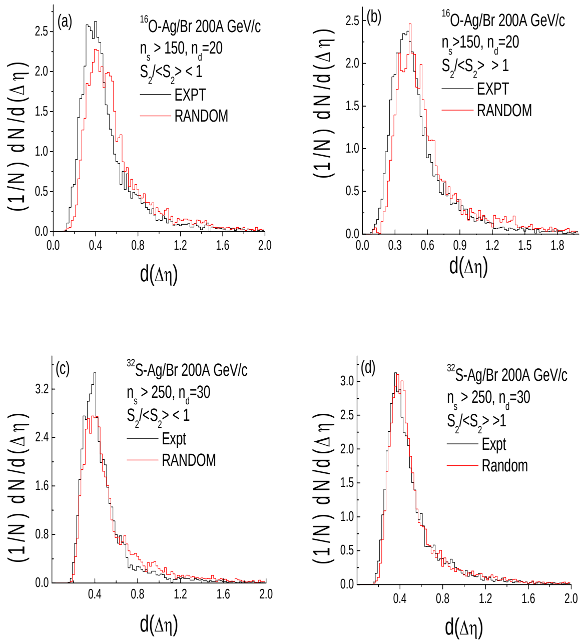

Figure 5. Distribution of $\Delta\eta_d$ for both ^{16}O and ^{32}S interactions. The ring and jet structure regions are shown separately.

The position of the jet / ring-like substructures can be investigated by studying the η_m distribution. Following [10] the distributions are divided into three categories: (i) $S_2/\langle S_2\rangle < 0.95$ - the region where ring-like effects dominate, (ii) $0.95 < S_2/\langle S_2\rangle < 1.1$ - the region of statistical background, and (iii) $S_2/\langle S_2\rangle > 1.1$ - the region where jet like structures dominate. In Figure 3 the η_m distributions for all three categories mentioned above, and for both types of interactions under consideration, have been graphically plotted. A critical examination of the η_m distributions show, that they are more or less symmetric about a central value. Among the three categories mentioned above, the jet-like structure characterized by the condition $S_2/\langle S_2\rangle < 0.95$, shows definite experimental excess over random number prediction in left to the centre region. The feature is observable in both ^{16}O and ^{32}S induced interactions. In all other cases the experimental and random number generated distributions more or less mach each other within statistical errors.

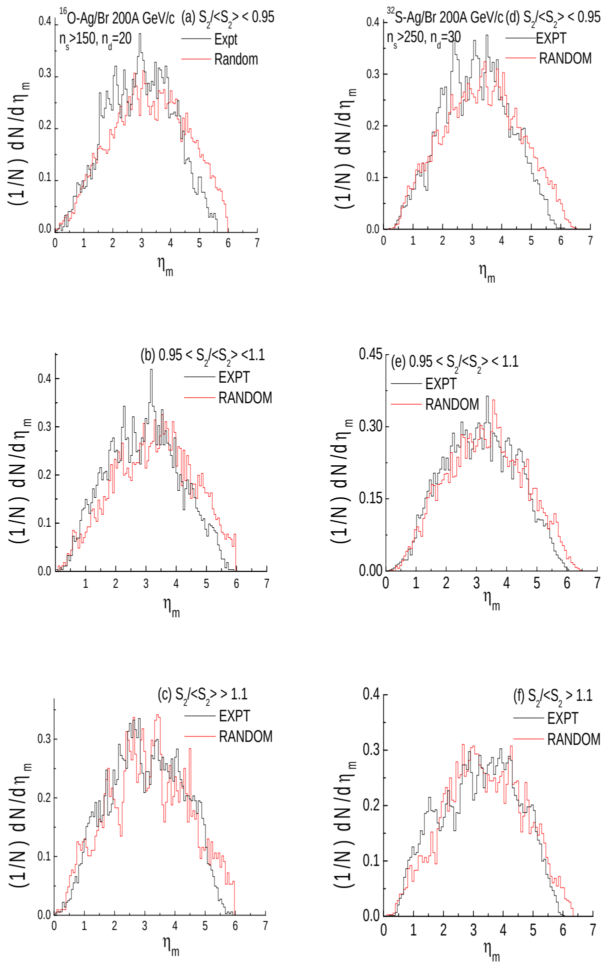

Figure 6. Distribution of η_m for three categories and for both types of interactions. Figure (a), (b) and (c) – ^{16}O events and Figure (d), (e) and (f) – ^{32}S – events.

5. DISCUSSION

In this paper we have presented a preliminary investigation of the ring and jet like substructures in the emission of secondary charged hadrons coming out of ^{16}O-Ag/Br and ^{32}S-Ag/Br interactions at 200A GeV/c. In more specific words, presence of such substructures, their average behavior, size, and position of occurrence have been examined. Major observations of our analysis can be summarized in the following way.

(i) More stopping of the ^{16}O projectile than the ^{32}S projectile has taken place in collisions with Ag/Br nuclei. There are both similarities as well as differences in jet/ ring like structures between the two types of interactions.

(ii) The average behavior of S_1 and S_2 parameters exhibits presence of jet like structures in both types of interactions that are limited both in η and φ directions. Such a behavior will lead to strong 2-dimensional intermittency characteristics as was seen in Ref. [11] for the same data. No strong indication regarding ring structure can be seen from the average behavior of S_1 and S_2 parameters. Our observation in this regard is similar to that of Ref. [6].

(iii) A closer look at the distributions of structure size and their position once again suggests that features of jet structure cannot be reproduced by a simple random number generated independent emission model. The same in the ring-like structure region are replicated by the random numbers within statistical uncertainties.

Though some interesting observations could be made from this preliminary analysis of our data on ^{16}O-Ag/Br and ^{32}S-Ag/Br interactions at 200A GeV/c, we feel that a more detailed analysis is necessary with a larger statistics and with other choices of n_d values. It would also be a worthwhile exercise to compare our results with similar other results existing in literature. Recently, the wavelet technique has been employed for fluctuation study of particle production in narrow regions of phase space, which is also underway for our set of data.

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