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Strong azimuthal fluctuations of pions produced in nuclear interactions at a few GeV/n

Dipak Ghosh*, Argha Deb, Swarnapratim Bhattacharyya, Keya Dutta (Chattopadhyay) and Jayita Ghosh
Nuclear and Particle Physics Resarch Centre,
Department of Physics, Jadavpur University, Kolkata-700 032, India

E-mail : dipakghosh_in@yahoo.com

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Abstract This paper presents a detailed study on the azimuthal fluctuations of the pions produced in nuclear emulsion from high energy relativistic interactions initiated by ^{16}O-AgBr at 2.1AGeV, ^{12}C-AgBr interactions at 4.5 AGeV and ^{24}Mg-AgBr interactions at 4.5AGeV. The outcome of this analysis signifies the existence of strong azimuthal asymmetry in the multipion production process. Asymmetry is also found to depend on the number of pions produced.

Keywords Azimuthal asymmetry, pionisation, relativistic nucleus-nucleus collisions

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1. Introduction

To know the ultimate structure of matter, various experiments have been performed mainly with lepton-lepton, lepton-nucleus, hadron-hadron, hadron-nucleus and nucleus-nucleus interactions at relativistic and ultra relativistic energies. The observations from these experiments reveal the existence of non-statistical fluctuations during the multiparticle production.So the analysis of non-statistical fluctuations are believed to throw light on the inner dynamics of particle production process. Thus, the study of non-statistical fluctuations during multiparticle production is of major interest today. A lot of methodologies have been developed to study the large non-statistical fluctuations. Some well known physical phenomena like correlation, intermittency, may be considered as the manifestation of the fact that the production of pions are dominated by large fluctuations arising out of dynamical reasons. Over the last few years, a lot of investigations have been done on correlation [1-10] and intermittent type of fluctuations[11-16].

Non-statistical fluctuations may be a manifestation of quark gluon plasma (QGP) phase transition which might occur at ultra-relativistic nucleus-nucleus collisions and need special attention. A very simple but useful tool to study non-statistical fluctuations, is azimuthal asymmetry. Few publications on this are available in the literature[17-23]. However, the physics of nuclear interactions is not yet conclusive and it is the high time to take advantages of modern tools for understanding of the fluctuations arising out of dynamical reasons. This paper reports a study on azimuthal asymmetry of the pions produced in nuclear emulsion from high energy relativistic interactions initiated by ^{16}O-AgBr at 2.1AGeV, ^{12}C-AgBr interactions at 4.5 AGeV and ^{24}Mg-AgBr interactions at 4.5AGeV.

Though at relativistic energy, chance of QGP phase transition is most unlikely, the study of non-statistical fluctuations at this energy, helps to make a comparison of the nature of dynamical fluctuations with that at ultra relativistic energy. This comparison helps us to get a clear idea about how the fluctuation pattern changes as the energy and projectile are varied.

2. Experimental details

The data are obtained by exposing Illford G5 emulsion plates exposed to ^{16}O beam of energy 2.1 GeV at BEVALAC BERKELEY[24] and the data of ^{12}C-AgBr interactions and ^{24}Mg-AgBr interactions are obtained by exposing NIKFI BR2 emulsion plates at 4.5 AGeV from JINR, Dubna, Russia [25,26].

*Corresponding Author

A Leitz Ortholux microscope with a 10X objective and 25X ocular lens provided with a Brower stage is used to scan the ^{16}O initiated interaction plates and a Leitz Metaloplan microscope with a 10X objective and 10X ocular lens provided with a semi-automatic scanning stage is used to scan the ^{12}C- AgBr and ^{24}Mg -AgBr plates. Each plate is scanned by two independent observers to increase the scanning efficiency. The final measurements are done using an oil-immersion 100X objective. The measuring system fitted with it has 1μm resolution along the X and Y-axes and 0.5 μm resolution along the Z-axis.

After scanning ,the events are chosen according to the following criteria:

(i) The incident beam track should lie within 3^0 from the main beam direction in the pellicle. It is done to ensure that we have taken the real projectile beam.

(ii) Events showing interactions within 20 μm from the top and bottom surface of the pellicle are rejected. This is done to reduce the loss of tracks as well as to reduce the error in angle measurement.

(iii) The tracks of the incident particle, which induce interactions, are followed in the backward direction to ensure that it is a projectile beam starting from the beginning of the pellicle.

According to the emulsion terminology [27], the particles emitted after interactions are classified as :

(a) Black particles : Black particles consist of both single and multiple charged fragments.They are target fragments of various elements like carbon, lithium, beryllium *etc* with ionization greater or equal to $10\,I_0$, I_0 being the minimum ionization of a singly charged particle. The range of black particles in the emulsion medium is less than 3 mm. They have velocities less than 0.3c. where *c* is the velocity of light in vacuum. Energies of these particles are generally less than 30 MeV. In the emulsion experiments, it is very difficult to measure the charges of the fragments. So identification of the exact nucleus is not possible.

(b) Grey particles : They are mainly fast target recoil protons with energy upto 400 MeV. Ionisation power of grey particles lies between $1.4\,I_0$ to $10\,I_0$. Their ranges are greater than 3 mm. These grey particles have velocities lying between 0.3*c* to 0.7*c*.

(c) Shower particles : The relativistic shower tracks with ionization I less than or equal to $1.4\,I_0$ are mainly produced by pions (π^+, π^-, π^0) and are not generally confined within the emulsion pellicle.These shower particles have energy in GeV range.

(d) The projectile fragments are different class of tracks with constant ionization, long range and small emission angle.

To ensure that the targets in the emulsion are silver or bromine nuclei, we have chosen only the events with at least eight heavy ionizing tracks of (black+grey) particles. *i e* central and quasi-central events are taken. The events that have the number of heavy tracks less than eight, is due to the collision of the projectile beam with carbon, nitrogen and oxygen nucleus present in the emulsion. These types of events are called CNO events.

According to the above selection procedure, we have chosen 730 events of ^{16}O-AgBr interactions at 2.1AGeV [24], 800 events of ^{12}C-AgBr interactions at 4.5 AGeV [28] and 800 events of ^{24}Mg -AgBr interactions at 4.5AGeV[29]. The emission angle (θ) and azimuthal angle (ϕ) are measured for each track by taking readings of the coordinates of the interaction point (X_0 ,Y_0, Z_0) , coordinates (X_1, Y_1, Z_1) at the end of the linear portion of each secondary track and coordinate (X_i, Y_i, Z_i) of a point on the incident beam. In case of shower particles, the variable used is pseudo rapidity and it is defined as $\eta = -\ln(\tan\theta/2)$.The uncertainty in the measurement of emission angle which is very essential for this study never exceeds 0.1 mrad. Nuclear emulsion covers 4π geometry and provides very good accuracy in the measurements of angles of produced particles and fragments due to high spatial resolution and thus, is suitable as a detector for the study of fluctuation in the fine resolution of the phase space considered.

3. Method of analysis

To study the fluctuations in azimuthal plane, Takibaev's method [30] is followed here. According to this method, we divide the whole azimuthal plane having 2π angular range into two equal angular intervals and the difference in the number of shower particles emitted in the two intervals for each of the events is found out. We repeat the process and continue it by shifting the line of division over the azimuthal plane by 10^o and by taking the difference in the number of shower particles in the two halves, each time. This process is carried out till the position of the line of division is repeated. The maximum difference obtained for each event is taken as Δn_{si}, *i*, indicates the event. The probability of azimuthal asymmetry for the *i*-th event is defined as

$$W_i = \Delta n_{si}/n_{si}\,, \tag{1}$$

where n_{si} is the total number of shower tracks in the *i*-th event of the group of events in a particular N_s interval. For a group of m events in an N_s interval, the probability of azimuthal asymmetry is given as

$$\overline{W} = \sum W_i/m\,. \tag{2}$$

To calculate the asymmetry parameter ($\overline{W}$) the data sample is divided into groups such that all the events in a particular group have almost equal number of shower tracks. Then, we calculate $\overline{W}$ for different $\overline{N_S}$ intervals for the data set of oxygen. For any particular N_s interval, the weighted average of N_s is given by

$$\overline{N_S} = \sum P_{N_S} N_s , \tag{3}$$

where P_{N_S} represents the probability of getting an event with N_s number of shower tracks.

4. Results and discussion

To study the variation of the degree of azimuthal asymmetry with the number of shower tracks, we have divided the total number of events into multiplicity sub-groups. The subgroups are chosen such that each sub-group contains sufficient number of events and the variation of multiplicity within a group, is not significant. The multiplicity ranges for the three data sets are shown in Tables 1, 2 and 3 respectively. As the shower multiplicity varies a little within a particular sub-group, we have calculated the weighted mean multiplicity ($\overline{N_S}$) of each sub-group using eq. (3). For every sub group of the three data sets the degree of azimuthal asymmetry ($\overline{W}$) is calculated using eq. (2). The calculated values of $\overline{W}$ are Tabulated in Tables 1, 2 and 3 for high energy, interactions initiated by ^{16}O-AgBr at 2.1AGeV, ^{12}C-AgBr interactions at 4.5 AGeV and ^{24}Mg-AgBr interactions at 4.5AGeV, respectively.

Table 1. Values of the probability $\overline{W}$ of azimuthal asymmetry in different $\overline{N_S}$ intervals for ^{16}O-AgBr interactions at 2 1 AGeV for both the experimental and randomised data sets.

Interaction	N_S	$\overline{N_S}$	Experimental value ($\overline{W}$)	Randomized value ($\overline{W}$)
	1-5	3.5	1.00± 05	0 88
	6-8	7 0	0 69±.04	0 64
^{16}O-AgBr (2 1 AGeV)	9-11	10 9	0 58± 01	0 59
	12-18	16.14	0.57±.06	0.49
	19 - 23	21 50	0.53± 01	0 50

Table 2. Values of the probability $\overline{W}$ of azimuthal asymmetry in different $\overline{N_S}$ intervals for ^{12}C-AgBr interactions at 4 5 AGeV for both the experimental and randomised data sets

Interaction	N_S	$\overline{N_S}$	Experimental value ($\overline{W}$)	Randomized value ($\overline{W}$)
	1-5	3 44	0.80±.02	0.79
	6-10	7 82	0.71±.09	0 54
^{12}C-AgBr (4 5 AGeV)	11-15	12.32	0 60±.07	0 49
	16-18	16.75	0.58±.05	0 52
	19-29	21.90	0.49±.04	0 37

Table 3. Values of the probability $\overline{W}$ of azimuthal asymmetry in different $\overline{N_S}$ intervals for ^{24}Mg-AgBr interactions at 4 5 AGeV for both the experimental and randomised data sets

Interaction	N_S	$\overline{N_S}$	Experimental value ($\overline{W}$)	Randomized value ($\overline{W}$)
	1-6	3 67	.80± 05	75
	7-10	8 34	64± 02	56
^{24}Mg-AgBr (4.5AGeV)	11-15	12 79	54± 01	.44
	16-21	18 45	41± 07	37
	22-32	26 15	33± 01	31

We have plotted $\overline{W}$ against $\overline{N_S}$ with the experimental data sets of oxygen in Figure 1, carbon in Figure 2 and magnesium in Figure 3. The figures corresponding to all data sets reveal that

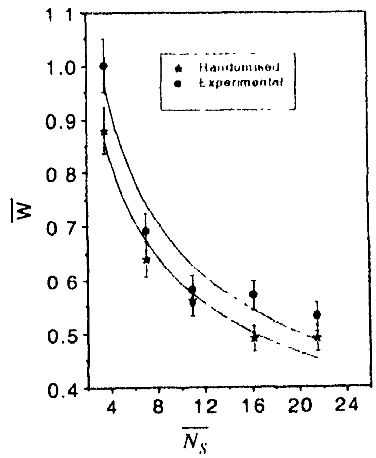

Figure 1. Represents the plot of the probability $\overline{W}$ of azimuthal asymmetry in different $\overline{N_S}$ intervals for ^{16}O-AgBr interactions at 2 1 AGeV for both the experimental and randomised data sets

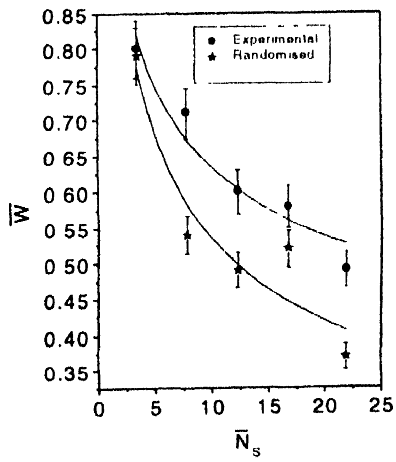

Figure 2. Represents the plot of the probability $\overline{W}$ of azimuthal asymmetry in different $\overline{N_S}$ intervals for ^{12}C-AgBr interactions at 4.5 AGeV for both the experimental and randomised data sets

the degree of asymmetry $\overline{W}$ for shower tracks depend on the multiplicity $\overline{N_s}$ interval. $\overline{W}$ decreases with the increase of $\overline{N_S}$ indicating that asymmetry decreases with the increase in number of shower multiplicity.

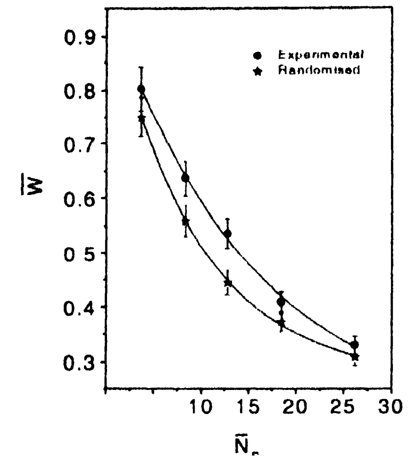

Figure 3. Represents the plot of the probability $\overline{W}$ of azimuthal asymmetry in different $\overline{N_S}$ intervals for ^{24}Mg AgBr interactions at 4 5 AGeV for both the experimental and randomised data sets

It may happen that the observed asymmetrical behaviour is due to the statistical fluctuations and inner dynamics of multiparticle production has nothing to do with it. To counter such an argument and to ensure that the observed asymmetrical behaviour is not due to statistical fluctuations, we have redistributed all the particles of each event randomly throughout the considered phase space interval and the same analysis has been performed. $\overline{W}$ calculated from the randomized data sets of oxygen, carbon and magnesium have also been plotted against $\overline{N_S}$ in Figures 1, 2 and 3, respectively. The results for the randomized data sets, show that the probability of azimuthal asymmetry for all the points differ appreciably from that of the experimental values (considering the error bars). In fact, the azimuthal asymmetry for randomized events is less than that of experimental events. Such an outcome obviously confirms the existence of non-statistical fluctuations in particle production process.

We have tried to fit the $\overline{W}$ *vs.* $\overline{N_S}$ plot in a form $\overline{W} = p.\overline{N_s}^q$ and noted that for every fit, X^2/DOF (Degrees of freedom) is less than 1.

The values of p and q obtained from best fits for the data sets of ^{16}O-AgBr interactions at 2.1 AGeV, ^{12}C-AgBr interaction at 4.5 AGeV and ^{24}Mg -AgBr interactions at 4.5AGeV are given in Table 4. We see from this table that the values of p obtained from best fit of oxygen data and those from carbon data and magnesium data are not the same and so also the case for q values.

The value of q in fact, determines how rapidly the azimuthal asymmetry decreases with the number of shower particles. Larger the value of q, more rapidly the $\overline{W}$ decreases.

Table 4. Values of p and q per degree of freedom for ^{16}O-AgBr interaction at 2.1AGeV, ^{12}C- AgBr interactions at 4.5 AGeV and ^{24}Mg -AgBr interactions at 4.5AGeV.

Interactions	P	q
^{16}O-AgBr (2.1AGeV)	1.43	- 34
^{12}C-AgBr(4 5AGeV)	1.13	- 25
^{24}Mg-AgBr(4 5AGeV)	1 55	- 45
^{32}S-AgBr(200AGeV)	1 90	- 33
^{16}O-AgBr(60AGeV)	1.98	- 34

From the table, it can be said that the rate of decrement of azimuthal asymmetry is fastest in case of ^{24}Mg-AgBr interaction and slowest in case of ^{12}C-AgBr interactions.

It is useful to compare our results with that obtained from the pionisation of ^{32}S-AgBr interactions and ^{16}O-AgB interactions at ultra-relativistic high energies[23]. In this case also the degree of azimuthal asymmetry decreases with the increase of shower multiplicities and is consistent with our findings. The values of p and q obtained from these two interactions are also shown in Table 4. From the table, it is seen that the values of p are almost the same for the two interaction at ultra-relativistic high energies.The same statement is valid in case of q values too.

It is also to be noted from Table 4 that the q values for ^{16}O-AgBr interactions at 60AGeV and 2.1 AGeV are same. An interesting point is that for ^{24}Mg-AgBr interactions and ^{12}C-AgBr interactions, the values of q are different though their energies are same.

5. Conclusion

To conclude we may write

(i) The production of shower particles is asymmetric in azimuthal plane.

(ii) Asymmetry decreases with the increase in number of shower multiplicity.

(iii) At lower energy, this asymmetry depends on the mass and energy of the projectile and at ultra-relativist energy, this asymmetry is almost independent of them

(iv) The decrement of the degree of azimuthal asymmetry is independent of energy for the same projectile

(v) However for the same energy of different projectiles the degree of azimuthal asymmetry decreases faster for the heavier projectile.

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