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Experimental results of heavy ion interactions in emulsions

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1. Introduction

Heavy Ion Interactions in nuclear emulsions have been studied for the last 40 years or so. Earlier experiments used heavy ions from Cosmic Rays , and Bevalac at Berkely (USA) served the community for the last twenty years. With the availibility of heavy ion beams at SPS-CERN (60A GeV) and AGS-BNL (14.6A GeV) in 1986 the interest in the field got a boost. The recent experiments have been aimed to explore the possibility of deconfinement or QGP in heavy ion interactions. Another important, but modest, aim is to understand the mechanism of nucleus nucleus interactions at these energies. In other words, the study of high energy heavy ion interactions, where hundreds (even thousands with future beams) of particles are produced, is in itself a quite challenging and interesting task even if our observations are unable to give any unambiguous clue asto the formation of quark gluon plasma.

2. Measurements in emulsions

A nuclear emulsion detector is equipped with the highest spatial resolution and 4π coverage. In usual emulsion experiments, the emulsion stacks are exposed horizontally to beams of heavy ions. The observed mean-free paths for heavy ion emulsion interactions [1,2] satisfy Bradt-Peter relation [3] for reaction cross sections :

$$\sigma_{\mathrm{PT}} = \mathrm{r}_0^2 \left(\mathrm{A}_\mathrm{P}^{1/3} + \mathrm{A}_\mathrm{T}^{1/3} - \delta\right)^2. \qquad (1)$$

The charged particles, observed in heavy-ion interactions, are categorised into different groups; black tracks (defined by Range $\leq$ 3 mm) are essentially evaporation products from the target nuclei, grey tracks (R $>$ 3 mm and grain density $>$ 1.4 g_{min}) are mainly recoiling protons and shower tracks (grain density $\leq$ 1.4 g_{min}) are mainly pions and projectile protons with $\beta > 0.7$. Black and grey tracks, termed as heavy tracks,are associated with target whereas shower tracks are due to the produced particles. In addition, projectile fragments of Z $\geq$ 2 are emitted in a narrow forward cone; the half angle of fragmentation cone depends upon the energy of the incoming projectile.

There are two problems in the study of ultrarelativistic heavy ion interactions using horizontally exposed emulsions stacks. The first is the ambiguity about the target nucleus, because an emulsion is a composite medium and contains a mixture of target nuclei (H, CNO and AgBr). The other difficulty is about the number of produced particles which runs into hundreds. In horizontal exposures it is difficult to resolve these shower tracks and measure their angles. Both these difficulties are tackled in emulsion chamber technique. An emulsion chamber consists of several sheets of emulsions and we can also have thin sheets of specific materials as targets. The emulsion chambers are exposed vertically and the produced particles can be resolved and measured in succesive emulsion sheets of chamber. The measurements are made using a microprocessor based measuring system.

Observed multiplicities of shower, black and grey tracks for the, O, Si and S-emulsion interactions are given in Table 1 [4,5]. Data from p-emulsion interactions and predictions from FRITIOF and VENUS are also included for comparison. We can see that $\langle N_b \rangle$ stays constant, but $\langle N_g \rangle$ increases when we go from p-emulsion interactions to heavy ion interactions. $\langle N_s \rangle$ increases with masss number and energy of the projectile. We further notice that both FRITIOF and VENUS predict $\langle N_s \rangle$ values which are quite close to the experimental values.

Table 1: Average Multiplicity

Beam	Energy A GeV	$\langle N_S \rangle_{Jain}$[4] (VENUS)	$\langle N_S \rangle_{EMU}$[5] (FRITIOF)	$\langle N_b \rangle$	$\langle N_g \rangle$
^{4}He	140	23.59 ± 1.2			
^{16}O	14.6		20.3 ± 0.8	4.8 ± 0.2	5.2 ± 0.2
^{16}O	60	34.12 ± 2.3 (36.32)	39.0 ± 2.1 (39.4 ± 0.4)	4.5 ± 0.2	5.7 ± 0.4
^{16}O	200	57.30 ± 3.1 (57.77)	56.5 ± 2.7 (58.0 ± 0.6)	4.1 ± 0.2	4.3 ± 0.3
^{28}Si	14.6	30.75 ± 1.5	28.2 ± 1.3	4.6 ± 0.2	5.4 ± 0.3
^{32}S	200	79.20 ± 4.1 (80.10)	79.9 ± 4.1	3.9 ± 0.2	4.7 ± 0.3
p	67		9.35 ± 0.16	4.76 ± 0.14	2.74 ± 0.10
p	200		13.84 ± 0.16	5.02 ± 0.10	2.60 ± 0.06

3. Target fragmentation

Slow particles give black and grey tracks and are associated with the fragmentation of the target. Q_{ZD}, the charge of the particles emitted in a narrow forward cone ($\theta_{cone} = 0.6/p_{beam}$), is used as a measure of centrality of the heavy ion reactions. Smaller value of Q_{ZD} indicates that most of the nucleons in the projectile have interacted or the reaction is central, similarly higher values of Q_{ZD} mean peripheral reactions. In Fig. 1 the variation of average multiplicities is shown for different degrees of centrality measured by Q_{ZD} values [5]. Fig. 1 shows data for Oxygen-emulsion interactions at 3 energies $15A$, $60A$ and $200A$ GeV. Multiplicity distributions for grey and black prongs are similar for 3 incident energies ; the same is also true for scaled multiplicities of shower particles. The dynamic range of $\langle N_b \rangle$ is smaller than for the two other categories, indicating that of the three, the black prongs have the weakest correlation to the centrality. However, this behaviour

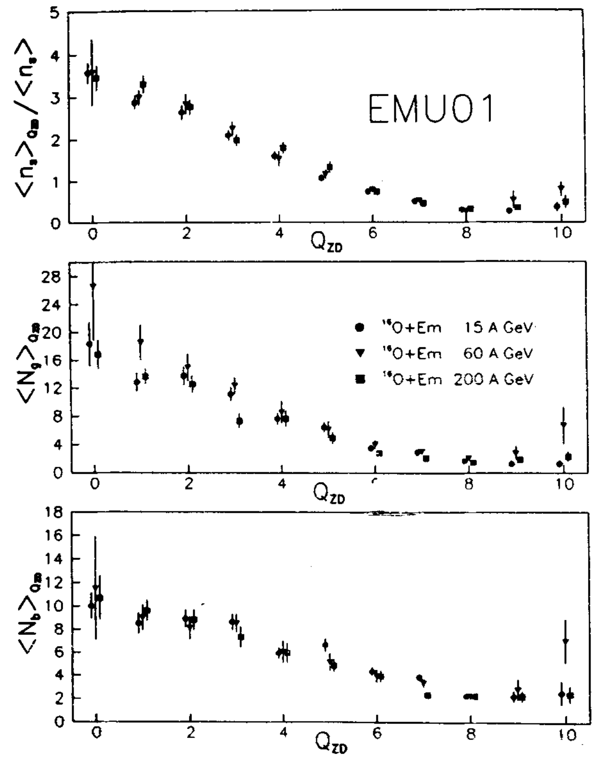

Figure 1. Average multiplicities as a function of Q_{ZD} (charge flow in forward direction)

of multiplicities shows that criteria for centrality based upon high multiplicity is consistent with the criteria of low values of Q_{ZD}.

The angular distributions of black and grey prongs also carry information on the production mechanisms and thus put constraints on models. In Fig. 2 angular distributions of black and grey tracks from different samples are shown [5]. As can be seen the angular distributions are similar i.e. independent of energy, colliding system and centrality. For the grey particles the angular distribution is also similar to the one observed for proton induced interactions [6]. There is no trivial reason why the angular distributions, particularly for the grey prongs, should be independent of projectile and centrality.

S. Raniwala [7] has undertaken a detailed study of angular distributions of black and grey tracks in ^{16}O-emulsion interactions at 200A GeV. The observed angular distributions of black, grey and heavy tracks are compared with the predictions of model in which these are assumed to be emitted from a thermal source moving along the beam direction. The emission from a thermal source is assumed to follow the Maxwell-Boltzmann distribution with χ_0, the ratio of the longitudinal velocity to spectral velocity (related to temperature) of the source, as the free parameter. The observed and the fitted distributions for black, grey and heavy tracks are shown in Fig. 3. Reasonable fits indicate that above hypothesis can explain the emission of slow particles in heavy ion interactions. For black tracks, Fig. 3b, an excess over MB distribution is observed for particles emitted near 90 degrees. An attempt is

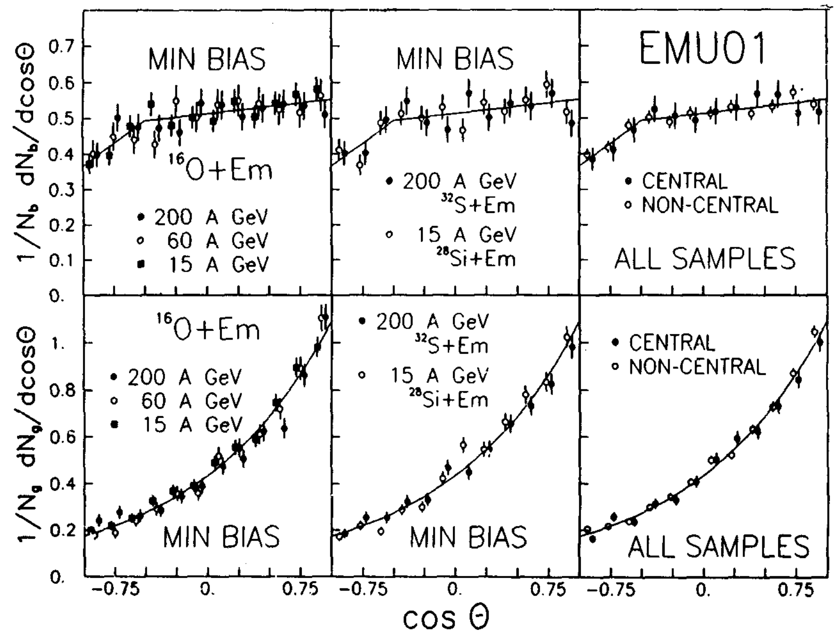

Figure 2. Angular distribution for black and grey prongs from various samples

made to explain this excess around 90 degrees by assuming a bounce off for the target spectator, the direction of maximum momentum flow being the direction of bounce off. Inclusion of bounce off reduces the $\chi^2/$ dof from 4 to 1.6 , indicating a possibility of bounce off for the target spectators. Having obtained the values of χ_0 (β_{II}/β_0) by fitting the angular distribution of black tracks to MBD, β_{II} and β_0 can be individually estimated by fitting the observed range distributions to MBD (Fig 4). The estimated velocities compare well with the results at $2A$ GeV [8]. Both the longitudinal and the spectral velocities show a slight increase with increase in the energy of the fragments.

By studying the azimuthal correlation between projectile and target fragments, one can investigate collective phenomena e.g. bounce off effect in high multiplicity events. This effect was first studied by H.H. Heckman et al. [9] in U + AgBr reactions. By analysing quasi central Kr + AgBr interactions, R. Arora et al. [10] observed that azimuthal correlation between PF's and Tf's shows weaker bounce off effect. H.S. Palsania et al. [11] analysed La + emulsion interactions at $1.1A$ GeV with criteria $N_h \geq 8$ and $N_{pf} \geq 4$. Study of back to back correlation in azimuthal plane shows that the strength of the bounce off effect in La interactions lies between Kr + AgBr and U + AgBr interactions. The results of these experiments are shown in Fig. 5.

4. Particle production

Particles produced in heavy ion emulsion interactions are measured as shower tracks ($\beta > 0.7$); this aspect has been studied widely using recent ultrarelativistic beams.

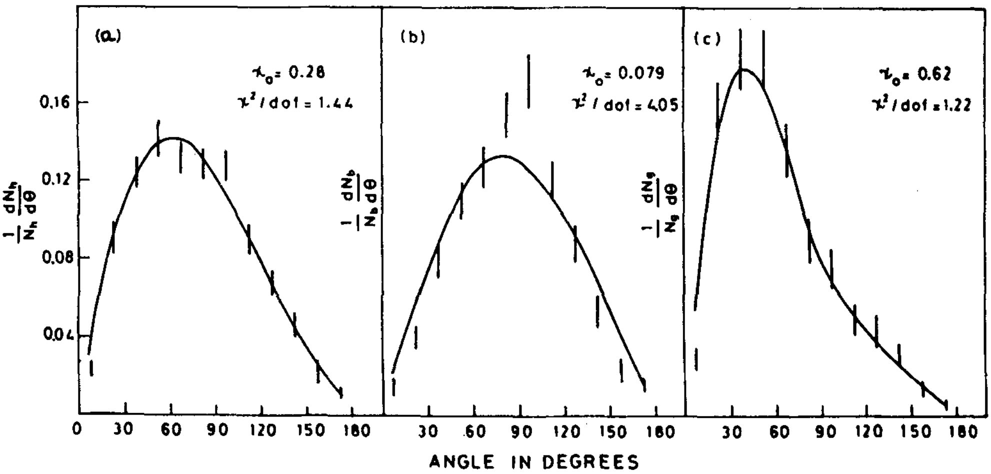

Figure 3. Maxwell-Boltzmann parametrization for heavy, black and grey track angular distributions : minimum bias samples

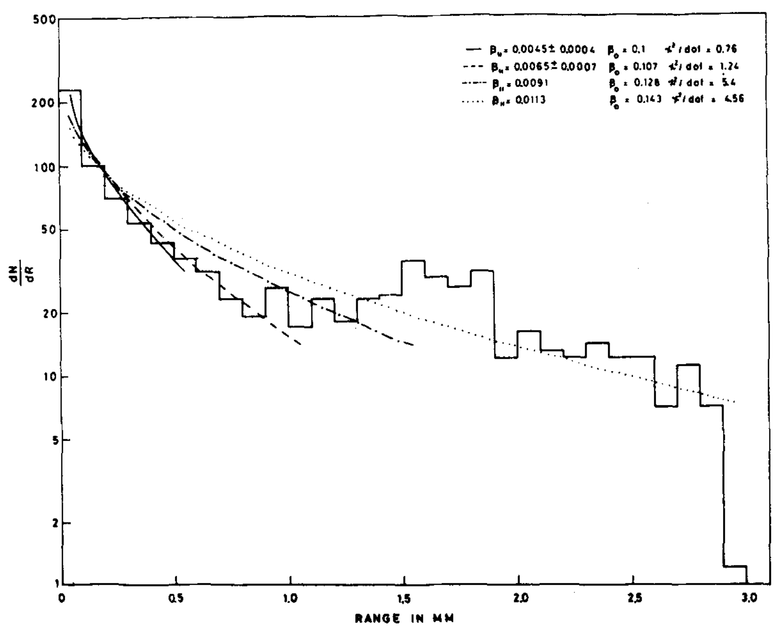

Figure 4. Range distribution of black tracks. minimum bias sample. Maxwell-Boltzmann fits for range intervals ≤ 0.6, ≤ 1.1, ≤ 1.6 and ≤ 3.0 mm

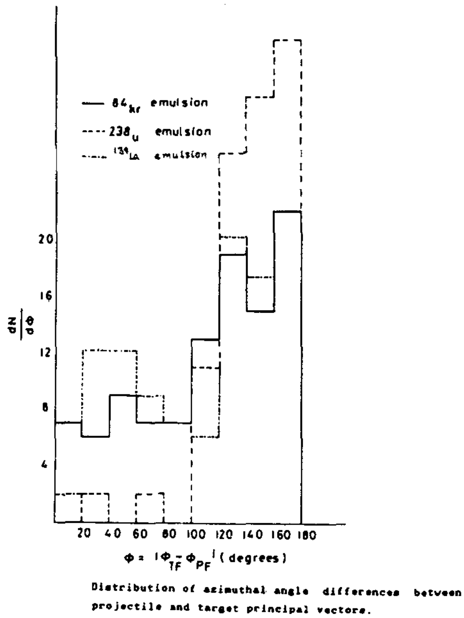

Figure 5. Distribution of azimuthal angle difference between projectile and target principal vectors

Only representative results related to multiplicities, pesudo rapidity distributions and fluctuations of produced particles are discussed in this section.

Experimentally observed values of average number of shower particles, $\langle N_s \rangle$, in proton-emulsion interactions [12] and in Oxygen-emulsion interactions [13] are represented by the following linear relations :

$$\langle N_s \rangle_{p-em} = 2.34 \langle N_{ch} \rangle_{p-p} - 4.12 \quad \text{and} \qquad (2)$$
$$\langle N_s \rangle_{O-em} = 10.1 \langle N_{ch} \rangle_{p-p} - 16.6 \, , \qquad (3)$$

where $\langle N_{ch} \rangle_{p-p}$ is the charged particle multiplicity in pp interactions. These relations show that the energy dependence of $\langle N_s \rangle$ in heavy ion interactions and proton interactions are similar, energy dependence in both cases is contained in $\langle N_{ch} \rangle_{p-p}$. These relations also show that multiplication (slope) is decided by the geometry, number of participants from projectile and target or number of nucleon-nucleon collisions.

Observed N_s distributions for ^{16}O-emulsion reactions at 200*A*, 60*A* and 14.6*A* GeV have been studied and compared with the predictions of Lund model FRITIOF [14]. The agreement observed in such comparisions show that Lund model represents the data well.

Angular distributions of shower tracks are represented as pesudorapidity, η distributions. η distributions for *O*-emulsion reactions at 14.6, 60 and 200*A* GeV are compared [15], in target (lab frame) and projectile rest frames. These observations give evidence for limiting fragmentation in target fragmentation regions and projectile fragmentation regions respectively. The observed pesudorapidity distributions

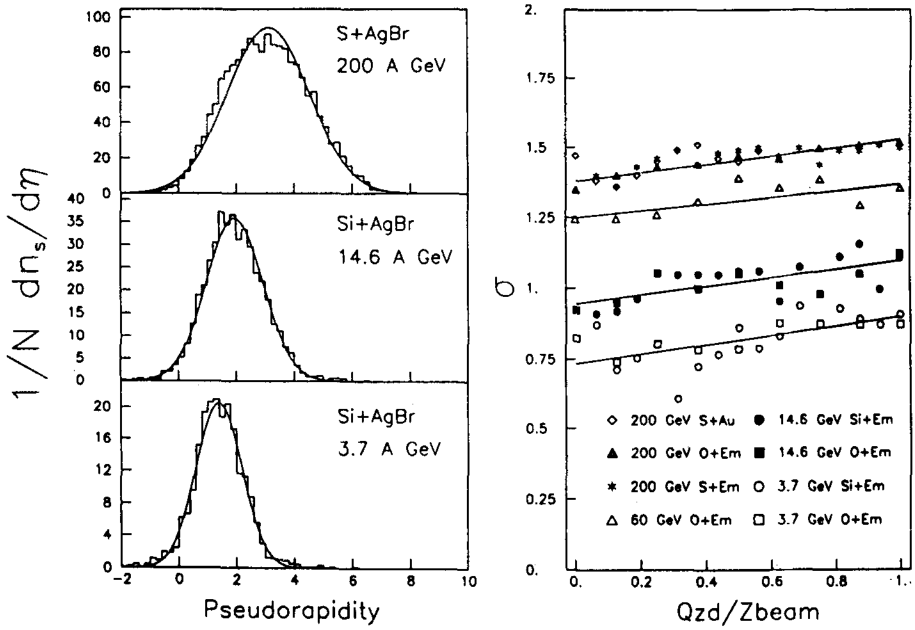

Figure 6. (a)-(c). Examples of pesudorapidity distributions for central events and corresponding Gaussian fits. (d) Widths of pesudorapidity distributions and their centrality (Q_{ZD}/Z_{beam}) dependence for various interacting systems at different energies. [typical errors are (2-5)%]

for 200*A* GeV and 60*A* GeV have been found to agree quite well with the predictions from FRITIOF for central samples as well as for minimum bias samples. P. L. Jain et al. [4] have found that the data for multiplicity distributions and η distributions in ^{32}S and ^{16}O interactions can be well represented by VENUS code.

H. Von Gersdroff et al. [16] parameterized the observed pesudorapidity distributions for ^{16}O-emulsion interactions to gaussian distributions. EMU01 collaboration [17] have used gaussian parameterization to compare η distributions of produced particles in different colliding systems and at different energies. In Fig. 6(a)-(c) three examples, for central samples of ^{32}S + AgBr (3.7*A* GeV), are shown. As can be seen the distributions are well described by the gaussian form :

$$\rho(\eta)d\eta \quad = \quad \rho_{\max}\exp\left[\frac{-(\eta-\eta_{\max})^2}{2\sigma^2}\right]d\eta. \tag{4}$$

Here η_{peak}, $\rho_{\max}$ and σ represent the position of the peak, the height and width of the distribution respectively. The integrated miltiplicity n is given by

$$n \quad = \quad \sqrt{2\pi}\sigma\rho_{\max}. \tag{5}$$

In Fig 6(d) the widths of the distributions for many samples are shown. For fixed incident energy σ is observed to be independent of the interacting system or projectile, (10-20) % variation is seen when going from the most central ($Q_{ZD}/Z_{beam} \approx 0$)

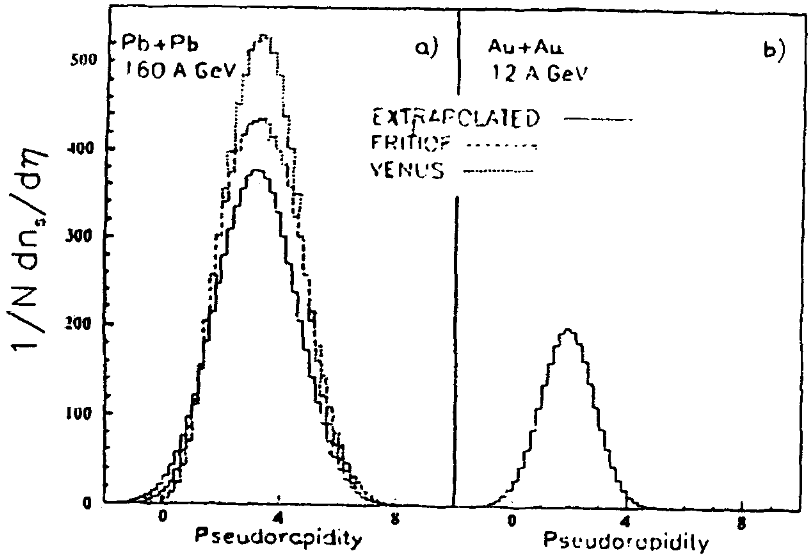

Figure 7. Extrapolated pesudorapidity distributions for (a) central Pb+Pb interactions at 160A GeV and (b) central Au+Au interactions at 12A GeV. At 160A GeV the obtained distribution is compared with corresponding predictions from VENUS and FRITIOF

to the most peripheral events ($Q_{ZD}/Z_{beam} \approx 1$). The straight line fit can be represented as :

$$\sigma = S_1 + S_2 Q_{ZD}/Z_{beam} \tag{6}$$

Here S_1 increases with energy, but S_2 does not seem to vary much with energy.

Using the gaussian parameterization of the η distributions , η distributions for Pb + Pb collisions at 160A Gev can be predicted. The number of produced particles per participant is perametrized as [13,18] :

$$n/p = 0.73\,N_{ch} - 1.44. \tag{7}$$

This gives, n/p ~ 3.84 for 160A GeV. If central Pb+Pb interactions are considered in which ~ 340 nucleons participate,a total charged particle multiplicity of ~ 1300 is predicted. Using $\sigma = 1.38$ at 160A GeV, one can find ρ_{max}. The η distribution for Pb+Pb interactions at 160A GeV can thus be extraploted. Fig. 7 shows the extrapolation alongwith predictions from FRITIOF and VENUS [17].

Fluctuations in observed rapidity density have been illustrated in event by event plots in ^{32}S - Au interactions [19]. Bialas and Peschanski [20] proposed a method, based on scaled factorial moments, to analyse these fluctuations; many articles have appeared using this method. R. Holynslki et al. [21] analysed ^{16}O interactions at 60A and 200A GeV and proton interactions at 200 and 800 GeV and concluded an intermittent behaviour of fluctuations. M.I. Adamovich et al. [22] studied this effect and find that intermittent indexes decrease with increasing incident energy and multiplicity, and increase with target and projectile mass. P.L. Jain and G. Singh [23] analysed the data in one and two dimensions and observed that the

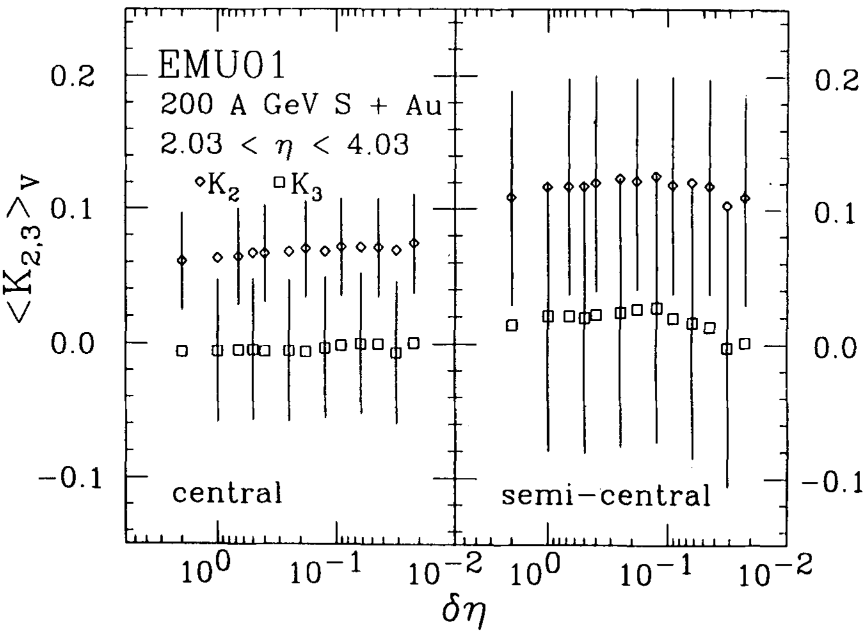

Figure 8. Second and third order factorial cumulant moments for the 200A Gev S+Au central and semicentral events. The windows in pseudorapidity used is $2.03 < \eta < 4.03$

effect is more pronounced for higher dimensions. Recently, an investigation is reported [24] in which pesudorapidity fluctuations are analysed using scaled factorial cumulant moments. Factorial cumulants are related to the factorial moments e.g.

$$K_2 = F_2 - 1 \quad \text{and}$$
$$K_3 = F_3 - 3F_2 + 2,$$

where K_2 and K_3 are scaled factorial cumulant moments of second and third order and F_2 and F_3 are the corresponding factorial moments. Factorial cumulants remove the effects of lower order correlations upon a given moment. Fig. 8 shows the second and third order factorial cumulant moments for the central and semicentral S + Au interactions. In this investigation significant second order cumulants and cumulant indicies are reported. The presence of non-zero cumulants indicates that the multiplicities are not poissionian. Cumulant indices are studied for various projectiles and are observed to have an inverse dependence upon average pseudorapidity particle density.

5. Conclusions

1. The emission of target associated particles, multiplicities and angular distributions, shows energy independence.

2. Some indications of bounce off or collective behaviour are observed in the analysis of projectile and target fragmentation products.

3. Multiparticle production in heavy ion interactions is broadly described by geometry and by the energy available. Models, like FRITIOF and VENUS, are able to describe the data on multiplicities and pseudorapidity distributions.

4. Pseudorapidity distributions of produced particles can be parameterised as gaussian distributions in heavy ion interactions over a wide range of energies.

5. The question of nonstatistical fluctuations needs to be pursued further before drawing definite conclusions.

Acknowledgements

My thanks are due to Prof. I. Otterlund (spokesperson) and other collaborators of EMU 01 whose work has been reported here. I am thankful to Prof. S. Lokanathan, S. Raniwala and Shailendra Gupta for discussions. A research grant from DST (Govt. Of India) is acknowledged with thanks.

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Discussion

R.V. Gavai : Could you please compare your results on intermittancy with those of other experiments?

K.B. Bhalla : KLM (PRL 1989) results show an increase of intermittancy indices with energy of ^{16}O projectile, whereas EMU 01 (Z. Phys. C1991) results show a decreasing trend. KLM analysis of p-emulsion interactions at 200 and 800 GeV also shows an intermittant behaviour of fluctuations, Jain and Singh (PRC 1991) have studied the effect in one and two discussions and found that the effect is more pronounced in higher dimensions. EMU results indicate that the signal in two dimensions very weak, when background due to γ conversion is subtracted.

J.C. Parikh : Why do (pseudo) rapidity distributions fit Gaussian distributions at high projectile energies?

K.B.Bhalla : KLM (PRL 1989) have also fitted the η distributions, from ^{16}O interactions at 14.6, 60 and 200 A GeV, to gaussian distributions. According to them the observed value of width (σ =1.53) is consistent with the predictions of Landau's hydrodynamical model. Klar and Hufner (PRD 1985) have analysed pp, pAr and pXe data at 200 GeV in terms of two gaussians.