DOE/ER/40271--T4

PROGRESS REPORT

Central Collisions of Heavy Ions

October 1, 1992 to August 31, 1993

prepared by

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DOE Nuclear Science Program

Grant Number DE-FG03-86ER40271

August 1993

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1 Introduction

This report describes the activities of the Heavy Ion Physics Group at the University of California, Riverside from October 1, 1992 to August 31, 1993. During this period, our AGS E802/E859/E866 experiments focused on strange particle production, and the fluctuation phenomenon associated with correlation studies in nucleus nucleus central collisions. We have designed and are implementing a new detector to replace the Target Multiplicity Array (TMA) for the E866 runs. As part of the PHENIX collaboration, we contributed to the Conceptual Design Report (CDR), and worked on a RHIC silicon microstrip detector R&D project, the central core of the multiplicity-vertex detector (MVD). In the coming year, we planned to complete the New Multiplicity Array (NMA) detector for the gold projectile E866 experiment, and analyzed the data associated with this new system. We are continuing our efforts in the preparation of the PHENIX detector system.

2 Heavy-ion Collisions Study at AGS energies

The Riverside Group has been a part of the BNL E802 collaboration since 1986. This is the first major experiment utilizing the 14.5 GeV/c heavy ion beam at the AGS. Its goal is to study particle production in nucleus nucleus central collisions. The apparatus consists of a large aperture magnetic spectrometer, with segmented Cherenkov counters, scintillation counter arrays, time projection chamber and wire chamber for tracking and particle identification; a smaller aperture gas Cherenkov system tuned to identify higher momentum particles; a lead glass array to measure total neutral energy; a streamer tube array to determine total multiplicity and measure pseudorapidity of emerging particles; and a small total absorption sampling calorimeter to measure the total kinetic energy of the projectile fragments at small forward angles. The data collection for E802 was completed in 1989. Investigations on particle production and nuclear stopping power were carried out.

We continue our study at the AGS with the second and third generation experiments, E859/E866. In E859, the concentration is on rarer events, utilizing a second level particle identification trigger to enhance pion, kaon and antiproton collection. The physics emphasis is on particle correlation study, strange particle and resonance production, and high momentum transfer phenomenon. The data collection for E859 was completed in 1992. The third generation experiment, E866, has just started with the newly commissioned gold beam. We are building a new multiplicity detector and a new

forward small aperture spectrometer for E866. The E802/E859/E866 collaboration is continuing works on data analyses, including the intermittency and particle production study carried out at Riverside.

2.1 Results from E802

2.1.1 Intermittency analysis for E802

A large concentration of particles in narrow rapidity regions was observed in ultra high energy cosmic ray experiment such as JACEE. The concept of intermittency was applied to this data analysis to understand the underlying physics of multiparticle production. Subsequently, this phenomenon was studied in electron-positron hadron-hadron, hadron-nucleus, and nucleus-nucleus collisions. In E-802, we use the Target Multiplicity Array (TMA) for this study. The TMA can measure the particle pseudorapidity η from -1.2 to 3.1 with almost full azimuthal coverage. An intermittency analysis was carried out on these data to study short range multiparticle correlations. Scaled factorial moments for the central collisions between 14.6 A-GeV/c ^{16}O projectiles and targets of Al, and Cu have been calculated with bin size up to $\delta\eta = 0.06$. An intermittency behaviour, power-law growth of moments with decreasing bin size, was seen up to $\delta\eta \sim 0.1$, with a stronger effect in lighter target than heavier target. The magnitude of the exponent parameter increases monotonically from the second order moment through the sixth order moment. Monte Carlo simulations with Fritiof and GEANT show that about half of the measured signal is accounted for from gamma-ray conversions, Dalitz decays, and detector effects; the remaining signal must be due to other physical processes. A paper has been written for this analysis and will be submitted for publication [Appendix A]. Results from this analysis together with the negative binomial distribution fits to multiplicity distributions were presented at the Quark Matter'93 conference in Sweden [Appendix B]. Further investigations are planned using such methods as strip correlation integral by P. Carruthers, and higher dimensional analysis. To estimate the contributions of the short range correlation to the intermittency, it might be possible to conduct similar analyses with the forward spectrometer data from the gold beam.

2.1.2 Correlation of particle yields with the angular orientation of projectile fragment transverse momenta

Ratios of produced pion and deuteron+triton yields to proton yield were examined in Si+Au collisions at intermediate impact parameters to determine the role of rescattering. The zero degree calorimeter (ZCAL) provides position information of the forward energy deposition, which can in turn be related to the left-right (x) and up-down (y) direction of the transverse momentum of projectile fragments. A left-right asymmetry of $(+34 \pm 8)\%$ in the ratio between pion and proton is observed, favoring interactions which take place on the near side of the target nucleus. No such asymmetry is observed in the up-down

direction. The deuteron plus triton to proton ratio surprisingly exhibits an asymmetry of $(-46 \pm 10)\%$ which favor interactions which take place on the far side of the target nucleus. This trend persists for Al and Cu targets at the same 44° spectrometer setting. These results suggest the possibility of studying the mechanism of nucleus-nucleus collisions at intermediate impact parameter range. The details of this study is published in Physical Review Letters [Publication 8]

2.1.3 Anti-proton production in p+A and Si+Au collisions

The anti-proton yield, due to the large annihilation cross section, is sensitive to the baryon density and hadronic formation times. The initial E802 investigation of anti-proton production in Si+Al and Si+Au collisions was limited by statistics. The total sample of anti-proton is $\sim 1,000$. The inverse slope, parametrizing the exponential distribution in transverse mass for anti-proton in central collisions, was found to be 140 ± 14 MeV. It is the smallest in comparison with the slopes of kaons and protons, but similar to the pion slopes. It is also similar to the anti-proton slopes obtained in pp and pA collisions at slightly higher energies than ours. The ratios of anti-proton to pion and kaon decrease with increasing target mass. The cause could be due to the large anti-proton annihilation cross section, the degradation of projectile energies while traversing the medium.

To continue this study, the antiproton production cross sections were measured in minimum biased p + A collisions at 14.6 GeV/c, with Be, Al, Cu to Au target. The laboratory rapidity coverage is from 1.0 to 1.6. The data was analyzed over one wide bin $\Delta y = 0.6$, as the total sample of antiprotons for all targets is ~ 300 . The inverse m_t slopes for various targets are similar, and the average value is 83 ± 18 MeV, the smallest compared to those of K, π , and p. Rapidity density distributions at this y range shows almost no target dependence. The relativistic cascade code (ARC) developed by Kahana et al. gives good agreement with the data by invoking a three-body screening mechanism which suppresses antiproton absorption in the medium. The experimental results were reported in Physical Review [Pub 9].

We have collected over $\sim 10,000$ antiprotons in central Si+Au collisions using the second level trigger in E859. The rapidity range is $0.8 \leq y \leq 1.8$. Preliminary results were reported by Peter Rothschild in HIPAGS93 in MIT. The inverse m_t slopes are almost independent of the rapidity, and drops slightly at $y > 1.3$. The mean value is approximately 213 ± 15 MeV, similar to the inverse slope for proton and consistent with the prediction of hydrodynamic expansion model. Two models, RQMD proposed by Jahns et al., and ARC, give comparable antiproton yields in agreement with the E859 data. However, they differ greatly in the production and subsequent absorption mechanism. RQMD gives enhanced production via collective production process and strong absorption to suppress the final states. ARC relies on mostly first high energy baryon-baryon collisions, while invoking a three-body screening mechanism to provide a

weaker absorption cross-section. To distinguish these very different processes, the Si+Al and high statistics Au+Au data will be essential.

2.1.4 Centrality dependence of K^+ and π^+ production in Si+A collisions

The forward energy deposited in the zero degree calorimeter (ZCAL) was used to classify centrality in A + A collisions in E802 in the study of strange particle production. A correlation between projectile participants and ZCAL kinetic energies was established. K^+ and π^+ multiplicities were studied in five windows as a function of projectile participants. For Al target, and for the most peripheral interactions for Cu and Au targets, multiplicities increase linearly with the number of projectile participants. For the highest three windows corresponding to the central collisions, the data rise much faster than linearly, and reflect the importance of multiple interactions. The K^+/π^+ ratio is the highest for central collisions with the largest target. These findings were published in Physics Letters [Pub 2]

2.2 E859 Status and Results

The E859 collaboration extends the investigation of particle production started by E802 to rarer events associated with high transverse momentum, interactions with small cross sections such as strange particle and anti-proton production, and multi-particle correlation. The major addition to the E802 apparatus includes a second level on-line programmable trigger for particle identification, and a phoswich detector array to study target rapidity proton production. The runs for E859 were completed in June, 1992 and the data are being analyzed.

2.2.1 Second Level Particle Identification Trigger

For the second generation E859 runs, a second level trigger associated with the magnetic spectrometer was implemented to select specific event topologies and to fully utilize higher intensity AGS heavy ion beams. This enabled us to obtain significantly more statistics in the measurements of inclusive spectra (π , K, p, d and anti-proton) and two-particle correlations ($\pi\pi$, KK, and pp). The input from the wire chambers as well as time of flight modules was processed for each track. The resulting data were fed into pre-calculated look-up tables, stored in five sets of Memory Look-up Units (MLU), to extract the momentum and the mass of this track. Information from all tracks emerging from the magnetic spectrometer was combined to form, for example, K^+ , K^- /anti-proton, 2π , $2K^-$, K^+K^- triggers. The operation of this trigger is programmable at run time. J. Kang is a member of the Second Level trigger group. He carried out the simulation of particle trajectories through the spectrometer system for hit locations in

wire chambers and time of flight modules, developed the code to generate the look-up tables, and maintained a set of particle identification tables.

2.2.2 K^+K^- and pion-correlation in Si+Au collisions

The Hanbury-Brown-Twiss (HBT) interferometry technique was applied to the positive kaon pairs for the first time to extract the interaction source size in central Si+Au collisions. The second-level trigger implemented for E859 enabled us to collect an enriched sample of 16,444 kaon pairs and 86,125 pion pairs. Only one-dimensional correlation function was used to fit the kaon data. After correcting for the motion of the pair frame, the rms radius for the kaon source is 3.22 ± 0.37 fm. This is to be compared with that of the pion source, 3.93 ± 0.28 fm. The pion data was obtained in a separate run with the spectrometer rotated to maximize rapidity overlap between the detected pions and kaons. The kaon source size is smaller than that for pions. This difference is comparable to the uncertainties in the data. Its significance must await further measurements before any meaningful interpretation on the production dynamics and reinteraction process can be extracted. These results were published in the Physical Review Letters [Pub 7].

2.2.3 E859 target rapidity proton distributions

The addition of the Phoswich Detector Array extends the minimum pseudorapidity coverage from $\eta=0.5$ to -0.76 . Since protons with negative pseudo-rapidities ($\theta > 90^\circ$) cannot be produced in free nucleon-nucleon collisions, any data in the backward angles can be used to study "collective effects." Proton kinetic energy spectra were measured with the Phoswich Array for various fixed angles, and grouped into three ZCAL energy bins. Energetic protons were observed at large angles. The spectra are well fitted to exponentials. For Si+Au, there is strong dependence on angle in the proton yield and in the inverse slope. No such dependence is seen for the central Si+Al collisions. These preliminary results were published in Nuclear Physics [Pub 4], and presented by Craig Sangster at the HIPAGS'93.

2.2.4 Resonance with strangeness final states

One of the interesting finds of E859 was the detection of the ϕ in the K^+K^- channel at 14 degrees. An enhancement in its production cross section was seen by NA38 at SPS energies. We are particularly interested in the production of ϕ and other vector mesons such as the K^* . These are of interest for two reasons. First their cross sections are expected to be enhanced for the same reasons that the K's are expected to be enhanced. Secondly, their masses and widths might be affected in dense, strongly-

interacting matter. However, present data does not allow us to calculate the cross section with sufficient accuracy.

E859 spent several days running a two K trigger at 5 degrees where the yield of ϕ 's should be greater. We also took some triggers with a minimum bias trigger so that cross sections between central and peripheral events can be directly compared. We have obtained a sample of several thousand ϕ mesons in the K^+K^- decay channel for central events. The inverse slope parameter is 176 MeV, similar to the kaon slope parameters. An interesting fact is that this implies that the slope parameters are not associated with the mass as expected from a thermally expanding source, where one would expect the ϕ inverse slope parameter to be similar to that of the proton. The cross section calculated is consistent with an extrapolation in energy of the known p-p cross section. A measurement of the cross section for peripheral collisions is necessary for a definitive result. Unfortunately we do not have enough data in our sample of peripheral collisions. Quian Zhu, a post-doc with our group is pursuing this subject. He will also study the ϕ from the upcoming E866 runs. This will be particularly interesting since the volume of the Au on Au collision is larger than for Si on Au and more of the ϕ 's will decay inside the fireball. Au on Au collisions at the AGS are expected to produce the highest baryon densities achievable in the laboratory (RHIC goes into the regime in which the nuclei are "transparent" and hence the baryon density for the central region will be near zero). Masses and widths are expected to be modified in high baryon density matter [1].

2.3 E866 Status

2.3.1 Introduction

In June 1992 the new booster at BNL made available for the first time gold beams for heavy ion experiments. This maiden run, E866, used the E802/E859 detector, moderately upgraded to handle higher multiplicities, and was proved to be very successful. For the major runs in the coming months, the collaboration is building a brand new small aperture forward spectrometer and a new multiplicity array detector.

The present segmentation of the wire chambers in the E802 spectrometer, designated "Henry Higgins", is mismatched at angles smaller than 14° against the large multiplicities in Au-Au collisions. The second spectrometer with 1/5 of the acceptance of the Henry Higgins, will be used to cover angles between 3° and 19° . August Smith, an undergraduate who has won an NSF award for minority students has been working with R. Seto on the calculation of the acceptance of the ϕ in E866. His preliminary calculations show that the acceptance of the new spectrometer at 3° is equivalent to the Henry Higgins at 14° making it possible to detect the ϕ in E866 given enough statistics. We are now looking into the possibility of triggering both spectrometers.

2.3.2 Motivation for target multiplicity array upgrade

As is presently configured E866 has only one global event trigger, namely the Zero-degree Calorimeter, ZCAL. A hardware trigger of $E_{ZCAL} < 400$ GeV (the most central 4% of the cross section) was used in the first run of E866. It is expected that this trigger would continue as the primary centrality trigger in future runs, especially in the case of symmetric collisions. ZCAL provides basic information about the geometry of the collision; however it is desirable to add complementary information of a global nature on an event by event basis to make further cuts. Of great interest are those events with high energy density, high baryon density or high entropy density, since extremes in these variable are necessary for the appearance of new types of physics such as a phase transition to the quark gluon plasma, or to a chirally symmetric state. High multiplicities would be associated with the production of entropy. In the case of the transition to a QGP even for a limited region of the fireball, the entropy is expected to increase since the number of degrees of freedom available to 3 quarks is more than is available to nucleons. Even without this phase transition large multiplicities would be associated with events which had an unusually high number of collisions. Such a situation would arise if the nuclei were more highly compressed resulting in an abnormally high baryon density. High baryon densities are of interest since effects such as shifts in the masses of particles resulting in the copious production of anti-baryons or a shift in the invariant mass spectrum of ϕ mesons decaying to kaons might be unambiguously observed. It would be nice to be able to plot various quantities, such as the K/π ratio, pion multiplicity, anti-proton multiplicity, and inverse slope parameters as a function of the multiplicity for the most central collisions to look for a correlated change in several different signatures. This would be done by comparing taking a sample of central events, that is events with little energy in the ZCAL, and comparing events with high and low particle multiplicity in the NMA.

Data taken in the first run of E866 already shows a range of ET's for the most central collisions using the lead glass, which will not be used in future runs. Figure 1 shows a contour plot of $ET(L+R)$ versus E_{ZCAL} , where $ET(L+R)$ is the transverse energy in the PBGL summed over both big and small blocks. One observes the upturn toward large ET and lowest ZCAL indicating that a range of ET values correspond to the most central events. Events with the lowest ZCAL and the highest ET would choose central events for which the produced particle production is high.

At present neither the TMA nor the lead glass are planned to be used for future runs. To provide a second global measurement, we are proposing to add a multiplicity array to E866.

2.3.3 Detector Design Goals

In addition to the obvious constraint of making the detector fit into the E866 setup, our goals in designing the detector are as follows:

1. To count produced particles (pions) and not nucleons, the majority of which are from the original Au nuclei.
2. To have a large coverage in pseudorapidity and as much azimuthal coverage as possible. Since the $dN/d\eta$ pion distribution is symmetrically peaked around $\eta=1.9$, we chose to measure from $\eta = -2$ to $\eta=2$, initially. A future upgrade to cover to $\eta=3.5$ or so can also be done at very little cost after studies of possible contamination in the forward spectrometer of secondary particles produced by this device can be studied during the next run.
3. To keep the background in the spectrometers to a minimum i.e. negligible. It is also necessary to keep the mass of the detector small in order that reasonable support structures can be constructed.
4. To minimize the delta ray contamination in the measurement of the multiplicity.
5. Low cost.

In addition to the total multiplicity, the proposed device will also measure $dN/d\eta$ on an event by event basis, and it will have the capability of measuring the reaction plane for cross section studies as a function of the azimuthal angle. It may also be able to provide a means of continuing the intermittency studies of Ju Kang and Tony Abbott.

2.3.4 Proposed detector

The proposed detector would be composed of about 500 modules of a solid cerenkov detector which would surround the target area. For the run in September 1993, a prototype of about 30 modules is now being constructed (figure 2). A picture of a basic module is shown in figure 3. The selection of Cerenkov light as the basic detection principle allows us to reject slow particles (mostly protons) giving us a device that measure primarily produced particles fulfilling requirement 1 above.

A second consideration in the design of the module was to convert photons so that π^0 's would be included in the multiplicity distributions. This is done by putting 0.3 radiation lengths (2 mm) of lead converter in front of the module. On the average each photon will have a 25% chance of conversion. This means that on the average each π^0 will contribute one minimum ionizing electron to the signal. (Every second π^0 will contribute an e^+e^- pair).

The lead has the additional advantage of stopping delta rays. In combination with a requirement that an electron penetrates at least 2 cm of the lucite to have a signal that is mistaken for a minimum ionizing particle, delta electrons with energy below 10-20 MeV will be rejected. This means that for a 1% interaction length gold target, and a central collision with about 700 particles in the final state, the error in the measured multiplicity introduced by delta rays is less than 3 percent.

2.3.5 Tests

Tests of the module were made using both the test beam available at BNL in August of 1993, and cosmic rays [Appendix 3]. Modules of various sizes and two materials, lucite, and BC480 were tested. BC480 is a lucite based material made by Bicron in which the Cerenkov light is absorbed by a waveshifter and re-emitted isotropically at a lower wavelength. It was hoped that the BC480 would show less of a position dependence than the lucite due to the isotropic nature of the emitted light. This turned out not to be the case, and we opted to use lucite. Figure 4 shows the pulse height obtained from the phototube of a 6cm^3 block of lucite as a function of position across the face of the module. There is a 20% increase in the region of the phototube. The number of photoelectrons collected was about 200. The position dependence increases the resolution from the intrinsic 7% due to the statistics to about 9% for a single particle. The overall resolution in the multiplicity will be of the order of 3%. Due to errors from other sources, such as delta rays and particles with velocities less than the Cerenkov threshold, we expect to make a measurement of $dN/d\eta$ with a resolution of better than 5%.

As was mentioned previously, we expect to have a prototype of about 30 modules installed for the run in 1993. This should allow us to have a preliminary measurement of the multiplicity distribution $dN/d\eta$. It will allow us to measure the resolution of the detector in the Heavy-Ion beam itself, and give us a measurement of the delta-ray background. Other uncertainties such as the response to slow particles should also be understood after this run.

2.3.6 Manpower

The group from UCR has been the driving force in the design and construction of this new detector. At present the modules are being fabricated in the UCR machine shop and shipped to BNL. Construction of the support structure is being done at BNL under the leadership of James Chang, the UCR post-doc at BNL. Several graduate students, Hong Xiang, Warren Eldredge, and Huan Liu are also involved working at BNL this summer. Phototubes were acquired from a group at Columbia. The bases, electronics and high voltage for the prototype are being provided by BNL.

2.4 Analysis of Au+Au data

Q. Zhu is working on the analysis of 11.6 GeV/c per nucleon Au+Au collisions. The data was taken by E866 at AGS in April 1992. Preliminary results from 44-degree spectrometer setting show a clear increase of K^+/π^+ ratio with total transverse energy of the collision E_t (an increase of almost 300% is observed in the kinematic region covered by the experiment). It is argued that strangeness enhancement or increase of inverse slope parameter from charge particle p_t distributions are possible signatures for the quark gluon plasma. After combining data from all spectrometer settings, we plan to perform detailed studies on the dependence of (1) K^+/π^+ ratio and (2) slope parameter from charge particle p_t distributions as functions of E_t , forward energy and rapidity.

3 PHENIX R&D

Riverside has joined the PHENIX collaboration to carry out future RHIC experiments. Our interests lie in the measurement of as many potential signatures of the Quark-Gluon-Plasma (QGP) as possible. These include the di-lepton production, direct and indirect photon production, hadron spectra, and global observables such as multiplicity and rapidity density.

We are part of the multiplicity-vertex detector subgroup to work on specifically the silicon multiplicity/vertex detector.

3.1 Multiplicity-Vertex Detector

Our group has taken a major role in the design and construction of the Multiplicity-Vertex Detector (MVD) for the PHENIX collaboration. This detector will have the dual purpose of providing a global multiplicity measurement and of finding the primary interaction vertex. High multiplicity events are an indication of the centrality of a collision and will be used as one of the primary ingredients to the level-1 trigger. A major change was made in the collaboration in that the subgroup originally responsible for the Multiplicity detector has redirected their interests to the tracking effort in the outer detector. Consequently the subgroup originally involved with the Vertex Detector took over this effort. Largely due to the ideas of Richard Seto, one of the members of the UCR group, a redesign effort took place integrating both the tasks of finding the vertex and determining the multiplicity into one detector, resulting in substantial cost savings, while actually increasing η range for both measurements.

The detector is constructed from an array of silicon detectors surrounding the vertex region. We are responsible for the fabrication of the mechanical structure. The structure immediately supporting the silicon wafers will be a ribbed cage of Rohacell foam. Rohacell is a lightweight, rigid polymethacrylimide foam developed for use by the aerospace industry. This material comes in several weights and grades. From the R&D results last year, and from the experience of the machinists, Rohacell 71 IG was chosen. Our machinists have successfully made a single ribbed structure, and work is now progressing to machine one full "ladder" at the full detector length of 60 cm. We have encountered some problems with warping of longer lengths of the material. This is due to the uneven density of the material due to cooling during the manufacturing process. This problem is approaching a solution.

In the progress report last year we reported seeing volume changes in Rohacell due to water absorption - a well known property of the material. Several coatings were tried and several worked satisfactorily. Volume changes were negligible for the coated samples at 100 % humidity until the temperature was increased to $140^{\circ}F$. At this temperature the sealing properties of the coating appeared to break down. This will not present any problem since the environment of the detector will be temperature controlled. We are

now in the process of fabricating the a full prototype of the Rohacell support structure. We have identified a source for inexpensive Silicon wafer blanks and will use these to simulate the detectors. The full assembly will then be subjected to tests for stability against cracking and warping due to temperature changes, humidity, and mechanical stresses. Much of this work was done by Dale Thompson, an undergraduate working with our group.

As mentioned earlier, we plan to construct a full scale prototype of the Rohacell support structure complete with silicon blanks for the detectors. We will then use the environmental chamber made last year to test its durability under temperature and humidity changes.

3.2 Silicon detector and electronics work

We are setting up a system to read out some "off the shelf" silicon detectors such as the SVX-D chip made for CDF at FNAL, and the AMPLEX chip. We have purchased several SVX-D chips, two Silicon detectors and the necessary readout modules (the SDA, SRS, port card and receiver card). The system includes a VAX for readout and communication with the SRS and SDA modules and a planned laser test box with an X-Y stand which is computer controlled.

Several undergraduates, Miguel Noriega, August Smith, Albert Gomez were involved with this effort. The goal was to build an x-y table with a infrared laser diode as a source to mimic minimum ionizing particles. One of the tasks was to focus the beam to less than 50 microns, the pitch of some commonly used detectors. Typically an optical fiber is used. On the advice of some of the optical physicists here, we opted to use lenses and focus the beam without the use of a fiber. The second task was to measure the response of particles transversing the detector at large angles. The multiplicity trigger depends on the fact that the charge collected by particles passing though the detector non-zero angles is proportional to $1/\cos\theta$.

The students constructed a computer driven x-y table which has a position resolution of 5 microns. A 1100 nm laser diode was purchased from EG & G corporation. The spot size, measured using the table, was focussed to a diameter of 20 microns. Initial tests were made using cosmic rays and a beta-electron source. These tests have proven more useful than laser tests for the study of large angle particles, because of the large index of refraction in silicon. It was found for beta particles, that the charge collected was proportional to $1/\cos\theta$ for angles less than about 45° . At larger angles less charge was collected than expected. We are at present studying this, since the effect could be due simply to multiple scattering of the low energy betas. Miguel Noriega and August Smith are continuing the work this summer. Ultimately a beam test is necessary. This is being planned for next year.

3.3 MC simulation for PHENIX

For the PHENIX experiment, Monte Carlo simulations using GEANT have been installed into an integrated program named PISA (PHENIX Integrated Simulation Application) and detector specific subroutines are being prepared by each subgroup responsible for each detector.

3.3.1 MVD MC work

Ju Kang, a post doc with our group has been responsible for a large part of the simulation work for the design of the MVD. He was responsible for setting up the initial files for the description of the detector in the larger frame-work of PISA - the PHENIX simulation program. Recently, there has been concern about the possible electron background from photons converting in the MVD. He is in the process of studying the effect of removing one or more of the "ladders" on both the physics measurement and also the electron background. Monte Carlo background estimations along with other simulation studies like vertex finding efficiencies will be pursued to optimize the design of the MVD.

3.3.2 Other MC work

Richard Seto continues to be interested in studying signals for the phase transition. In a summer workshop held at LANL Seto gave a presentation on the possibility of looking for particles - for example the ϕ meson decaying to dileptons, immediately at the phase transition boundary. Recent calculations made by Ko et al. [2] indicate that the mass of the ϕ is dependent on the temperature. Above the phase transition, no resonances are expected to exist. However, during the phase transition, hadronic matter will coexist with the Quark-Gluon Plasma at the phase transition temperature. If the transition is first order then the system will stay at a single temperature for a time of several fermi. ϕ 's which decay during this time will have a well defined mass shifted from the vacuum mass- giving a second peak in the dilepton mass spectrum. The second mass will be an indication of the transition temperature, while the rate will be an indication of the length of time the system took to completely change phases.

4 Other Investigations

4.1 Pair correlation study with HISS

The $\pi^-\pi^-$ correlation analysis using the data of 1.2 GeV/A La+La collisions collected with the HISS at the Bevalac has been completed. The source size is slightly oblate in shape. A dependence of the size on the mean momentum of the pion pairs is confirmed, with a smaller source size for the large mean momentum sample. A dependence on centrality is also observed, with a smaller size for the more central events. These results were published in the Physical Review [Pub 5].

4.2 Distortion of Two-pion Interferometry by Multipion Correlations

We investigated the effect of multipion correlations arising from the summetrization of the n -pion wave function on the extracted parameters from two-pion correlation measurements. Using two Bevalac streamer chamber data samples, we showed the effect is more significant on a smaller projectile/target system. These results were published in the Physical Review [Pub 1].

4.3 Muon-neutrino Carbon interaction

Muon-neutrinos from the in-flight pion-decay source at the LAMPF accelerator were used to study carbon charged-current interaction near the muon threshold. An inclusive cross-section was obtained which is in best agreement with the Fermi-gas model. However, there is a depletion of high energy muons, not predicted by the model. This study is reported in the Physical Review [Pub 6].

5 Personnel changes

James Chang, a postdoctoral in our group is stationed at BNL, together with a visiting scientist, Guanghua Xu. Quian Zhu, a graduate from Rice University, has joined our group as a postdoc. T. Abbott, now teaching at Reedley College, spends a month each summer with the group. Also working with us are two second-year graduate students, Warren Eldredge and Hong Xiang and two first-year graduates, Huan Liu, and August Smith. Three undergraduates, A. Gomez, M. Noriega and A. Smith, have graduated. Gomez will go to graduate school at U.C. Santa Cruz; Noriega plans for medical school.

Smith, a five-year NSF minority fellow, has joined the graduate program at UCR, and will continue to work in the Group.

6 Summary and Outlook

We have applied the intermittency analysis to the E802 oxygen data. The results are being written up for publication. We shall continue to investigate in depth this phenomenon at AGS energies. For the E859 we will take on the study of K^+K^- and K^* resonance formation. For the upgrade of E866 experiment, we are implementing a Cerenkov detector to replace the streamer tube TMA wall. We continue our development work of a silicon strip detector as a multiplicityvertex detector in PHENIX and our *R&D* efforts for RHIC.

Figure 1: $ET(L+R)$ of the PBGL versus the ZCAL energy for Au+Au from dedicated lead-glass run 11212 of April '92 (INT trigger.) Note the range of ET's for the most central events indicated by $T_{ZCAL} < 500\text{GeV}$

Figure 2: *Skematic of the prototype detector being installed for the 1993 run.*

Figure 3: *Design of one module of the NMA. The detector is composed of 500 modules.*

Figure 4: a) Pedestal subtracted pulse area distribution for particles hitting the center of one module. b) The position dependence of the pulse area across the face of one module.

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13. "Multiplicity Dependence of Two-Pion Correlations", HIPAGS '93 Proceedings, 397-405.

Version:4.1

Intermittency in Central Collisions of $^{16}\text{O}+\text{A}$ at 14.6 A·GeV/c

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Abstract

Fluctuations in pseudorapidity distributions of charged particles from central collisions of $^{16}\text{O}+\text{Al}$ and $^{16}\text{O}+\text{Cu}$ at 14.6 A·GeV/c are analyzed using scaled factorial moments. A power-law growth of moments with decreasing bin size is observed down to $\delta\eta \sim 0.1$. MC calculations with Fritiof and GEANT show that about half the measured signal arises from γ -conversions, Dalitz decays and detector effects.

The study of non-statistical fluctuations in particle densities produced during high energy collisions has recently attracted much attention. The initial motivation for these studies was the observation of large localized fluctuations in some high-energy experiments[1, 2], pointing to the possible existence of interesting new phenomena. Bialas and Peschanski introduced the method of scaled factorial moments to analyze these fluctuations[3]. This

technique is sensitive to structures on all scales, and thus provides a test for self-similarity in particle production. If the scaled factorial moments of a particle density distribution show a power law behaviour as the resolution is increased the distribution is said to exhibit “intermittency”. The term intermittency originated in the study of turbulent fluid flow, referring to large local fluctuations on many scales which exhibit self-similarity and power-law scaling. In the realm of high energy collisions, power-law scaling of the moments consistent with intermittency has been experimentally observed in various nuclear, leptonic, and hadronic interactions[4]. Several explanations have been proposed to account for these observations including parton showers leading to jet production[5], short-range correlations[6], and second-order phase transitions[7, 8]. It seems that many distinct processes could generate such fluctuations and a careful study of the moments could clarify the dynamics involved.

The data presented come from BNL experiment E802 using relativistic heavy ion beams available at the Tandem-AGS complex. A detailed description of the full E802 setup has been published[9], so only the detector system relevant to this measurement will be discussed here. The Target Multiplicity Array (TMA) is one of the detectors designed for global event characterization in E802. It measures the production angles of charged particles in the pseudorapidity range $-1.2 < \eta < 3.1$ with almost full coverage in azimuthal angle ϕ ; the primary gap in ϕ coverage is due to a small opening in the forward region to minimize the amount of material between the target and the E802 spectrometer. The TMA consists of resistive plastic tubes operated in proportional mode and read out from image signals induced on

cathode pads. There are 3240 pads in total and their sizes vary to ensure a nearly uniform occupancy rate. In order to eliminate electrical cross-talk over tube boundaries, thin copper grounding strips are located between the tubes. These strips are electrically connected to ground via conducting silver paint, and act as local RF shields which prevent pads from detecting signals on adjacent wires. It is still possible, however, to observe some small amount of cross-talk between tubes when particle tracks actually cross the boundaries between tubes; such “cross-counting” has been studied extensively using MC simulations and will be discussed in more detail below. Using proportional tubes with pad readout can produce another type of cross-talk which occurs between adjacent pads along the same tube: when two adjacent pads fire it is impossible to determine whether a single charged particle passed between the two pads, inducing signals on both, or whether two distinct particles caused the signals. To address this problem, a conservative TMA counting convention was adopted: during data analysis, two-clusters along a wire are always treated as single particles passing through local regions between the adjacent pads. Monte Carlo simulations indicate that this convention is correct for over 88% of two-cluster signals[10] in $^{16}\text{O}+\text{Cu}$ central collisions. In the remaining 12% of cases, however, one or more nearby tracks are lost; these losses will of course tend to reduce the measured strength of any highly localized fluctuations in the charged particle density.

Central collisions of $14.6 \text{ A} \cdot \text{GeV}/c$ ^{16}O on the lightest targets available (Al and Cu) were chosen for analysis to reduce multi-hit losses in the TMA detector and to minimize the ratio of target spectator protons to produced particles. Using information provided by the E802 Zero-Degree

Calorimeter[9, 11], the forward-going kinetic energy was required to be less than that of a single projectile nucleon (13.6 GeV). This cut, demanding that little or no kinetic energy remain in the projectile spectator region, served as the primary criterion for centrality. From a nuclear geometry calculation[12], only 0.23% (O+Al) and 3.2% (O+Cu) of minimum bias events would be expected to pass this cut. The number of events in the sample passing the centrality cut was 3555 for $^{16}\text{O}+\text{Al}$ and 20994 for $^{16}\text{O}+\text{Cu}$. Restrictions were also placed on which hits in the TMA detector were accepted for analysis. Due to the spectrometer opening and some malfunctioning tubes, an azimuthal angle cut of $40^\circ < \phi < 240^\circ$ was applied. The analysis was also restricted to those tracks falling in the pseudorapidity range $1.2 < \eta < 2.2$. This range includes the peak in the pseudorapidity density for both targets and is in the region where the detector segmentation and angular resolution are high and nearly uniform. Within these intervals, the detector had an hardware inefficiency of 6% (mostly due to malfunctioning pads), and an average resolution of $\sigma_\eta \sim 0.025$ in η and $\sigma_\phi \sim 0.027$ radians in ϕ . After including multiple scattering (mostly from the target), overall resolutions are $\sigma_\eta \sim 0.03$ and $\sigma_\phi \sim 0.034$ for the $^{16}\text{O}+\text{Cu}$ system.

Using the event simulator Fritiof[14], MC samples having the same number of events as the data were generated. Dalitz decay of π^0 was added to Fritiof and the output was fed through the GEANT package to simulate the detector response and secondary physical effects such as multiple scattering, γ -conversions, and particle decays. The GEANT output, which is a list of struck pads, was then analyzed after discarding malfunctioning pads just as in the real data. The small amount of cross-talk over tube boundaries was de-

terminated after comparing the measured rate of two-pad clusters on adjacent wires to the MC rate which included all the physical (conversions, decays) and geometrical effects. The rate at which pads on adjacent wires fired was 7% in the data and 3% in MC events; the difference of 4% was therefore added to the final MC, which was used in the subsequent analyses, to simulate the cross-counting which occurs in the real data. In Fig. 1, multiplicity distributions within the ϕ and η windows and pseudorapidity distributions after the ϕ cut are shown with the solid line (data) and dashed line (MC). The ZCAL requirement mentioned above for centrality was an indirect cut on multiplicity and thus did not produce a sharp edge on the lower side of the distributions, so the multiplicity distributions of charged particles inside the angular window are close to Gaussian with a slight asymmetry toward the high side. The mean values of the distributions are 16.4(5.0) for $^{16}\text{O}+\text{Al}$ and 22.6(5.5) for $^{16}\text{O}+\text{Cu}$ data with slightly smaller values for the MC. The numbers inside the parenthesis represent the dispersion $\sigma = \sqrt{\langle (n - \langle n \rangle)^2 \rangle}$; they are slightly greater than the $\sigma = \sqrt{\langle n \rangle}$ expected from Poisson statistics.

The scaled factorial moments, using “vertical” analysis, of order q is defined as [3, 13]

$$\langle F_q \rangle_V = \frac{1}{M} \sum_{m=1}^M \frac{\langle k_m(k_m - 1) \dots (k_m - q + 1) \rangle}{\langle k_m \rangle^q} . \quad (1)$$

M is the number of bins of size $\delta\eta$ into which the pseudorapidity distribution is divided, k_m is the multiplicity in the m th bin and $\langle k_m \rangle$ is the event-averaged multiplicity in the m th bin. The above moments become constants ($\langle F_q \rangle = 1$) if the fluctuations are purely statistical, since

$\langle k_m(k_m - 1) \dots (k_m - q + 1) \rangle = \langle k_m \rangle^q$ for the Poisson distribution. The measured moments using $^{16}\text{O}+\text{Al}$ and $^{16}\text{O}+\text{Cu}$ data are plotted in Fig 2a and Fig 2b, respectively. As shown by the solid fitted lines, a linear increase of $\ln(F_q)$ with increasing $-\ln(\delta\eta)$ is observed at all orders q down to $\delta\eta = 0.1$. Beyond $\delta\eta = 0.1$ the slopes $\phi_q = -d(\ln F_q)/d(\ln \delta\eta)$ roll over toward zero, especially for the lower-order moments. As will be discussed later, Monte Carlo calculations indicate that such slope changes at finer resolutions could be explained by finite detector resolution and segmentation. In the remaining four plots in the figure, the MC results are compared with the data for the second and fourth order moments. As already described, we used the conservative counting convention for two adjacent pads in the same tube, and we explicitly measured cross-talk over tube boundaries and included it in the final MC. Thus the additional intermittency we observe in our data must come from sources other than γ -conversions, Dalitz decays and instrumental cross-talk.

There are two different types of scaling rules which might apply to the measured slopes: “moments” scaling rules relate slopes of higher moments to ϕ_2 within the same data set, while “multiplicity” scaling rules relate slopes of fixed order in data sets having different mean multiplicity densities. One moments scaling rule has been proposed by Bialas and Hwa as a probe for the quark-gluon plasma[7]. They showed that the slope parameters ϕ_q were related to the anomalous dimensions d_q by

$$\phi_q = (q - 1)d_q , \quad (2)$$

and that all the anomalous dimensions of different q should be equal when

a system undergoes a second-order phase transition. As shown in Fig. 3a, our final slopes from the corrected moments¹ do not exhibit such behavior; instead, the moments scaling rule

$$\phi_q = \frac{q(q-1)}{2} \phi_2 \quad (3)$$

is approximately followed with a slight upward deviation. This scaling rule was proposed by Bialas and Peschanski[3] and was derived in the limit of a large number of cascade steps in their α -model of intermittency. This behaviour was also observed in another experiment[15]. A multiplicity scaling rule has also been proposed[16] to account for the tendency of the slope parameters to decrease with increasing pseudorapidity density[17, 18]. This observation is explained by assuming that high multiplicities are generated by the random superposition of S independent intermittent sources, in which case the slopes are decreased by a factor $1/S$. Since S is directly related to the pseudorapidity density the slopes can be plotted against $dN/d\eta$. In Fig 3b, the final slope parameters ϕ_2 from our experiment are plotted as a function of $dN_d/d\eta$, which is defined as the multiplicity detected in a particular ϕ and η interval per unit η without correcting for ϕ acceptance. For comparison, data points from two other experiments[17, 15] are included.

Care must be taken in interpreting these data since it can be shown that the measured slope parameter strongly depended on single track resolution and occupancy (or, two-track resolution) of the detector. To study the de-

¹The measured values of F_q are corrected for instrumental effects by subtracting $\Delta F_q^{\text{instr}}$, where $\Delta F_q^{\text{instr}} = F_q^{\text{det}} - F_q^{\text{input}}$ is determined by the Monte Carlo. Note that in Fritiof the input $F_q \simeq 1$ for all cases.

tector effects in a more generic way, a set of Monte Carlo events using the α -model of intermittency[3] was generated. The events show intermittency since the model generates a self similar random cascade exhibiting power law scaling. The power-slopes can be tuned to a desired value using two parameters(α, β) and the average multiplicity of the generated events can be varied to study the effect of different occupancy rates on the detector. The generated tracks were then thrown at a simulated detector having a segmentation chosen to match the angular resolutions estimated for our real detector in the chosen window of η and ϕ . Iterative techniques used to calculate inclusive $dN/d\eta$ and $dN/d\phi$ distributions[10] were employed to deduce that the multi-hit rate (ie, the rate at which a single pad is struck by two or more particles) in the $^{16}\text{O}+\text{Cu}$ data is approximately 1.5%. Using this number, average occupancies were estimated to be 9% for the $^{16}\text{O}+\text{Al}$ and 12% for the $^{16}\text{O}+\text{Cu}$ system. The effect of detector resolution and occupancy on the measurements of the moments was evaluated and results are shown in Fig. 4. In Fig. 4a, the slope parameter was chosen to have about the same magnitude as our measured slopes. For lower multiplicity events with occupancy 1%, the moments (see Fig. 4a) are smeared mainly due to finite angular resolution. The discrepancies between the expected and measured results increase as the bin size approaches the finite angular resolution of the detector. This effect becomes more pronounced with increasing occupancy because more tracks are lost in the detector due to multiple hits. The smearing is also more significant at smaller bin sizes where the resolution and occupancy effects combine to cause the slopes to roll off toward zero. Decreasing the slope of the true moments (by changing the parameter β in the

α -model) (Fig. 4b) increases the distortion and moves the roll-off to larger bin sizes. Thus, samples with smaller slopes must be measured with more finely segmented detectors to get comparable accuracy. For the particular model[3] used to estimate the detector smearing of the measured slope parameters (Fig. 4a), the true input slope of 0.028 in the interval $0.1 \leq \delta\eta \leq 1.0$ would be measured as 0.021, 0.018, and 0.015 for mean occupancy rates of 1%, 10%, 20%, where the middle value corresponds to the conditions of this experiment. Since the smearing effect may very well be model dependent, no correction is applied to the measurements and the results presented are the measured values. For strict tests of individual models, corrections would have to be calculated on a case-by-case basis, including a full detector simulation. The smearing effects for higher moments have also been evaluated and the ratio of the measured and input slopes are the same for the higher moments and F_2 within the statistical error.

In summary, the scaled factorial moments were calculated from central collisions of $^{16}\text{O}+(\text{Al,Cu})$ at $14.6 \text{ A} \cdot \text{GeV}/c$. The moments exhibited a power-law behavior up to $\delta\eta = 0.1$. An MC calculation which included γ -conversions, Dalitz decays and the instrumental cross-talk was performed and its moments were compared with the measured moments. It was found that about half the measured signal was explained by the above effects, whereas the remaining portion must be due to other physical effects not included in the MC. The measured moments were corrected for the above instrumental effects and the final slopes were then estimated. The final slope parameters approximately follow the scaling rule given by $\phi_q = q(q-1)\phi_2/2$. It was also found that the final slope magnitudes scale with detected multiplicity

as $1/(dN_d/d\eta)$. A study of detector effects using the α -model of intermittency and a simple idealized detector revealed that detector smearing due to finite resolution and segmentation modifies the measured slope and that the smearing increases for samples with smaller underlying slope parameters.

This work has been supported by the U.S. Department of Energy under contracts with ANL (W-31-109-ENG-38), BNL (DE-AC02-76CH00016), Columbia University (DE-FG02-86-ER40281), LLNL (W-7405-ENG-48), MIT (DE-AC02-76ER03069), UC Riverside (DE-FG03-86ER40271), and by NASA (NGR-05-003-513), under contract with the University of California, and by the U.S.-Japan High Energy Physics Collaboration Treaty.

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Figure 1: Multiplicity (a, c) and charged particle pseudorapidity (b, d) distributions, for central ^{16}O collisions with Al and Cu targets. These plots are uncorrected for acceptance and ϕ -bite ($10^\circ < \phi < 210^\circ$) and the multiplicities are for only tracks within the η window (shown with dotted lines in b and d) as these tracks are used for the intermittency analysis. Solid lines are from the data and dashed lines are from the MC.

Figure 2: Scaled factorial moments for central collisions of $^{16}\text{O}+\text{Al}$ and $^{16}\text{O}+\text{Cu}$. Lines represent linear fits to the moments up to $\delta\eta = 0.1$, which are then extrapolated to $\delta\eta = 0.05$. The F_q 's from the data are shown in (a) and (b). F_2 's from the data (circles) and MC (squares) are shown in (c) and (d), and F_4 's from the data and MC are shown in (e) and (f).

Figure 3: The tests of scaling rules. $2\phi_q/q(q-1)$ are shown in (a) as a function of q . The final slopes of the second order moments are shown in (b) as a function of average detected multiplicity density. The dashed line shows a line satisfying $\phi_2 \sim 1/(dN_d/d\eta)$. Data from EMU01[15] and KLM[17] are also shown.

Figure 4: F_2 's for α -model events with $\beta = 0.25$ are shown in (a). Dashed line shows true moments; the measured moments including the effects of the detector are shown for different occupancy rates. F_2 's for α -model events with $\beta = 0.1$ are shown in (b). Note that the scale here is a factor of 3 smaller than in (a).

Negative Binomial Distribution Fits to Multiplicity Distributions in Restricted $\delta\eta$ Intervals from central $^{16}\text{O}+\text{Cu}$ Collisions at 14.6A GeV/c and their Implication for “Intermittency”

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Fluctuations in pseudorapidity of charged particles from central (ZCAL) collisions of $^{16}\text{O}+\text{Cu}$ at 14.6 A·GeV/c have been analyzed by the E802 Collaboration using the method of normalized factorial moments as a function of the interval $\delta\eta$. In agreement with previous measurements, an apparent power-law growth of moments with decreasing interval is observed down to $\delta\eta \sim 0.1$. Experience with E_T distributions suggests that fluctuations of multiplicity and transverse energy can be well described by Gamma or Negative Binomial Distributions (NBD) and excellent fits to NBD were obtained in all $\delta\eta$ bins. The k parameter of the NBD fit was found to increase linearly with the $\delta\eta$ interval, which due to the well known property of the NBD under convolution, indicates that the multiplicity distributions in adjacent bins of pseudorapidity $\delta\eta \sim 0.1$ are largely statistically independent.

1 Introduction

AGS-E802 has been making an intermittency analysis of charged multiplicity data from the target multiplicity array (TMA) in central $^{16}\text{O}+\text{Cu}$ collisions. The centrality cut was made using the Zero degree Calorimeter (ZCAL) and requiring that the forward energy be less than one projectile nucleon (i.e. $T_{\text{ZCAL}} < 13.6$ GeV).

The concept of “Intermittency” was introduced to try to explain the ‘large’ bin-by-bin fluctuations on individual event (JACEE) rapidity distributions. In order to study fluctuations as a function of the size of rapidity interval, Bialas and Peschanski proposed

* Research supported by the U.S. Department of Energy, NASA, and the U.S.-Japan High Energy Physics Collaboration Treaty.

to use Normalized Factorial Moments and further proposed that the “spikes” in the rapidity fluctuations were evidence of **fractal** or “**intermittent**” behavior. Intermittency would be indicated by a power-law increase of normalized factorial moments of multiplicity over rapidity bins as the bin size is reduced[1]. The Normalized Factorial Moment with the clearest interpretation is

$$F_2 = \frac{\langle n(n-1) \rangle}{\langle n \rangle^2} = \frac{\langle n^2 \rangle - \langle n \rangle}{\langle n \rangle^2} = \frac{\sigma^2 + \langle n \rangle^2 - \langle n \rangle}{\langle n \rangle^2} = 1 + \frac{\sigma^2}{\mu^2} - \frac{1}{\mu}$$

where $\mu \equiv \langle n \rangle$ and σ^2 is the variance. Note that the Normalized Factorial Moments are all equal to unity for a Poisson Distribution.

The formulation of this new concept of intermittency in terms of moments was taken by many as an inelegant and confusing development, particularly since the greatest advance in multiplicity distributions in 20 years had recently been made by the UA5 Collaboration[2] who actually determined the functional form of multiplicity distributions. The Negative Binomial distribution was used by the UA5 collaboration as a “remarkable” description of their measured multiplicity distributions in intervals of rapidity which are not significantly constrained by conservation laws, and also for the total multiplicity. One could not help but wonder what “intermittent” behavior would look like in terms of distributions rather than moments—since once the distribution is known, then **ALL** the moments are known.

2 Negative Binomial Distribution (NBD)

The negative binomial distribution of an integer m is defined as

$$P(m) = \frac{(m+k-1)!}{m!(k-1)!} \frac{\left(\frac{\mu}{k}\right)^m}{\left(1 + \frac{\mu}{k}\right)^{m+k}}$$

where $P(m)$ is normalized for $0 \leq m \leq \infty$, $\mu \equiv \langle m \rangle$ and some higher moments are:

$$\sigma = \sqrt{\mu\left(1 + \frac{\mu}{k}\right)} \quad \frac{\sigma^2}{\mu^2} = \frac{1}{\mu} + \frac{1}{k} \quad F_2 = 1 + \frac{1}{k}$$

The NBD has an additional parameter k compared to a Poisson, and becomes Poisson in the limit $k \rightarrow \infty$.

3 NBD fits to the data

The AGS-E802 multiplicity distributions for central $^{16}\text{O}+\text{Cu}$ in bins of $\delta\eta = 0.1, 0.2, 0.3, 0.5, 1.0$, where the bin of 1.0 covers $1.2 \leq \eta \leq 2.2$ in the laboratory, are shown in Fig. 1. For each bin size, $\delta\eta$, all the distributions have approximately the same number of events, 19667. The solid lines on the data are NBD fits. Note that the exact details of the centrality cut are important for Fig. 1 and presumably also for intermittency analyses by moments. The excellent fits of the NBD to all the distributions makes it credible that the ZCAL centrality cut, which is an indirect cut on multiplicity, may in fact give a shape for the rising (lower) half of the distribution that has a real physical meaning. Approximately 3.2% of minimum bias events would be expected to pass the centrality cut, thus the data in Fig. 1 correspond to ~ 0.6 million interactions.

3.1 A striking result

The k parameter of the NBD fits is plotted in Fig. 2 and shows a totally unexpected and striking **linear** dependence on $\delta\eta$. The linear evolution of the NBD fit parameter k with $\delta\eta$ indicates that the multiplicity in each rapidity bin is largely statistically independent of that in the next bin, since the linear evolution of the NBD parameter k means that the multiplicity distributions convolute as the bin size is extended. The fact that the measured multiplicity distributions are excellently fit by distributions (NBD) with well known properties under convolution enables this observation to be made by inspection.

This result explains and demystifies “intermittency”. **Intermittency is nothing more than statistical independence of the multiplicity in rapidity bins of size $\delta\eta \sim 0.1$ (in central O+Cu collisions)!** The “Intermittency” phenomenology, which looks for *self-similar fluctuations at all scales* $\delta\eta$ by an fractional power-law increase of bin-averaged Normalized Factorial Moments with decreasing bin size $\delta\eta$, **obscures the real physics of multiplicity fluctuations** which is given simply and elegantly by the linear evolution of $k(\delta\eta) \equiv 1/(F_2 - 1)$. The apparent fractional power law is simply an artifact of using $F_2 - 1$, which is the inverse of a linear quantity.

4 Relationship to two-particle correlations

The importance of Two-Particle correlations to completely determine the multiplicity distribution was pointed out by Fowler and Weiner[3]. More recently, Carruthers and Sarcevic[4] contended that “the increase of bin-averaged factorial moments with decreasing size of the rapidity bin δy can be understood on the basis of conventional short range correlations. . . .”

The Reduced 2-particle Correlation is parameterized in an exponential form

$$R(y_1, y_2) = \frac{C_2(y_1, y_2)}{\rho_1(y_1)\rho_1(y_2)} = R(0, 0) e^{-|y_1 - y_2|/\xi} \quad (1)$$

where $\rho_1(y)$ is the inclusive single particle density, $C_2(y_1, y_2)$ is the Mueller[5] 2-particle correlation function, and ξ is the correlation length. Then, for an NBD [6, 3, 4]

$$k(\delta\eta) = \frac{1}{F_2 - 1} = \frac{\langle n(\delta\eta) \rangle^2}{\int^{\delta\eta} dy_1 dy_2 C_2(y_1, y_2)} = \frac{1}{R(0, 0)} \frac{\delta\eta/2\xi}{(1 - e^{-\delta\eta/2\xi})} \quad (2)$$

This formula represents a mathematical expression of the observation that the linear increase of k with $\delta\eta$ is an indication of the randomness of the multiplicity in adjacent $\delta\eta$ bins, while the constancy of k with increasing $\delta\eta$ would be an indication of 100% correlation. In the limit $\delta\eta \ll \xi$, when the $\delta\eta$ interval is well inside the correlation length, $k(\delta\eta) = 1/R(0, 0)$, a constant. In the limit $\delta\eta \gg \xi$, k increases linearly with $\delta\eta$. $k(\delta\eta) \simeq \delta\eta/2\xi$, as expected from convolutions of independent bins. The dashed line on Fig. 2 is a fit to Eq. 2 which indicates a weak correlation strength $R(0, 0) = 0.066 \pm 0.004$ and a very short rapidity correlation length $\xi = 0.12 \pm 0.01$. These derived parameters are still preliminary, and it is estimated that approximately half the correlation strength is instrumental.

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Figure 1: E802 multiplicity distributions for O+Cu central collisions in individual $\delta\eta$ bins as indicated. The data are plotted scaled in multiplicity by the mean $\langle n \rangle$ in each bin. The solid lines are NBD fits.

Figure 2: The k parameter from fits to the data in Fig. 1 as a function of $\delta\eta$. The dashed line is discussed in the text.

SUMMARY OF TESTS OF THE PROTOTYPE E866 NMA MODULES

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August 1993

1 INTRODUCTION

The Heavy Ion Research Group at the University of California, Riverside has been deeply involved with the Target Multiplicity Array (TMA) detector of the original E802 experiment. The experiment E866 is a continuation (preceded by E859) of the E802, using the recently commissioned gold beam at the AGS. The original TMA is inadequate for the much higher multiplicities of particles associated with the gold on gold collisions. For this reason, a proposal for a New Multiplicity Array (NMA) was presented to the E866 collaboration. The proposal is well justified from physics point of view, and the E866 management is supportive of the idea.

The physics associated with the NMA can be described briefly. To handle the high multiplicities of the gold on gold collisions, the NMA is designed to respond only to a select group of particles, namely the charged particles traveling faster than $\beta > 0.67$. This is accomplished by utilizing the threshold Cerenkov light created in a optical grade acrylic plastic commonly known as Lucite. This material is readily available commercially and is relatively cheap. A block of this plastic (to be called UVT subsequently) coupled to a photomultiplier tube (PMT) makes up a single module. A simple diagram of the module is shown in figure 1. An array of these modules all point at the target, and the coverage is such that most of the select group of particles it sees are pions. Since pions are produced particles that are created in the collision, measuring pion multiplicity gives the measure of how violent the collision was. By selecting the most violent collisions, one can hopefully observe the signatures of high baryon density states expected at the AGS energies.

The NMA is scheduled to be implemented in two phases. First is the prototype containing a fraction of the full array. This device will be tested

in the E866 engineering run during the month of September, 1993. The goal of this run is to see how the modules work as a group, and to understand the systematic effects associated with it. The second phase is the full array itself to be completed before the E866 data taking run in the late spring of 1994.

Before any array is built, we must understand how an individual module works. We have been testing the UVT Cerenkov module during the past year, beginning with cosmic rays and computer simulations. During the months of June and July, 1993, we tested the modules in the test beam at the AGS. The B1 line (E866 experimental area) received secondary negative particles during the night. Getting beam into the area during daytime was not possible due to the on-going preparations and constructions for the E866 experiment. The beam consisted of roughly 80% negative pions and 20% electrons, and had momentum of either 2 GeV/c or 12 GeV/c. Our test setup is shown in figure 1. It consisted of three beam defining counters. The S2 counter had an active area the size of 0.5 cm x 0.5 cm, and was used to determine the hit location on the test module that sat immediately downstream of it. The trigger requirement was a triple coincidence of $S1 \cdot S2 \cdot S3$. With this requirement, the trigger rate was about 30 counts per spill, where a spill lasts for about a second. The test modules themselves sat on a platform that could be moved via rope and pulley system. The motion was restricted to the transverse direction. The pulley system was simple and crude, but it was easy to use and provided us with sufficient position accuracy. The actual position of the module relative to the S2 counter was monitored by a closed-circuit TV camera. Data acquisition was done using a CAMAC and MacIntosh computer.

We had several goals in mind when the beam tests began. They were:

- See if enough Cerenkov light can be collected.
- The resolution of the module. That is, see if the resolution is good enough to be able to distinguish between one particle and multiple particles.
- See how the response depends on the hit position on the module.
- Compare the test beam results to the cosmic ray results and computer simulations. Use the data to fine tune the simulation parameters for later design use.

The results and interpretations are summarized in the following sections.

2 Test Beam Results

The UVT sample tested is the Ultra-Violet Transparent grade acrylic plastic manufactured by the Polycast Corporation. Polycast was kind enough to send us a 6.3 cm (2.5 inches) thick sample of their product for testing. We also tested a waveshifting material BC480 manufactured by the Bicron Corporation. This is basically an optical grade acrylic plastic with waveshifting organic molecules doped into it. BC480 has two features that distinguish it from UVT: First, the Cerenkov light created by the charged particle is absorbed by the organic molecules and re-emitted at a longer wavelength. The emitted wavelength is closer to the optimum wavelength band of the PMT, thus giving a greater photoelectron yield. Second feature is that the re-emission of light is isotropic, as opposed to the directional nature of the light in a Cerenkov cone. The idea was to see if the isotropic property would reduce the position dependence.

The test consists of reading out the CAMAC ADCs for a given module with the beam hitting the module at a known location. Figure 2 shows a typical ADC distribution. The mean and width are extracted from the peak. Various sized modules were tested, and the results are summarized in table 1. The last column gives the resolution of the module, and as one can see, both UVT and BC480 have about the same resolutions at 5 to 10%. The best resolution we observed is 4% from the 2.5 x 2.5 x 5 cm UVT. If one assumes that this width is purely due to statistical fluctuations, then the number of photoelectrons seen is $(1/0.04)^2 = 625$. This is considerably more than we had predicted, and is quite encouraging.

The position dependence of signals from the modules is plotted in figure 3. A signal at a given position is normalized to the center signal. As one can see in the figure, both materials suffer a drop of 10 to 20% in signal depending on the size. The small 2.5 x 2.5 x 5 cm module (both UVT and BC480) displayed no sign of position dependence. And as expected, larger modules suffer more signal loss at the edges. Earlier cosmic ray results have shown that signal would decrease as the distance from center increased; thus

the test beam results in this regard was not surprising.

2.1 Module Compensation

Ideally one would like to design a module that shows no position dependence. Our interpretation of the decrease in signal is two-fold: First, the light created at the edges must travel a greater distance before entering the PMT; so the light attenuation becomes a factor. Second, the the PMT face glass itself acts as a Cerenkov radiator, as seen in the last row of table 1. Again, if we assume statistical fluctuation only, the number of photoelectrons seen due to the 1.5 mm thick glass is about 30. This is roughly 5% of the 625 photoelectrons due to 5 cm of UVT plus the glass. So whenever a hit occurs outside the radius of the PMT (1.5 cm), then the signal is reduced by 5% automatically. With these in mind, we attempted to make the signal more uniform across the module. The first obvious method was to drill a hole, with a diameter same as that of PMT, on the opposite side. This so-called *compensated* module is illustrated in figure 4. The primary goal here is to reduce the signal from the center by removing a portion of the radiating material. Figure 5 shows the position responses for two hole depths in the 6.3 cm UVT blocks. As one can see, the first attempt at compensation (3 cm deep hole) does not work. The center signal is still considerably stronger than the edge signals. The second case (5.3 cm deep hole), however, shows signs of reduction of center signals relative to the edge signals. We also tried compensating 3 cm thick UVT blocks, and the results are shown in figure 5; one can see that compensating does not work in this case. Looking over the results, we make the following observations and interpretations:

- The compensated modules, whether they work or not, suffer in terms of resolution. While the σ/mean for the uncompensated modules were in the range 5 to 10%, the compensated modules have σ/mean in the 10 to 17% range.
- Simply removing radiating material from the center region is not sufficient enough to reduce the relative signal. When a hole is introduced in the center, it creates a cylindrical wall that reflects away a lot of light from the edges. Thus, the edge signals also suffer.

- To really reduce the center signal, one must cut into the Cerenkov cone that gets accepted directly into the PMT. This cone is illustrated in figure 4, and for the UVT/PMT combination ($n_{UVT} = 1.5$, $R_{PMT} = 1.5$ cm) the height of the cone is 1.34 cm. This is probably the reason why the 3 cm deep hole did not work while the 5.3 cm deep hole (both are 6.3 cm thick blocks) showed signs of compensation.
- The 3 cm thick UVT compensation did not work even though we cut into the direct Cerenkov cone. We interpret this in the following way: In order for compensation to work, sufficient light must be created at the edges to overcome the losses due to the introduction of a hole. And apparently the 3 cm thickness is not sufficient enough.

3 Summary and Future Work

Although some of the interpretations given above are conjectures at best, the test beam results gave us a much better understanding of how the module behaves. Unfortunately, the AGS test beam ended before we could explore more compensation ideas. We have, however, enough data to fine-tune the computer simulation parameters for design work.

It is clear that a simply drilling a hole for compensation does not work sufficiently well. When one folds in the intrinsic resolution with the position dependence of an uncompensated module, the net effect is such that the module can still distinguish up to 3 particle hits. Furthermore, position dependence is mostly a problem for big modules; these modules will be situated in the backward angles where average occupancy is very low. So, one does not gain much by compensating the position dependence and making the intrinsic resolution worse.

As far as the choice of material is concerned, both UVT and BC480 performed about the same. BC480 has a drawback in that it is more expensive, and also has a small (about 10%) scintillation light component.

The plan for the prototype array is to use the UVT material and keep the modules uncompensated, since the net resolution is shown to be good enough. The array, however, will be flexible enough to accommodate test modules (a compensated module, for example) at any time during the run. The full array will not be so flexible since space is very constrained. The

final decisions for module configuration will have to be made after looking at the data from the actual gold on gold collisions.

4 Acknowledgements

The test beam setup and data-taking were done by Guanghai Xu, Hong Xiang, Warren Eldredge, Richard Seto, James Chang, all from University of California at Riverside. We also had some help from Larry Ahle and Craig Ogilvie of MIT. The author would like to thank Karim Ashktorab of BNL for a great deal of help in data acquisition.

Enlarged view of the test module

Test beam setup at the AGS B1 beamline

Figure 1: Top: Sketch of a test module. Bottom: Test beam setup at the AGS B1 line. S1 and S2 are 30 cm apart, as is the S2 and S3.

Figure 2: Typical ADC spectrum. This one is from a 3.2 cm thick BC480 with 4 cm x 4 cm dimensions. The UVT spectrum looks similar.

Figure 3: Relative signal as a function of distance from the center for different sized modules. The UVT and BC480 are plotted separately to avoid cluttering.

Figure 4: Top: Sketch of the compensated module. The diameter of the drilled hole is same as that of the PMT, about 3 cm. Bottom: The Cerenkov cone that goes directly into the PMT.

Figure 5: Top: Compensated modules' responses for 6.3 cm thick UVT. Bottom: Same plots for 3 cm thick UVT.

MATERIAL	SIZE (cm)	THICKNESS (cm)	DISTANCE FROM CENTER (cm)	MEAN ADC	σ	$\frac{\sigma}{MEAN}$
UVT	2.5 x 2.5	5.0	0.0	517	18	0.035
"	"	"	1.0	523	17	0.033
UVT	4 x 4	6.3	0.0	498	20	0.040
"	"	"	0.6	490	21	0.043
"	"	"	1.3	467	24	0.051
"	"	"	1.9	455	21	0.046
UVT	6 x 6	6.3	0.0	525	38	0.072
"	"	"	0.6	525	41	0.078
"	"	"	1.3	464	41	0.088
"	"	"	1.6	458	40	0.087
"	"	"	2.5	440	37	0.084
UVT	8 x 8	6.3	0.0	642	38	0.059
"	"	"	0.6	634	36	0.057
"	"	"	1.3	559	39	0.070
"	"	"	1.9	529	36	0.068
"	"	"	2.5	514	32	0.062
"	"	"	3.2	514	33	0.064
"	"	"	3.8	517	30	0.058
BC480	2.5 x 2.5	5.0	0.0	568	27	0.048
BC480	4 x 4	3.2	0.0	372	31	0.083
"	"	"	0.6	355	23	0.065
"	"	"	1.3	329	29	0.088
"	"	"	1.9	315	22	0.070
BC480	6 x 6	3.2	0.0	360	31	0.086
"	"	"	0.3	360	31	0.086
"	"	"	1.0	344	27	0.078
"	"	"	1.6	304	27	0.089
"	"	"	2.2	290	23	0.079
"	"	"	2.9	284	26	0.092
BC480	8 x 8	3.2	0.0	725	40	0.055
"	"	"	0.6	699	69	0.099
"	"	"	1.3	614	55	0.090
"	"	"	1.9	579	47	0.081
"	"	"	2.5	563	43	0.076
"	"	"	3.2	548	43	0.078
"	"	"	3.8	533	42	0.079
Bare PMT	N/A	N/A	0.0	95	17	0.180

Table 1: Summary of scanning the various module sizes.

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