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Ultra-Relativistic Heavy Ion Nuclear Physics
Progress Report

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W.J. Braithwaite, PI
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I. Introduction to ultra-relativistic heavy ion nuclear physics

G.T. Anderson, W.I. Braithwaite, M.T. Burks, C.A. Byrd, C.M. Byrd, M.R. Clark, A.D. Climer, C.W. Ford, W.C. Hall, W.H. Howe, G.D. Mauldin, S.E. McCloskey, D.L. Roetzel, A.A. Rollefson, A.T. Sustich and D.C. Wold

Physics goals of the UALR/URHI research group

This report describes an on-going research initiative for the University of Arkansas at Little Rock (UALR): investigating the physics of ultra-relativistic heavy ions, i.e. collisions between massive nuclei which have been accelerated to kinetic energies so large that the rest mass of the ions is a negligible fraction of their total mass-energy. This progress report is being submitted in conjunction with a 3-year grant-renewal proposal, containing additional materials.

Three main categories drive the UALR ultra-relativistic heavy ion research. (1) investigations of multi-particle Hanbury-Brown-Twiss (HBT) correlations in the CERN and RHIC energy domains strongly influence the URHI experimental effort, (2) participation in the NA49 Experiment to study 33 TeV (160 GeV/nucleon) Pb on Pb collisions using the SPS facility at CERN, and (3) participation in the STAR collaboration which is developing a major detector for use with the STAR Experiment at the Relativistic Heavy Ion Collider (RHIC), being built at BNL.

The URHI group's interest in HBT correlation analysis of relativistic nuclear collisions is focusing the group's experimental efforts primarily on TPC technology, starting in 1992 with our participation with IKF Frankfurt in the NA35 TPC data reconstruction algorithms (Roland, 1992; Byrd, 1994). Recent URHI contributions to STAR's main TPC are Optimizing tracking software for the STAR's main time projection chamber (section V.) and Use of event displays to improve tracking in time projection chambers (section VI.). The URHI group is contributing to vertex tracking in STAR because of its contributions to improved momentum resolution for secondary particles, important for HBT analysis. Also, a vertex tracker will allow the use of pairs of neutral K_s for HBT interferometry (Keane, 1992), where each neutral kaon is reconstructed in the vertex tracker from its charged pion decays: A Rough-Set based grouping algorithm for charged particle tracking (section IV.). The URHI group is working with the STAR TPC group to extend the TPC technology to a low-mass vertex TPC (Wieman, 1994; 1995a; 1995b). See section II: Using a micro-strip readout chamber for testing a new micro TPC concept and section III: A tracking module for a low-mass, vertex time projection chamber.

Student participation in the UALR/URHI research group

The objectives of the URHI group include a training component for undergraduate and graduate students which merits attention equal to that of the research goals of the group. Student development is consistent with our research goals because of the time and focus students bring to the projects on which they work once they are

"brought up to speed." Student research presentations are vital to focusing student research efforts. For new students, an APS presentation provides a forum for early successes when a full paper is not yet warranted. For more mature projects, a presentation at a professional meeting with edited proceedings allows each student to write up a detailed account of the research work. Meetings with edited proceedings require the submission of a completed manuscript at the time of the oral presentation. Students work with amazing diligence to complete their research projects and manuscripts. Budgetary issues determine the conferences students may attend. The URHI group has made extensive use of the annual meetings of the Arkansas Academy of Science, as students may give presentations there, followed by submission of papers to the Proceedings Editor, with those selected being published.

How are students "brought up to speed?" A critical mass of undergraduate and graduate students is important so more advanced students are available to help the new students. One feature of student-to-student mentoring is both students increase their skills. Student motivation is crucial, but almost automatic when students start to make significant research contributions. Care is taken in recruiting the highest quality students to assure the best work is done with the least wasted effort. Once a student makes research contributions meriting publication, this success encourages subsequent research and learning is increased. Also, students with excellent academic records and research publications are able to compete successfully for financial support, even at the undergraduate level. These financial successes have allowed the URHI group to leverage the DOE grant, so it was able to provide support for several undergraduate and graduate students.

Role of HBT considerations on the UALR experimental effort
[see proposal section on Hanbury-Brown Twiss Interferometry]

One possible consequence of stimulated pion emission is the production of a fairly large number of coherent, low energy pions. This idea provides additional motivation for increasing the efficiency of low-momentum pions in the primary detectors. The UALR/URHI group has worked on Optimizing tracking software for the STAR's main time projection chamber (section V.) where the reconstruction efficiency for low-momentum pion tracks is improved.

The main TPC tracking algorithm did not take into account energy losses for low-momentum pions as they passed through the TPC. This failure resulted in single low-momentum tracks being speciously broken into two (or more) tracks. These incorrectly fragmented tracks appeared as two (or more) pions with low relative momentum, which could produce a false peaking in an HBT analysis.

This detection of false-pairs from the tracking reconstruction algorithm was made possible, in part, by the UALR visualization effort in the Use of event displays to improve tracking in time projection chambers (section VI.).

II. Using a microstrip readout chamber for testing a new micro TPC concept

Howard Wieman (LBL), Morgan T. Burks, W.J. Braithwaite, Wen Gong (LBL), Spiros Margetis (LBL) and A. Andre' Rollefson

A drift chamber type radiation detector is being used to examine design criteria for a new type of detector called a micro Time Projection Chamber (micro TPC) which is being proposed for use in high energy nuclear physics experiments. The main advantage of the micro TPC detector is its very low radiation thickness compared to its silicon counterpart, the Silicon Vertex Tracker (SVT).

A partial end view of the of the micro TPC (VTX) is shown on the right. In STAR, the VTX is designed to be the detector placed closest to the collider vertex, inside or in place of the SVT.

The micro TPC is a charged-particle detector which will be optimized for good two track resolution which is needed in a high track density environment. Such performance requires low electron diffusion and high resolution readout.

Diffusion is reduced by limiting the drift distance to 15 cm and by using a low diffusion gas such as dimethyl ether. [A cutaway side view of VTX (the micro TPC) is shown on the right.]

High resolution in VTX will be obtained using the new readout technology called microstrips.

Microstrips are a recent development using photolithography techniques that allow the creation of anodes a few microns in width with submicron precision. Microstrips are being used in a test chamber whose main purpose is to demonstrate the feasibility of a micro TPC design using a low diffusion gas and to insure that sufficient signal remains after electron attenuation. The drift chamber design and the testing procedures are described.

In high energy nuclear physics experiments, such as those proposed for the Relativistic Heavy Ion Collider (RHIC), high particle density puts an extra demand on a detector's ability to distinguish between close pairs of tracks. A new type of detector has been proposed (Wieman, 1994) which will be optimized for low mass and good two-track resolution. This detector is called a micro TPC because it utilizes microstrip anodes for readout.

A time projection chamber works on the principle that radiation passing through a gas ionizes the atoms in its path and leaves a trail of electrons along the way. The electrons are forced by means of an electric field to drift towards anode wires at one end of the chamber. As the electrons approach a distance of a few times the wire radius r , the electric field felt by the electrons increases as $1/r$. In this high potential region, the electrons accelerate enough to ionize other electrons which in turn accelerate and ionize even more electrons and an avalanche forms. This avalanche is known as the amplification or the gas gain and insures that a sufficient number of electrons are produced to obtain a detectable signal.

Traditionally, the anodes were thin wires capacitively coupled to readout pads. Recently, however, a new technology known as the microstrip detector (Oed, 1988; Angelini, 1991 and 1992) has been developed which can be used in a micro TPC as an alternative readout technique. These microstrip detectors use thin metal electrodes on an insulating substrate which, by using precise photolithography techniques, can be spaced accurately on the order of a few microns. This distance is significantly smaller than what one is able to accomplish with conventional readouts and the position and two-track resolution are correspondingly improved. For this project, microstrip detectors have been fabricated at the Berkeley Micro-Fabrication Laboratory (Gong, 1994).

Dimethyl ether (DME) has been chosen as a promising candidate for the drift gas of the chamber. The limits of position resolution and two-track resolution in the micro TPC design are set by the diffusion of the drift gas, and DME has been shown to have a very low diffusion constant (Villa, 1983). In addition, limiting the drift length of the chamber to 15 cm will help to keep the diffusion low.

One of the main concerns in the use of DME in the micro TPC design is the electron attenuation due to electron attachment coupled to the relatively slow drift velocity, resulting in a loss of part of the signal. The number of electrons lost increases exponentially with the drift length and the concentration of electro-negative pollutants (Sauli, 1977). Since the proposed drift length is relatively long,

the purity must remain exceptionally high for proper functioning of the detector. Thus, a primary purpose of this test chamber is to measure the electron attenuation to insure that a sufficient number of electrons reach the microstrip anodes. Also, if necessary, purification methods will be studied to determine how to best minimize pollutants that cause electron attenuation.

The test chamber (right) is an aluminum cylinder with quartz windows located on one side for the purpose of shining a laser into the gas chamber. The laser will act as an electron point source by ionizing atoms of the gas. The quartz windows are attached with high vacuum quality flanges. The other side has two thin aluminum windows to allow the passage of X-rays from an ^{55}Fe source. Also, the top of the chamber has a quartz window to allow a laser to shine in from the top. The position of this laser is varied with a translation stage for the purpose of measuring the diffusion width of the electron cluster.

In summary, a new type of detector, called a micro TPC, has been proposed. This detector would help meet the needs of high energy nuclear physics experiments to track charged particles in high track density environments. The performance of the micro TPC will require a low diffusion drift gas combined with high resolution readout. DME has been chosen initially for the drift gas. The test chamber described above is needed to demonstrate the feasibility of a micro TPC design and to test the performance of DME as a drift gas.

A simulation has been done showing the dependence of the performance of the micro TPC on various parameters such as geometry, multiplicity of particles and the measured value of the DME diffusion constant (Wieman, 1995). Unlike other properties of DME, however, the value of electron attenuation at a drift length of 15 cm is very uncertain and must be measured. In addition, measurements of the other properties of DME are being made to confirm earlier reported measurements of its properties.

Also, this chamber allows testing of different cleaning strategies for DME, in order to minimize the attenuation of ionization-electrons within the DME. Once the extent of this minimized attenuation is established as a function of drift length, these data will be used in a simulation for optimizing of the exact length of anode, in order to maximize two-track resolution while maintaining sufficient signal.

III. A tracking module for a low-mass, vertex time projection chamber

Christine A. Byrd, Wilson H. Howe, Amber D. Climer and W. J. Braithwaite

A charged-particle tracking module was written and tested using pixel data generated from CERN's Monte Carlo detector-modeling program Geant. This tracking module was customized for testing the design of a micro-strip gas time projection chamber, designed by Drs. Margetis and Wieman of the Relativistic Nuclear Collisions Group at Lawrence Berkeley Laboratory. This low-mass, high-resolution, small-geometry vertex time projection chamber was designed for use with STAR. Implementing this tracking module involved generating tables and source code in a manner which is accessible to any user who is familiar with general purpose programming, using event-based data-processing. This charged-particle tracking module project was initiated in Summer-1994 as part of a 10-week, undergraduate research project at Lawrence Berkeley Laboratory, sponsored by LBL's Office of Science and Engineering Education. Research on this project is continuing at UALR and at LBL to the present.

The Vertex Tracker (VTX), a small low-mass, high-resolution, vertex time projection chamber (TPC) with Micro-strip read-out, is a technology being explored to provide tracking in the forward region, close to the beam-pipe, and is the subject of a feasibility study underway as part of STAR's flavor physics program. The VTX detector is designed to provide tracking at smaller polar angles, more space-point measurements per track and less material than would, for instance, a silicon system located in this region (Angellini, 1990).

Plots were made of the maximum distance in phi ($d\phi$) and in z (dz) versus transverse momentum respectively with and without multiple Coulomb scattering. These plots are shown on the right.

The effect of point smearing was also investigated and is seen as the dominant effect of multiple Coulomb scattering on the momentum curve for primaries generated by a central Au + Au event.

The plots on the right are of $[d\phi/pt \text{ vs } dz/pt]$ of secondary tracks for 3 groups of 1000 neutral Kaon events. The efficiency for these charged secondaries, for dz less than 0.1 cm, is much less than that for primaries (at about 8.5%).

This result suggests that the box size in the pixel map must be optimized or another approach must be followed for the tracking of secondaries. The problem with increasing the box-size is that electron contamination becomes a problem. The problem with tracking these secondaries is currently being researched (as seen in Section IV below).

IV. A Rough-Set-based grouping algorithm for charged-particle tracking

Murray R. Clark, Christine A. Byrd and W.J. Braithwaite

An algorithm is being developed for grouping charged particle trajectory data, with an emphasis on tracking of charged particles emerging from secondary vertices. Since tracking of charged particles from secondary vertices has been less reliable than that of charged particles from the primary collision vertex, the tracking of charged pion pairs (from neutral K_S decays) was chosen as the focus of the present work. The algorithm under construction uses aspects of artificially intelligent decision making techniques, statistical clustering techniques, and image processing techniques to resolve and separate particle trajectories.

Before beginning the discussion of tracking of charged particles from secondary vertices, first consider how pixels from different vertex tracker planes are associated with individual charged particles emerging from the collider vertex. These individual charged particles emerge at constant (θ, ϕ) in spherical coordinates from the collider vertex. The grouper technique (Prindle, 1993) assumes each particle has a negligible path curvature in STAR's magnetic field, due to the vertex tracker's small geometry. Then the grouper identifies pixels from different tracker planes by associating those with nearly equal values of the spherical coordinates (θ, ϕ) . The following figure and the associated discussion illustrates this approach.

A vertex tracker (VTX), comprised of four pad planes, is sketched on the right. This VTX is cylindrically symmetric around the colliding-beam vertex, and the coordinate point for a pixel within each pad plane is (x, y, z) . Pixels in different pad planes from the same single charged particle emerging from the collider vertex are associated by clustering pixels with nearly the same (θ, ϕ) values. Written in terms of the vertex tracker's cylindrical coordinates: constant $\phi = \arctan(y/x)$ and constant $\theta \Rightarrow \text{constant } (z/\sqrt{x^2+y^2}) \cdot 10\text{cm}$.

The importance of the grouper to this work is its removal of most of the pixel activity from the vertex tracker data set, thus dramatically reducing the effort needed in searching for charged particles emerging from secondary vertices.

Identifying a neutral K_s from its decay products sets up two tasks: (1) Making a determination of the colinearity of hits for each set of pixel groups in adjacent VTX pads, associated with the same incident pion without apriori knowledge of the location of the secondary vertex. The secondary vertex occurs at whatever point the K_s happens to be when it decays, not the collider vertex. (2) There are many charged pion tracks, but at most only two are related to the same K_s decay, and the correct pair must be determined from the known physics of the $K_s \rightarrow \pi^+ + \pi^-$ decay process.

The figure on the right shows the geometry of a K_s decay, in terms of $\vec{r} \equiv (x, y, z)$ pixel coordinates in each pad plane for both charged pions. Apart from small distortions from the solenoidal field, the pions emerge from a common point (the decay vertex), with the pions pairs forming a plane containing both the decay vertex and the collider vertex.

The direction of the original K_s is given by the unit vector $\hat{k}_0$, which may be approximated by the average position vectors of the emerging pions. Thus, this unit vector points directly away from the collider vertex. Grouping the pixels coordinates (from different VTX pad planes) associated with each individual pion can be accomplished several ways, including colinearity tests like $r_2 - r_1$, $r_3 - r_2$, $r_4 - r_3$ and $r_2 \times r_1$, $r_3 \times r_2$, $r_4 \times r_3$.

The graph on the right shows the results of colinearity tests for cross products, using unit vector differences for pixels associated with an individual pion striking a line of VTX pad rows.

Pions from K_s decays and from background are shown in this figure. The first comprise the sharp peak on the left where the broader grouping (right) is from background used to test the code.

Opening angles between pion pairs were calculated using Geant TAS files for K_s which give the VTX pixel coordinates for each pion pair.

For each primary event calculation, roughly sixty groups of K_s decays have all four pixel coordinates available for each pion-pair event. The data source for this histogram (and the following two histograms) is the aggregate of pion pairs (from K_s decay) for two primary events.

The smaller $\pi^\pm$ opening angles (above) correspond, on the average, to larger values of linear momentum for K_s . The general features of this distribution of opening angles may be used to narrow the search space for finding the conjugate pion associated with an identified pion. This narrowing can improve the computational efficiency of the "pairing" algorithm.

There are many charged pion tracks, but at most only two are related to the same K_s decay, and the correct pair must be determined from the known physics of the K_s decay process. If a pion comes from the collider vertex, then it cannot form a plane from its direction of motion and the collider vertex. However, each pion direction (from a K_s decay) will form a plane with the collider vertex. If two pions come from the the same K_s decay, they must be in the same plane.

The coplanarity test for the pion pairs may be recast as colinearity tests between the vector cross-products of candidate pion pairs.

An alternate grouper approach for selecting pion pairs from a K_S decay uses a calculation of the distance of closest approach between the inferred path of the K_S and the collider vertex.

The measured direction ($\hat{k}_0$) of the K_S is obtained from the average of the pion (pair) directions, as shown in the figure on the right.

The histogram on the right shows most of the pion pairs (from TAS files of K_S decay) are consistent with a small distance of closest approach to the main collider vertex being inferred for the K_S .

Using the criterion of small closest approach promises to contribute to an accurate reconstruction of the K_S momentum vector (for most of the pion pairs) for the purpose of HBT analysis.

Rough set theory provides a method for extracting decision rules from observations of a reference decision process (Pawlak, 1984). Like neural networks, rough sets is a completely data-driven technique which may be used with inconsistent data. In order to use rough set theory to develop an artificially intelligent decision support system, a database of example decisions from a reference decision process is used. These example decisions consist of one or more inputs or "condition attributes" on which the decision is to be based, and the result of the process or "decision attributes". Rough set software can then generate a set of if-then rules which approximate the function of the reference decision process. Knowledge in the form of rules is easy for humans to comprehend and can be practically used in the knowledge base of rule-based expert systems (Grzymala-Busse, 1992).

Applications of Rough Set Theory for creation of rule-based grouping algorithms include:

- 1) Decision systems for evaluation of candidate groups
- 2) Decision systems for synthesis of candidate groups
- 3) Automated parameter takeoff for algorithm development

A decision support system was developed using rough set theory which could evaluate candidate groups using colinearity measures. The system was able to classify candidate groups as good or no good with 100% accuracy for a small test set containing complete, high momentum pion data only. It is expected that performance of this algorithm can be maintained at fairly high levels in the face of lower momentum and inclusion of incomplete track data through further development; this effort is ongoing.

The development of a rule-based system capable of the synthesis of candidate groups is an attractive possibility. This system would include a rule base which examines simultaneously a large number of hits on VTX pads, suggesting multiple candidate groups at its output. This approach would take advantage of the exclusive nature of the data (a hit may belong to only one track) through competition between candidate tracks which cannot be achieved if examining only one candidate track at a time.

Automated takeoff of algorithm parameters is also a possible application of rough sets in the development of grouping algorithms. Often, human programmers tune algorithms through trial and error. Although this is not inherently inappropriate, the opportunity exists for automating the decisions needed to fine tune algorithm parameters if exemplars exist, as is the case when simulation data are available for algorithm development.

V. Optimizing tracking software for STAR's main time projection chamber

Wilson H. Howe, Christine A. Byrd, Amber D. Climer, W.J. Braithwaite and Jeffery T. Mitchell (LBL/BNL)

The main TPC is designed to detect charged particles, identify them, obtaining the momentum and charge of each. The TPC can be viewed as electronically "taking a 3-D picture of the particle trajectories" as charged particles ionize its gas, as seen on the right. The electric field causes the ionization electrons to drift toward one or the other of the two ends of the TPC chamber, where the signal from each electron is amplified at a thin anode wire, with a signal being induced on a pad under the wire.

The placement of the signal on the pad gives two coordinates of the track, and the drift time gives the third coordinate. Up to 45 (x, y, z) pixel coordinates may be

associated with a single track, where tracking software groups these three-dimensional coordinates into particle tracks.

Measuring charged particle tracks is important because these tracks can be used to infer fundamental information about the primary central collision which created them. The curvature of each track can be used to calculate the charge and momentum of the particle, and the energy loss of a particle can be calculated by measuring the track density of ionized electrons as a function of this measured momentum. This energy loss may be used to determine the particle type (e.g., pion, kaon, proton). These measurements of what happens in the aftermath of each central gold on gold event are important to understanding the physical processes of each central gold on gold collision, inferred from their correlation patterns, etc.

Thousands of charged particles are created by each central gold on gold event. As may be seen in the figure on the right, tracking is difficult with such a high multiplicity.

Particles decay as they leave the vertex and create other particles, which must also be tracked. These created particles make tracking even more difficult since their tracks can start anywhere in the TPC instead of starting at the vertex. All particle tracks do have common characteristics, and these characteristics are used in designing tracking software. For instance, charged particles follow helical paths when in a magnetic field, so the tracking algorithm uses a helix to link hits into particle tracks.

The tracking algorithm starts by making groups out of all the hits on the outside pad planes of the TPC. Because of the lower track density, this algorithm begins with the outermost hit and moves inward toward the vertex. When working on a given hit, nearby, unused hits which successfully form a helix fragment with the given hit are found. Then the possible groups for that hit are evaluated, and the group which most closely resembles a helix fragment is kept. The hits from this group are removed from the pool of unused hits, and the next unused hit is grouped (Mitchell, 1994).

After all the initial groups are found, they are linked into longer tracks. Starting with a given group, all other unused groups with helix parameters similar to that of the first group are compared. The groups making the best helix are joined together into track segments. A single helix is then fit to the entire track segment, and any hits falling too far outside these helix parameters are removed from the track (Mitchell, 1994).

These track segments are then extended. Starting with the longest track segment, all hits which fall within the helix parameters are added to this long segment. Smaller segments can be destroyed in this process. After the track segments have been extended, most of the tracks are complete. Tracks of particles with low transverse momentum (below 300 MeV/c), however, often do not get completed in this process. Examples of low momentum tracks are shown in the figure on the right.

Particles with lower transverse momenta (pt) lose energy more quickly than particles with higher pt. Energy losses due to interactions of these particles with the gas cause their helix parameters to change as they proceed through the TPC. The normal tracking algorithm breaks these tracks into two or three pieces interpreting each piece as a separate track. A figure showing these faulty (broken) tracks appears in Section VI: Use of event displays to improve tracking in Time Projection Chambers.

Since this track fragmentation is in error, the last step of the algorithm was modified to merge these broken tracks together, by joining low pt tracks with similar helix parameters.

Because the detector is not yet built, a simulation software package called GEANT is being used to provide test data for tracking software development (Geant, 1994). GEANT is a Monte Carlo Program which provides data for simulating events, expected to occur within the TPC. Pixel data are constructed from the Geant simulation and arranged in the same format as data produced by the TPC. These pixel data are analyzed using a software package called the Physics Analysis Workstation (Paw, 1994). Software which tracks each helix of pixels was written at Lawrence Berkeley Laboratory (Mitchell, 1994) for use with the TPC Analysis Shell.

As the generator of secondary events, GEANT is able to provide all the information about each simulated particle, which then is used to test whether the tracking software correctly reconstructs each particle's type, speed and momentum. Thus, the efficiency of the tracking software is measured using known input data (Jones, 1994). Improvements in the tracking algorithm can be obtained by looking at the tracking efficiency of the software and by using event displays.

Given the difficulty in associating low pt particles with fixed helical parameters, tracking efficiency drops at these lower pt values. Since particles of pt less than 125 MeV/c do not often make it into the TPC, efficiency drops dramatically at this low pt. Tracking efficiency is defined as the number of generated tracks in which all hits end up on one track divided by the total number of tracks. Also, partially or completely unrecorded tracks, broken tracks, and tracks with hits on two or more reconstructed tracks lower tracking efficiency.

From the event displays, problems were found with the tracking code which lowered the tracking efficiency. These low pt tracking problems were solved by changing the algorithm which compared the helix parameters of the broken tracks.

An 8% improvement in efficiency was made for tracking low transverse momentum particles, i.e., particles with transverse momenta around 150 MeV/c. This increase in tracking efficiency improves the probability the TPC will successfully measure the trajectories of particles with a low transverse momentum.

VI. Use of event displays to improve tracking in time projection chambers

Amber D. Climer, Christine A. Byrd, Wilson H. Howe and W.J. Braithwaite.

Visualization has become an important part of data analysis in physics. Due to the introduction of standard graphics packages, visualization of events has become more easily accessible by physicists and a regular part of major experiments. CERN's program-library graphics and interactive data display programs have been discussed at some length (Burks, 1994) in connection with CERN's Monte Carlo detector-modeling program, Geant. Display packages for Geant are available both on-line and off-line for tracking particles in three-dimensions through most detector geometries, including particle-transport through externally-imposed fields.

Use of visualization is especially helpful in such tasks as the debugging of reconstruction algorithms and monitoring the detector during its commissioning. Pixel data, generated from Geant, has been used to test particle-tracking algorithms in Time Projection Chambers. This pixel data is grouped so as to be indistinguishable from real TPC data, except Geant provides the particle-identification information. The success of a tracking algorithm is determined by the fraction of correct identifications it makes.

The figure above shows specious results from a tracking algorithm. This example of grossly erroneous output from the tracking algorithm shows the ease with which an erroneous result may be identified with the help of visualization.

The figure on the right shows specious results from a tracking algorithm for low pt particles reported in Section V: Optimizing tracking software for STAR's main time projection chamber. Unlike the previous figure, these broken track assignments (due to energy

loss of low momentum particles) are all the more troublesome, as they are not very obvious. This example does show, however, the power of visualization in finding tracking problems even when the errors are subtle.

In the past 2-D visualization allowed physicists to study more closely low-multiplicity collision events like W/Z decays and jets, but now with the creation of 3-D graphics tools like stereo vision and animation the high-multiplicity data from STAR may be visualized adequately. TPCs must track the paths of thousands of secondary charged particles simultaneously in the high multiplicity environments of collider experiments, so creating and optimizing TPC tracking software is a difficult task. It is often helpful to visualize pixel data along with their assigned paths, as wrong assignments may be seen, suggesting corrections to the algorithm.

VII. Summary of main collaborators outside UALR

The main collaborating institution for the UALR/URHI group is University of Washington. The PI, an affiliate Professor of Physics at UW, was invited by Dr. Reinhard Stock (Frankfurt) to join the CERN NA35/NA49 Experiments as part of the UW team. Professor John Cramer is our main collaborator on the HBT research and the NA35/NA49 data analysis, and Dr. Duncan Prindle is the author of the "grouper" technique for identifying charged-particles emerging from the primary collision vertex with pixel-groups in the multiple planes of a vertex tracker. This latter effort is the important first step in the vector matching with the main TPC; vital to charged-particle HBT analysis at STAR.

Our TPC and vertex tracker research is in collaboration with LBL. Dr. Howard Wieman is in charge of building STAR's main TPC; he and Dr. Spiros Margetis are investigating vertex tracker technology. The UALR/URHI group's vertex tracking effort is in both tracking and hardware development, with Morgan Burks on site at LBL, working with Christine Byrd at UALR. The UALR/URHI group has been working on TPC algorithms for 2-1/2 years, beginning at IKF Frankfurt, and tying in with LBL last year in a cooperative effort with Wilson Howe and Dr. Jeffery Mitchell (now at BNL) and more recently with Christine Byrd, Amber Climer and Dr. Iwona Sakrejda.

Finally, we have begun a collaboration with University of Texas with Amber Climer starting to use some of the visualization work of Professor C. Fred Moore and Dr. Herb Ward using the STAR Graphics Library. Christine Byrd and Amber Climer spent a week in Dr. Lanny Ray's Software Workshop at UT-Austin.

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Appendix A

The UALR/URHI Research Group: 1995

Ultra-Relativistic Heavy Ion Nuclear Physics

Annual Report for U.S. Department of Energy
[DE-FG05-92ER40753]

Contributing Faculty

<p>Wilfred J Braithwaite, BS (Physics), MS, PhD (Physics) University of Washington. Professor of Physics in the Department of Physics and Astronomy, and in the Department of Applied Science</p> <ul style="list-style-type: none"> • UW Cyclotron & Tandem Van de Graaff • Princeton AVF Cyclotron • UT Tandem Van de Graaff Accelerator • Los Alamos Meson Physics Facility • Indiana University Cyclotron Facility • CERN/NA35, NA49 and RHIC/STAR 	<p>A André Rollefson, BA, MA and PhD (Physics) Rice University. Professor of Physics in the Department of Physics and Astronomy, and in the Department of Applied Science</p> <ul style="list-style-type: none"> • Rice Tandem Van de Graaff • U of Pittsburgh Tandem Van de Graaff • Notre Dame Tandem Van de Graaff • Precision Energy Measurements at the Notre Dame Tandem Van de Graaff • RHIC/STAR
<p>Donald C Wold, BA, MA Univ of Wisconsin, PhD (Physics) Indiana University. Professor of Physics in the Department of Physics and Astronomy</p> <ul style="list-style-type: none"> • Theoretical [coupled-channels] nuclear • Very High Energy Cosmic Rays • UALR's GRANDE design work • NASA support in high energy physics • Primary interaction models and Geant • RHIC/STAR 	<p>Andrew T Sustich, BS (Engr), MS, PhD (Physics) University of Illinois. ASU Associate Professor of Physics in Computer Science, Math & Physics Dept.</p> <ul style="list-style-type: none"> • Nuclear multifragmentation theory • Primary interactions in medium and high energy nuclear (e.g., phase transitions, string formation/breakup) • NASA support in high energy physics • RHIC/STAR
<p>Gary T Anderson, BSEE Rice University, MS, PhD (Engr) Univ of Texas at Austin. Associate Professor in the Department of Applied Science</p> <ul style="list-style-type: none"> • Semiconductor Engr: Motorola, Austin • Memory Design Engr: Cypress, San Jose • IC Design Engr: Motorola, Austin • Artificial Neural Nets, Expert Systems • NSF & Whittaker Fd. research support • Data Acquisition: RHIC/STAR 	<p>Charles Ford, BS and MS (Computer Science) UALR, PhD (Computer Science) Florida State Univ. Assistant Professor in the Department of Computer Science</p> <ul style="list-style-type: none"> • object-oriented database for CEBAF • RHIC/STAR

Contributing Students

<p>DOE EPSCoR Grant Recipient (with WJ Braithwaite and AA Rollefson) Morgan T. Burks, BS (Physics) UALR. Department of Physics and Astronomy, Doctoral Student in Applied Science.</p> <ul style="list-style-type: none"> • Micro TPC Tests / di methyl ether gas • Interactive display/event visualization • BNL Summer '93 Software Workshop • Experienced with TPC Analysis Shell • CERN/NA49 and RHIC/STAR 	<p>Senior R&D Engineer, FMC Corporation (otherwise supported) Charles M Byrd, BA (Physics), MS UALR. Doctoral Student in Applied Science.</p> <ul style="list-style-type: none"> • High speed computing • Data acquisition and Geant modeling • Time Projection Chamber efficiencies • Experienced with TPC Analysis Shell • CERN/NA35 and NA49 • RHIC/STAR
<p>DOE EPSCoR Grant Recipient (with GT Anderson and WJ Braithwaite) Murray R. Clark, BS, MS (E&I) UALR. Doctoral Candidate in Applied Science.</p> <ul style="list-style-type: none"> • Artificial Neural Networks, Artificial Intelligence and Machine Learning • Modeling non-linear Dynamic Systems • Particle tracking using Rough Sets • RHIC/STAR, possibly CERN/NA49 	<p>Staff Member in Computing Services (otherwise supported) David L. Roetzel, BS (Physics) UALR. (occasional) part-time student in E&I.</p> <ul style="list-style-type: none"> • Experienced in Geant modeling, with the first slab-silicon Energy Loss • Interactive display/event visualization • Data archival and storage consultant • RHIC/STAR
<p>DOE EPSCoR Grant Recipient (with AA Rollefson) G. Douglas Mauldin, BS (Physics) UALR. Department of Physics and Astronomy, Masters Student in Applied Science.</p> <ul style="list-style-type: none"> • Strong Computer Science background • dE/dx particle identification (SVT) • BNL Summer '93 Software Workshop • Experienced with TPC Analysis Shell • CERN/NA35 and RHIC/STAR 	<p>UALR Donaghey Scholar and part-time DOE Undergraduate Research Assistant (with WJ Braithwaite) Christine A Byrd, Physics undergraduate.</p> <ul style="list-style-type: none"> • Awarded 10-wk LBL'94 Su. Internship • Porting/maintaining the CERN Library • response: STAR Microstrip Vertex TPC • In charge of user protocols: CERN Libr. • Experienced with TPC Analysis Shell • RHIC/STAR and CERN/NA49
<p>UALR Donaghey Scholar and DOE Undergraduate Research Assistant (with WJ Braithwaite) Wilson H. Howe, Physics undergraduate.</p> <ul style="list-style-type: none"> • Awarded 10-wk LBL'94 Su. Internship • Tracking Algorithms for STAR-TPC • Experienced with TPC Analysis Shell • Graphics and on-line Data Display • RHIC/STAR 	<p>UALR Donaghey Scholar and DOE Undergraduate Research Assistant (with WJ Braithwaite) Amber D. Climer, Physics undergrad.</p> <ul style="list-style-type: none"> • Awarded 10-wk LBL'95 Su. Internship • Awarded 8-wk '94 Su. Internship at Cornell Super Computing Center • Experienced with TPC Analysis Shell • Graphics & visualization: RHIC/STAR
<p>DOE Undergraduate Research Assistant (with WJ Braithwaite) Sue Ellen McCloskey, Physics undergrad.</p> <ul style="list-style-type: none"> • Monte Carlo Methods • Learning the TPC Analysis Shell • Graphics & visualization: RHIC/STAR 	<p>DOE Undergraduate Research Assistant (with WJ Braithwaite) William C. Hall, Physics undergraduate.</p> <ul style="list-style-type: none"> • Graphics and on-line Data Display • Learning Geant and the CERN Library • RHIC/STAR

Appendix B

Research Papers, Abstracts, Talks... 1992-95

Ultra-Relativistic Heavy Ion Nuclear Physics

Annual Report for U.S. Department of Energy
[DE-FG05-92ER40753]

Publications by the group in refereed/edited journals

"A Rough-Set-Based Grouping Algorithm for Particle Tracking in High Energy Physics" M.R. Clark, C.A. Byrd and W.J. Braithwaite. *Proceedings of the Fourth International Workshop on Software Engineering and Artificial Intelligence for High Energy and Nuclear Physics*, Pisa, IT; *International Journal of Modern Physics C*, (1995) in press.

"A Drift Chamber Utilizing Micro-Strip Readout for Testing a new micro TPC Concept" H. Weiman, M.T. Burks, W.J. Braithwaite, W.G. Gong, S. Margetis and A.A. Rollefson. Stanley Trauth, Editor. *Proceedings of the Arkansas Academy of Science* 49, (1995) in press.

"Optimizing Tracking Software for a Time Projection Chamber" W.H. Howe, C.A. Byrd, A.D. Climer and W.J. Braithwaite. Stanley Trauth, Editor. *Proceedings of the Arkansas Academy of Science* 49, (1995) in press.

"An Introduction to Monte Carlo Methods" S.E. McCloskey and W.J. Braithwaite. Stanley Trauth, Editor. *Proceedings of the Arkansas Academy of Science* 49, (1995) in press.

"Energy-Loss Particle Identification in 2-D Silicon Drift Detectors" D. Mauldin, A.A. Rollefson and W.J. Braithwaite. Stanley Trauth, Editor. *Proceedings of the Arkansas Academy of Science* 49, (1995) in press.

"Creation and Implementation of a Charged-Particle Tracking Module for a Small-Geometry, Vertex Time Projection Chamber" C.A. Byrd, W.H. Howe, A.D. Climer and W.J. Braithwaite. Stanley Trauth, Editor. *Proceedings of the Arkansas Academy of Science* 49, (1995) in press.

"Compton Scattering of γ -Rays from Electrons in Advanced Laboratory" Christine A. Byrd, Morgan L. Burks and Lawrence A. Yates and W.J. Braithwaite. Stanley Trauth, Editor. *Proceedings of the Arkansas Academy of Science* 48, (1994) 20-24.

"Using the CERN Program-Library Graphics and Interactive Data Display" Morgan L. Burks, Wilson H. Howe, Christine A. Byrd and W.J. Braithwaite. Stanley Trauth, Editor. *Proceedings of the Arkansas Academy of Science* 48, (1994) 25-27.

"Fluid Dynamics Model of Data Acquisition and Data Analysis for High Energy Physics" Charles M. Byrd, Christine A. Byrd, Wilson H. Howe and W.J. Braithwaite. Stanley Trauth, Editor. *Proceedings of the Arkansas Academy of Science* 48, (1994) 246-247.

"Applying Database Technology to Relativistic Heavy Ion Research" Y.C. Anderson, C.M. Byrd, C.A. Byrd and W.J. Braithwaite. *Proceedings of the Arkansas Undergraduate Research Conference*. D.N. Wright, Dir. (Inst. Research, DHE, 1994) 3-4.

"Data Acquisition for Relativistic Heavy Ions, Using the Transputer Computing Model" Wilson H. Howe, Christine A. Byrd, Charles M. Byrd and W.J. Braithwaite. *Proceedings of the Arkansas Undergraduate Research Conference*, D.N. Wright, Dir. (Institutional Research, Dept. of Higher Ed., Little Rock, AR 1994) 45-46.

"Role of MPP Granularity in Optimizing Monte Carlo Programming" Charles M. Byrd, Christine A. Byrd, David L. Roetzel and W.J. Braithwaite. P. Dragovitsch, S. Linn & M. Burbank, Editors. *Proc. of the International Conference on Monte Carlo Simulation in High Energy and Nuclear Physics* (World Sci. Publ Co, 1994) 40-44.

"Monte Carlo Detector Modeling and Display, using the CERN Library" Christine A. Byrd, Charles M. Byrd and W.J. Braithwaite. Stanley Trauth, Editor. *Proceedings of the Arkansas Academy of Science* 47, (1993) 26-28.

"Time Projection Chamber's Efficiency, Obtained using CERN's GEANT Code" Charles M. Byrd, Christine A. Byrd and W.J. Braithwaite. Stanley Trauth, Editor. *Proceedings of the Arkansas Academy of Science* 47, (1993) 29-30.

"User-Interface Coding for the CERN/GEANT Nuclear Physics Program" David L. Roetzel and W.J. Braithwaite. Stanley Trauth, Editor. *Proceedings of the Arkansas Academy of Science* 47, (1993) 98-101.

"Simulations of Silicon Vertex Tracker for the STAR Experiment at RHIC" with G. Odyniec, G., D. Cebra, W. Christie, D. Liko, S. Margetis, C. Naudet, L. Schroeder, W. Wilson, W.J. Braithwaite, J. Cramer, D. Prindle and T. Trainor. *Proceedings of the RHIC R&D Symposium*, [Brookhaven National Laboratory] (1992) 1-17.

"Analytical Relations for Pion and Kaon Source Sizes from Hanbury-Brown-Twiss Correlation Widths" with J.G. Cramer and J. Nettleton, *Proc. of the Ninth International Conference on Ultra Relativistic Nucleus-Nucleus Collisions* (1991) T53.

Abstracts by the Group

"A Rough-Set-Based Grouping Algorithm for Particle Tracking in High Energy Physics" M.R. Clark, C.A. Byrd and W.J. Braithwaite. *Abstracts of the 4th International Workshop on Software Engineering and Artificial Intelligence for High Energy and Nuclear Physics*, Pisa, IT (sel. for oral pres.), (1995) in press.

"Energy-loss corrections in track-predictions for low-momentum charged particles in a Time Projection Chamber" W.H. Howe, A.D. Climer, C.A. Byrd and W.J. Braithwaite. *Bull. Am. Phys. Soc.*, Trans. A, (1995) in press.

"A Track Reconstruction Algorithm for a Low-Mass, High-Resolution Vertex Time Projection Chamber" C.A. Byrd, W.H. Howe, A.D. Climer and W.J. Braithwaite. *Bull. Am. Phys. Soc.*, Trans. A, (1995) in press.

"Qualitative Testing of Particle Tracking Algorithms using 3-D Graphics Displays" A.D. Climer, W.H. Howe, C.A. Byrd and W.J. Braithwaite. *Bull. Am. Phys. Soc.*, Trans. A, (1995) in press.

"Optimizing Tracking Software for a Time Projection Chamber" W.H. Howe, C.A. Byrd, A.D. Climer and W.J. Braithwaite. *Abstracts of the 79th Annual Meeting of the Arkansas Academy of Science*, (1995) in press.

"An Introductory Module for Students of Monte Carlo Modeling" McCloskey, S.E. and W.J. Braithwaite. *Abstracts of the 79th Annual Meeting of the Arkansas Academy of Science*, (1995) in press.

"Determining the Feasibility of Using DiMethyl-Ether as a Drift Gas in a Micro-Strip Time Projection Chamber" M.T. Burks, S. Margetis, H. Weiman and W.J. Braithwaite. *Abstracts of the 79th Annual Meeting of the Arkansas Academy of Science*, (1995) in press.

"Energy-Loss Particle Identification in 2-D Silicon Drift Detectors" D. Mauldin, A.A. Rollefson and W.J. Braithwaite. *Abstracts of the 79th Annual Meeting of the Arkansas Academy of Science*, (1995) in press.

"Creation and Implementation of a Charged-Particle Tracking Module for a Small-Geometry, Vertex Time Projection Chamber" C.A. Byrd, W.H. Howe, A.D. Climer and W.J. Braithwaite. *Abstracts of the 79th Annual Meeting of the Arkansas Academy of Science*, (1995) in press.

"Use of Event Displays to Improve Tracking in Time Projection Chambers" A.D. Climer, C.A. Byrd, W.H. Howe and W.J. Braithwaite. *Abstracts of the 79th Annual Meeting of the Arkansas Academy of Science*, (1995) in press.

"An Integrated Data Acquisition and Data Analysis System for High Energy Physics" Charles M. Byrd, Christine A. Byrd and W.J. Braithwaite. *Abstracts of the 78th Annual Meeting of the Arkansas Academy of Science* (1994) p. 11.

"Using the CERN Program-Library Graphics and Interactive Data Display" Christine A. Byrd, Morgan T. Burks and W.J. Braithwaite. *Abstracts of the 78th Annual Meeting of the Arkansas Academy of Science* (1994) p. 11.

- "Energetic Photon Scattering from Electrons in Advanced Laboratory" Morgan T. Burks, Christine A. Byrd and W.J. Braithwaite. *Abstracts of the 78th Annual Meeting of the Arkansas Academy of Science* (1994) p. 16.
- "Data Acquisition for Relativistic Heavy Ions, Using the Transputer Computing Model" Wilson H. Howe, Christine A. Byrd, Charles M. Byrd and W.J. Braithwaite. *Arkansas Undergraduate Research Conference* (1994) p. 4.
- "Applying Database Technology to Relativistic Heavy Ion Research" Y.C. Anderson, C.A. Byrd, C.M. Byrd and W.J. Braithwaite. *Arkansas Undergraduate Research Conference* (1994) p. 4.
- "STAR/SVT track-matching by grouping events from adjacent SDD planes" C.M. Byrd, C.A. Byrd and W.J. Braithwaite. *Bull. Am. Phys. Soc.*, Trans. A, (1994) p. 1308.
- "Pulse pileup-rejection circuit for silicon detectors" W.J. Braithwaite, J.R. Comfort and F.E. Cecil, *Bull. Am. Phys. Soc.*, Trans. A, (1994) p. 1309.
- "Transputer technology for data acquisition and MPP data analysis" C.M. Byrd, C.A. Byrd and W.J. Braithwaite. *Bull. Am. Phys. Soc.*, Trans. A, (1994) p. 1309.
- "Using GEANT in the design of silicon detector telescopes" T.W. Wofford, E.D. Bearden, M.T. Burks, C.A. Byrd, C.M. Byrd, D.L. Roetzel and W.J. Braithwaite. *Bull. Am. Phys. Soc.*, Trans. A, (1994) p. 1309.
- "Effect of Granularity in Massively Parallel Processors on Monte Carlo Modeling" Charles M. Byrd, Christine A. Byrd, Angie Caraway-Coulter, David L. Roetzel and W.J. Braithwaite. *Abstracts of the International Conference on Monte Carlo Simulation in High Energy and Nuclear Physics* (1993) p. 12.
- "Time Projection Chamber's Efficiency, Obtained using CERN's GEANT Code" Charles M. Byrd, Christine A. Byrd and W.J. Braithwaite. *Abstracts of the 77th Annual Meeting of the Arkansas Academy of Science* (1993).
- "User-Interface Coding for the CERN/GEANT Nuclear Physics Program" David L. Roetzel and W.J. Braithwaite. *Abstracts of the 77th Annual Meeting of the Arkansas Academy of Science* (1993).
- "Monte Carlo Detector Modeling and Display, using the CERN Library" Christine A. Byrd, Charles M. Byrd and W.J. Braithwaite. *Abstracts of the 77th Annual Meeting of the Arkansas Academy of Science* (1993).

Publications as part of a Research Collaboration

The STAR-RHIC Collaboration

"The STAR Experiment at the Relativistic Heavy Ion Collider" J.W. Harris and the STAR Collaboration. *Proceedings of the Tenth International Conference on Ultra-Relativistic Nucleus-Nucleus Collisions, Nuclear Physics A566* (1994) 277c-285c.

"Conceptual Design Report for the Solenoidal Tracker at RHIC" STAR Experimental Group, for the U.S. Dept of Energy [Contract Number DE-AC03-76SF00098], Lawrence Berkeley Laboratory *Report LBL-PUB-5347* (June 1992).

"Update to the RHIC Letter of Intent for An Experiment on Particle and Jet Production at Midrapidity" with the STAR Expt'l Group, [*Revision to 1990 Letter of Intent*, to submit a contract] to US Dept of Energy [DE-AC03-76SF00098], Lawrence Berkeley Laboratory *Report LBL-31040, UC-414, 1-49* (July 1991).

The NA35/NA49-CERN Collaborations

"Transverse Momentum Dependence of Bose-Einstein Correlations in 200A GeV/c S + A Collisions" T. Alber, et al. (The NA35 Collaboration). *Phys. Rev. Letters*, 74 (1995) 1303.

"Two-pion Bose-Einstein correlations in nuclear collisions at 200 GeV/nucleon" T. Alber, et al. (The NA35 Collaboration). *Z. Phys. C66* (1995) 77.

"Strange particle production in nuclear collisions at 200 GeV per nucleon" T. Alber, et al. (The NA35 Collaboration). *Z. Phys. C64* (1994) 195-207.

"The NA49 Data Acquisition System" W. Rauch, et al. (The NA35 Collaboration). *IEEE Trans. on Nucl. Science*, Vol 41, No. 1, Feb. 1994, p. 30-36.

"Large Acceptance Hadron Detector for an Investigation of Pb-induced Reactions at the CERN SPS" with the CERN/NA-49 Experimental Group, *Experiments at CERN in 1991* ISSN 0259-093X, 100-103 (CERN, Geneva, 1991).

"Study of Nucleus-Nucleus Collisions" with the CERN/NA-35 Expt'l Group, *Experiments at CERN in 1991* ISSN 0259-093X, 74-78 (CERN, Geneva, 1991).

Progress Reports by the Group as part of a Research Collaboration

"CERN experiment NA35: 200 GeV/nucleon Sulfur on Cu, Ag, and Au" with P. Chan, J.G. Cramer, D.J. Prindle, T.A. Trainor, X. Zhu [and NA35], University of Washington Nuclear Physics Laboratory *Annual Report-1992*, 49 (1992).

"A Silicon Vertex Tracking Detector for the STAR Detector System at RHIC" with J.G. Cramer, D.J. Prindle and T.A. Trainor, University of Washington Nuclear Physics Laboratory *Annual Report-1991*, 44 (1991).

"Investigation of Coherence Effects in Pion HBT Correlations at RHIC Energies" with J.G. Cramer and G.I. Opat, University of Washington Nuclear Physics Laboratory *Annual Report-1991*, 43 (1991).

"Coherence Effects with Large Pion Sources" with J.G. Cramer. University of Washington Nuclear Physics Laboratory, *DOERenewal Proposal* [1 Nov 1991 to 31 Oct 1996], (1991) 44-45.

"Mixed-Charge' HBT Analysis of NA35 Data" with J.G. Cramer. University of Washington Nuclear Physics Laboratory, *DOERenewal Proposal* [1 Nov 1991 to 31 Oct 1996], (1991) 47.

"A Silicon Vertex Tracking Detector for the STAR Detector System at RHIC" with J.G. Cramer, D.J. Prindle and T.A. Trainor. University of Washington Nuclear Physics Laboratory, *DOERenewal Proposal* [1 Nov 1991 to 31 Oct 1996], (1991) 48.

"The NA35* Experiment— lead beams at CERN" with J.G. Cramer, D.J. Prindle and T.A. Trainor. Univ. of Washington Nuclear Physics Laboratory, *DOERenewal Proposal* [1 Nov 1991 to 31 Oct 1996], (1991) 47.

"The NA35 Collaboration at CERN" with J.G. Cramer, D.J. Prindle and T.A. Trainor. University of Washington Nuclear Physics Laboratory, *DOERenewal Proposal* [1 Nov 1991 to 31 Oct 1996], (1991) 45-46.

Addendum to U.S. Department of Energy Form F 241.1

Research Publications citing the U.S. Department of Energy Grant

[DE-FG05-92ER40753 Ultra-Relativistic Heavy Ion Nuclear Physics]

I. Journal Articles--Edited (& refereed) Papers & Conference Proceedings:

"Continuous Monitoring of STAR's Main Time Projection Chamber" W.J. Braithwaite and E.S. Braithwaite. S. Trauth, Ed. *Journal of the Arkansas Academy of Science* 52 (1998) 28-31.

"Coplanarity Test for Selecting a Pair of Charged-Particle Tracks Resulting from a Single Neutral-Particle Decay" W.J. Braithwaite and E.S. Braithwaite. S. Trauth, Ed. *Journal of the Arkansas Academy of Science* 51 (1997) 32-35.

"Separating $K^\pm$ from $\pi^\pm$ using In-Flight Decays to $\mu^\pm + \nu$ " W.J. Braithwaite and E.S. Braithwaite. S. Trauth, Ed. *Journal of the Arkansas Academy of Science* 51 (1997) 36-40.

"Measuring Strangeness Production from Relativistic Collisions between Pairs of Nuclei using a Vertex Time Projection Chamber" C.A. Byrd and W.J. Braithwaite. S. Trauth, Ed. *Proceedings of the Arkansas Academy of Science* 50 (1996) 36-41.

"Curing a Summing Error that Occurs Automatically when Fitting a Function to Binomial or Poisson Distributed Data" W.J. Braithwaite and E.S. Braithwaite. S. Trauth, Ed. *Proceedings of the Arkansas Academy of Science* 50 (1996) 22-27.

"A Rough-Set-Based Grouping Algorithm for Particle Tracking in High Energy Physics" M.R. Clark, C.A. Byrd and W.J. Braithwaite. B. Denby and D. Perret-Gallix, Eds. *New Computing Techniques in Physics Research IV*. (World Scientific Publishing Co., NJ, 1995), 777-782.

"A Drift Chamber Utilizing Micro-Strip Readout for Testing a new micro TPC Concept" H. Weiman, M.T. Burks, W.J. Braithwaite, W.G. Gong, S. Margetis and A.A. Rollefson. S. Trauth, Ed. *Proceedings of the Arkansas Academy of Science* 49, (1995) 181-183.

"Optimizing Tracking Software for a Time Projection Chamber" W.H. Howe, C.A. Byrd, A.D. Climer and W.J. Braithwaite. S. Trauth, Ed. *Proceedings of the Arkansas Academy of Science* 49, (1995) 75-79.

"Energy-Loss Particle Identification in 2-D Silicon Drift Detectors" D. Mauldin, A.A. Rollefson and W.J. Braithwaite. S. Trauth, Ed. *Proceedings of the Arkansas Academy of Science* 49, (1995) 104-108.

"An Introduction to Monte Carlo Methods" S.E. McCloskey and W.J. Braithwaite. S. Trauth, Ed. *Proceedings of the Arkansas Academy of Science* 49, (1995) 109-114.

"Creation and Implementation of a Charged-Particle Tracking Module for a Small-Geometry, Vertex Time Projection Chamber" C.A. Byrd, W.H. Howe, A.D. Climer and W.J. Braithwaite. S. Trauth, Ed. *Proceedings of the Arkansas Academy of Science* 49, (1995) 37-40.

"Compton Scattering of γ -Rays from Electrons in Advanced Laboratory" C.A. Byrd, M.L. Burks and L.A. Yates and W.J. Braithwaite. S. Trauth, Ed. *Proceedings of the Arkansas Academy of Science* 48, (1994) 20-24.

"Using the CERN Program-Library Graphics and Interactive Data Display" M.L. Burks, W.H. Howe, C.A. Byrd and W.J. Braithwaite. S. Trauth, Ed. *Proceedings of the Arkansas Academy of Science* 48, (1994) 25-27.

"Fluid Dynamics Model of Data Acquisition and Data Analysis for High Energy Physics" C.M. Byrd, C.A. Byrd, W.H. Howe and W.J. Braithwaite. S. Trauth, Ed. *Proceedings of the Arkansas Academy of Science* 48, (1994) 246-247.

"Role of MPP Granularity in Optimizing Monte Carlo Programming" C.M. Byrd, C.A. Byrd, D.L. Roetzel and W.J. Braithwaite. P. Dragovitsch, S. Linn & M. Burbank, Eds. *Proceedings of the International Conference on Monte Carlo Simulation in High Energy and Nuclear Physics* (World Scientific Publ. Co., 1994) 40-44.

"Monte Carlo Detector Modeling and Display, using the CERN Library" Christine A. Byrd, C.M. Byrd and W.J. Braithwaite. S. Trauth, Ed. *Proceedings of the Arkansas Academy of Science* 47, (1993) 26-28.

"Time Projection Chamber's Efficiency, Obtained using CERN's GEANT Code" C.M. Byrd, C.A. Byrd and W.J. Braithwaite. S. Trauth, Ed. *Proceedings of the Arkansas Academy of Science* 47, (1993) 29-30.

"User-Interface Coding for the CERN/GEANT Nuclear Physics Program" D.L. Roetzel and W.J. Braithwaite. S. Trauth, Ed. *Proceedings of the Arkansas Academy of Science* 47, (1993) 98-101.

II. Unedited Conference Proceedings:

"Distinguishing (Charged) Kaons from (Charged) Pions in a Time Projection Chamber using their Muon Decays" W.C. Hall (W.J. Braithwaite, Mentor). *Ronald McNair Scholars Program--Fifth Annual Research Symposium*, University of Arkansas at Little Rock, September 1998.

"Distinguishing Kaons from Pions in a Time Projection Chamber using their Muon Decays" W.C. Hall (W.J. Braithwaite, Mentor). *Abstracts of the Fourth Annual SAEOPP/UTK McNair Research Conference*, Knoxville, TN, July 1998, [2nd Place in Physical Science/Mathematics/Computer Science with 30 universities participating]

"Continuous Monitoring of Time Projection Chambers" W.J. Braithwaite and E.S. Braithwaite. *Bull. Am. Phys. Soc.* , Vol. 43, No. 2, (1998) 1074.

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Doctoral Degrees

Morgan T. Burks received the Ph.D. in May 1998 from the Department of Applied Science at UALR. His dissertation title is: "Development of Integrated Gas Microstrip Detectors for a Micro Time Projection Chamber." Morgan is currently working as a Postdoctoral Fellow at the Lawrence Berkeley National Laboratory.

Masters Degrees

G. Douglas Mauldin received the M.S. in 1996 from the Department of Applied Science at UALR. His thesis title is: "Energy Loss Particle Identification in Silicon Drift Detectors." Doug received his B.S. degree in Physics at UALR in 1989. [He is currently working as a Design Engineer at Baldwin Electronics, Inc. (B.E.I., Inc.) in Little Rock, Arkansas.]

Morgan T. Burks received the M.S. in 1995 from the Department of Applied Science at UALR. He took a special Masters Examination in lieu of a Masters Thesis. Morgan continued on for the Ph.D. (at UALR). Morgan received his B.S. degree in Physics at UALR in 1993. (He is currently a Postdoctoral Fellow at the Lawrence Berkeley National Laboratory in California.)

Charles M. Byrd received the M.S. in 1994 from the Department of Applied Science at UALR. His thesis title is: "Efficiency and Track Selection Criteria Calculations for use with High Energy Physics Detectors." Charles received his B.S. degree in Physics at UALR in 1992. (Charles is currently working as a Senior Engineer with Sun Microsystems in San Jose, California.)