EXPERIMENTAL HEAVY ION PHYSICS AT HIGH ENERGIES

PROGRESS REPORT

September 1992 — November 1993

Department of Physics and Astronomy
Vanderbilt University
Nashville, TN 37235

Prepared for the U. S. Department of Energy Under
Grant No. DE-FG05-92ER40712

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

MASTER

Contents

1	Introduction	1
2	PHENIX Collaboration Report	2
2.1	PHENIX UCDR Chapter 3: Physics Capabilities	3
2.2	Simulations: Strategy and New Results	7
2.2.1	Secondary Electrons on RICH	8
2.2.2	MVD Induced Conversion Electrons	12
2.2.3	Mass Resolution in the Central Arm	17
2.2.4	Dimuon Measurements	18
2.2.5	Revision for Photon Simulations	20
2.2.6	First Studies of the QED Background into the BBC	23
2.3	Presentation to the TAC Cost and Schedule Review	24
3	RD45 Experiment Progress	39
4	The Soft Photon Experiment	39
5	The 4π CsI Ball Project	51

1 Introduction

The report summarizes the research activities of the experimental high energy heavy ion physics group at Vanderbilt University carried out under Grant No. DE-FG05092ER40712 with the Department of Energy during the period October 1, 1992 to November 30, 1993. This research encompasses four areas of related inquiry in relativistic and high energy nuclear reactions:

1. The preparation of the PHENIX experiment which has been approved as one of the two major experiments at RHIC to start in 1998. Prof. Maguire has been appointed to the PHENIX Detector Council overseeing all integrated Monte Carlo simulations for the collaboration using the PISA/PISORP computer program chain.
2. The RD10/RD45 Muon Identifier experiment which will provide essential input for the design of the Muon Endcap arm detector sub-system in PHENIX. This experiment has been successfully carried out under the immediate, on-site direction of our graduate student Earl Cornell and is the subject of his thesis dissertation.
3. The E855 Soft Photon Experiment at the AGS designed to clarify the status of a possible quark-gluon-plasma signature with presently available heavy-ion collisions. This experiment has been a collaboration between us, Dan Shapira's group at ORNL, and BNL staff. These data have been rigorously analyzed in the past year and provide conclusive evidence of the absence of a soft-photon anomaly.
4. The construction CsI Ball detector project at Texas A&M which is designed as part of a comprehensive detector system which will probe the nuclear equation of state in the 50 MeV/nucleon domain. This project is a joint effort between us, Dan Shapira's group at ORNL, and the Texas A&M staff. Work has proceeded smoothly in the past year on completing construction of this device. All the mechanical and active detector pieces have been produced, and are slated to be installed in the next few months. An initial beam test is planned for December, 1993.

Further details and excerpts of reports and papers are presented in the following four sections. A separate document entitled "Vanderbilt Heavy Ion Group Research Proposal for 1994" accompanies this document.

2 PHENIX Collaboration Report

The participation in the PHENIX collaboration comprised the great majority of Prof. Maguire's effort in the past year. This activity was denoted by these important milestones:

- The preparation of the PHENIX Conceptual Design Report dated January 29, 1993. Prof. Maguire, as the Detector Council responsible for simulation, was designated as the co-editor for the important Chapter 3 ("Physics Capabilities") of the CDR. The physics simulations presented in this Chapter established that the proposed PHENIX detector would be capable of observing a variety of possible Quark-Gluon-Plasma signatures. In its review of the CDR, the Technical Advisory Committee gave high marks to the simulation group for its advances in the previous half year since the preliminary Conceptual Design Report.
- The further development of the PHENIX simulation program called PISA. In 1993 this program, and its companion analysis program PISORP, evolved through three successive upgrades which provided an ever more realistic version of the response of the PHENIX detector to complex central events.
- The preparation of the PHENIX Updated Conceptual Design report, dated November 11, 1993. Again Prof. Maguire was designated as the co-editor for the Physics Capabilities Chapter 3. The results of the more realistic, background-included simulations and their effect on the signal-to-noise simulations was included on a subsystem-by-subsystem basis in this update. And again, the TAC praised the PISA simulation effort and its wider dissemination in the collaboration.
- The preparation of the Work Breakdown Schedule (WBS) for the PHENIX Cost and Schedule review which coincided with the defense of the UCDR. It was Prof. Maguire's task to outline the evolution of the simulation effort over the next five years of the PHENIX construction project, paying close attention to the integration of simulation to the on-line and off-line software developments.
- The preparation of the Vanderbilt Memorandum of Understanding with the RHIC project and with the Department of Energy. This MOU is the basis of the long term commitment of the VU group to the PHENIX effort. While still in its draft form (as are all other PHENIX MOUs at this time), the document nonetheless outlines a clear path for the VU group to supervise the simulation effort and to continue its participation in the muon physics program of PHENIX.

The Chapter 3 section of the PHENIX CDR takes some 43 pages including 18 figures. Although much of this work is based on the PISA simulation effort and is a valuable introduction to the PHENIX detector capabilities, there is too much material to reproduce in the present progress report. Last year's progress report did contain some of our preliminary

simulation results which eventually were incorporated into the CDR. Instead, we shall include in this progress report the shorter contribution to the UCDR, as well as the summary presentation to the TAC at the Cost and Schedule Review. These give a more up-to-date snapshot of the PHENIX detector capabilities. The present drafts of the simulation WBS and the Vanderbilt MOU are contained in the accompanying continuation proposal of the Vanderbilt group for 1994.

2.1 PHENIX UCDR Chapter 3: Physics Capabilities

Although the major physics purposes were already described in the previous CDR, we summarize here very briefly these goals. Physics issues related to the quark-gluon plasma, in particular, in relation to the PHENIX experiment, are summarized in Table 1.

Two important aspects exist for the quark-gluon plasma. One is “deconfinement”, which is closely related to the Debye screening of the QCD potential. The basic mechanism of J/ψ suppression is that, if the J/ψ radius is longer than the screening length, then a $c\bar{c}$ pair would not be able to form a bound state due to a Debye suppression of the long-range term of the $c\bar{c}$ potential and, thus, J/ψ production is suppressed [1]. The degree of suppression depends strongly on the relative size difference between the meson radius and the screening length. Since $r(\psi') = 0.51 \text{ fm} > r(J/\psi) = 0.25 \text{ fm} > r(\Upsilon) = 0.13 \text{ fm}$, we expect that ψ' must melt first, then J/ψ , and finally Υ . Recently, a stronger suppression of ψ' than J/ψ has been reported by the NA38 group at CERN [2]. This result compels us to study these vector mesons systematically at RHIC. We plan to measure J/ψ in the mid-rapidity region by dileptons, and J/ψ , ψ' and Υ at forward angles by dimuons.

The other important element is “chiral symmetry restoration”. Because the mass of the ϕ -meson is close to twice the kaon mass, and because both ϕ and K could be distorted in the quark-gluon plasma, it was predicted [3] that a change would occur in: (a) the branching ratio between leptonic and hadronic channels, (b) the mass of the ϕ , and (c) the width of the ϕ . Here, high-resolution ϕ -spectroscopy is required to study these points. We plan to measure ϕ -mesons by both electron and hadron channels.

Thermal radiation from a hot gas has been a subject of controversy for many years [4]. There was a confusing period in which it was debated whether or not the radiation was enhanced or suppressed when the phase transition occurred. Recently, a consensus among theorists seems to be that the gluon content is high at an early stage of the quark-gluon plasma and an enhancement must be expected in the region of m_T (or, p_T for photons) greater than 2–3 GeV [5]. We plan to investigate this topic using the photon measurement.

The nature of the phase transition is a very interesting point to study. If the phase transition is first-order, then, an entropy jump would be expected at T_C , because internal degrees of freedom of the constituents increase by a factor of about 12 from the pionic gas to the quark-gluon gas. If one plots T as a function of the energy density (ϵ) of the system, the value of T increases with ϵ in the phase of a pionic gas until it reaches T_C . The system stays at this temperature, even as ϵ increases, until a sufficient energy density is accumulated to allow the system to complete the phase transition into a quark-gluon gas. At this point, the value of T starts to rise again as a function of ϵ . Since T is closely related to $\langle p_T \rangle$, the second rise in $\langle p_T \rangle$ as a function of ϵ is expected [6].

1. Deconfinement (Debye Screening of QCD Interactions)	
$r(\Upsilon) = 0.13 \text{ fm} < r(J/\psi) = 0.29 \text{ fm} < r(\psi') = 0.56 \text{ fm}$	
$\longrightarrow J/\psi \rightarrow e^+e^- \text{ at } y \simeq 0.$	$\implies \text{electrons}$
$\quad \quad \quad \rightarrow \mu^+\mu^- \text{ at } y \simeq 2.$	
$\psi', \Upsilon \rightarrow \mu^+\mu^- \text{ at } y \simeq 2.$	$\implies \text{muons}$
2. Chiral Symmetry Restoration	
Mass, Width, Branching: $\phi \rightarrow e^+e^-, K^+K^- \text{ with } \Delta m \leq 5 \text{ MeV}.$	$\implies \text{electrons} + \text{hadrons}$
Baryon Susceptibility: Production of antinuclei.	
Narrow σ meson?	
3. Thermal Radiation of Hot Gas	
Prompt γ , Prompt $\gamma^* \rightarrow e^+e^-.$	$\implies \text{photons, electrons, muons}$
4. Nature of the Phase Transition	
First Order: Entropy Jump $\rightarrow$ Second rise in $\langle p_T \rangle$	
$\quad \quad \quad \rightarrow \text{Spectra of } \pi, K, p.$	$\implies \text{hadrons}$
Second Order: Fluctuation $\rightarrow N(\pi^0)/N(\pi^+ + \pi^-), d^2N/d\eta d\phi.$	$\implies \text{hadrons} + \text{photons}$
5. Strangeness and Charm Production	
Production of $K^+, K^-, K_S^0.$	$\implies \text{hadrons}$
$\phi \rightarrow e^+e^-, K^+K^- \text{ at } y \simeq 0, \phi \rightarrow \mu^+\mu^- \text{ at } y \simeq 2.$	
D -Meson: $e\mu$ coincidence.	$\implies \text{electrons, muons}$
6. Jet Quenching	
High- p_T Jets via Leading Particle Spectra.	$\implies \text{hadrons}$
7. Space-Time Evolution	
HBT Correlations for $\pi\pi$ and KK .	$\implies \text{hadrons}$

Table 1: Physics issues related to the PHENIX experiment.

Such an entropy rise induces an increase of pressure and, thus, induces a hydrodynamical flow [7]. The flow effect is stronger for nucleons than for pions due to the mass difference. In order to study the flow effect, combined with the effect of an entropy rise, measurements of “identified” charged hadrons are extremely important. We plan to measure identified hadron spectra in the mid-rapidity region.

If the phase transition is second-order, then, “fluctuation” measurements could prove important, as pointed out recently by Wilczek [8]. We plan to measure $\pi^0/(\pi^+ + \pi^-)$ from the detection of both photons and hadrons.

Table 1 lists other important physics issues, such as strangeness and charm enhancement [9], jet quenching [10], and space-time evolution [11]. Here, we emphasize that simultaneous measurements of dielectrons, dimuons, photons, and identified hadrons are important

and necessary to pin down the formation of quark-gluon plasma at RHIC, because while all the theoretical predictions listed in Table 1 are very attractive, they all contain many weak points and ambiguities.

We plan to measure all the variables listed in Table 1 as a function of a reasonably well-defined experimental quantity which is proportional to the energy density. Because the energy density is given by [12]

$$\varepsilon = \frac{1}{\pi R_{\perp}^2} \frac{dE_T}{dy}, \quad (1)$$

the geometry of the collision (namely, $R_{\perp}$) will be fixed first by multiplicity measurements. A wide coverage for the multiplicity measurement is very important, because a possible fluctuation effect must be smeared out for the determination of the collision geometry. By using an electromagnetic calorimeter or a subset of the multiplicity detector, the quantity of dE_T/dy will be measured to probe the local energy density at that rapidity, including the effect of the fluctuation.

For each physics observable, short comments on how to detect these observables are described in what follows.

Dielectron Measurements

Three detectors are used for electron identification: RICH, TEC (for dE/dx), and EM Cal. Initial test results for a subset of the actual RICH detector, using pion and electron beams at KEK, clearly demonstrates that a Cherenkov photon ring is observed by a photo-multiplier read-out method and it shows that the pion rejection of 10^{-4} is possible for single pions and electrons. In the high-multiplicity environment, the pion rejection power will be reduced to the 10^{-3} level.

For the TEC in the 1 GeV/c region, the value of dE/dx in a gas is approximately 50% higher for electrons than for pions. This feature is used for electron identification. Test results show a clear separation between electrons and pions, and we confirmed that this method allows an additional 10^{-2} level pion rejection up to 2 GeV/c. The EM Cal further helps pion rejection by at least another one order of magnitude. Our design criterion of the pion rejection below 10^{-4} can thus be attained.

We also paid special attention to achieve a high mass resolution in the tracking system. Our Monte Carlo calculations have shown that the mass resolution of approximately 4 MeV for ϕ -mesons can be achieved for the e^+e^- channel and less than 1 MeV for the K^+K^- channel (see Section 3.2.3.).

Photon Measurements

In order to measure direct photons, the first step is to learn the background associated with π^0 and η . Invariant mass spectra for 2γ have the following general tendency: At low- p_T the background is high, and as p_T increases the peak is more pronounced. Thus, the yield ambiguity increases as p_T decreases (see Fig. 3.10.).

If π^0 and η peaks are found in the 2γ spectrum, the next step is to estimate the differential cross sections of π^0 and η and, then, to evaluate the spectrum of single photons by using these π^0 and η . If the reconstruction procedure is perfect, the reconstructed spectrum of single photons must be identical to the actual single photon spectrum recorded on the detector. This comparison is described later in Sec. 3.3. Our conclusion is that the direct photon measurement is possible at $p_T > 1$ GeV/c, if an enhancement of the direct photon is well above a few percent of the single photons from π^0 .

Photon measurements also allow us to study π^0 spectrum as well as two- π^0 interferometry [13].

Charged Hadron Measurements

A recent test of a prototype time-of-flight (TOF) counter ($1.2 \times 1.2 \times 100$ cm³) showed that the time resolution of $\sigma < 100$ ps is possible, even if the light guide was bent by 180° . With this resolution, a π -K separation up to 2.4 GeV/c is possible.

The first interesting subject is to measure single particle spectra of identified hadrons, as discussed above. Charged hadron measurements further allow us to study $\phi \rightarrow K^+K^-$ and two boson correlations. For the latter two-boson correlations, we can measure these correlations for both $\pi\pi$ and KK to determine the source radius up to 20 fm. For a source radius larger than 10 fm, the detector bin size of relative momentum has to be corrected rather carefully in particular for KK correlations, because the resolution of relative momentum, Δq , is proportional to γm and, thus, $\Delta q(\pi\pi) < \Delta q(KK)$.

The decay kinematics of $\phi \rightarrow K^+K^-$ together with the measurement of two-boson correlations determine the solid angle coverage (0.36 sr) of the TOF wall in the Baseline detector configuration.

Dimuon Measurements

Muon identification will be performed by a standard technology of streamer tubes, sandwiched by several layers of iron (Fe) absorbers. In contrast to pp collision experiments, it is not possible to track muons before the first absorber, because the multiplicity is too high in heavy-ion collisions. We therefore use the central magnet yoke as a first, thick absorber and the tracking system starts after the yoke which functions here as a pion attenuator.

The muon arm mass resolution is, consequently, relatively modest at about 85 MeV for the J/ψ (see Fig. 10.30 in the CDR) as compared to a resolution of about 18 MeV for this resonance via the dielectron channel in the central arm. Nonetheless, the muon arm mass resolution should enable a clear separation of the J/ψ and the ψ' thus being able to measure the possible differential suppression of these resonances as mentioned in beginning of this chapter.

A clear advantage at forward angles is a gain in the yield. Although the muon arm covers only 1 sr, which is half the solid angle of the electron arm, the value of $\Delta y \Delta \phi$ is 2.4π rad for the muon arm, while it is 0.7π rad for the electron arm. Because the pair yield is proportional to $[\Delta y \Delta \phi]^2$, the yield of J/ψ is, for example, about a factor of 10 higher in the muon arm than in the electron arm. For one year of RHIC running, we expect to have 5.7K of ψ' and 1.2K of Υ for 10% central collisions at the luminosity of 2×10^{26} .

Because the central magnet yoke imposes a relatively high momentum threshold (about 2.5 GeV/c) this tends to limit the y and p_T acceptance for low mass pairs. The two front Muon Identifier steel layers have been specially graded to compensate for this effect based on recent trigger simulations.

Electron-Muon Coincidence

Once both the electron and muon arms are installed, the measurement of the $e\mu$ coincidence is possible. The main leptonic decay mode of the D -meson is an emission of an electron or muon, like the β decay of the neutron. Therefore, the unlike-sign $e\mu$ pairs subtracted by the like-sign $e\mu$ pairs are primarily from $D\bar{D}$, where the unlike-sign pairs are mainly from combinatorial background pairs [14].

The previous CDR clearly demonstrates that the charm contribution is dominant in the mass spectrum for $e\mu$ pairs at $m_{e\mu} > 3$ –4 GeV. If the charm production is enhanced, one may probe $D\bar{D}$ at a lower mass region.

Multiplicity and Vertex

We plan to install both a silicon multiplicity-vertex detector (Si MVD) and the two sets of quartz Cherenkov timing counters (beam-beam counters).

Tests for the beam-beam counters showed 35 ps time resolution in the magnetic field of 3 kG. These counters are used as a time reference of the TOF counters. Also, they are used for the on-line vertex determination at the level of $\Delta z = 2$ cm.

The Si MVD is used to determine the event multiplicity and the determination of the vertex position. With this device the vertex can be determined within 100–200 μm .

2.2 Simulations: Strategy and New Results

In the original CDR an extensive series of integrated simulations was undertaken in order to establish the feasibility of the dielectron physics program in the PHENIX central arm (see the CDR subsection 3.3.1). However, since these simulations were the first proof-of-principle task, they were conducted under admittedly idealized conditions. Most importantly the background contributions originating from secondary reactions in the bulk of the central arm's structural material were largely ignored in the signal-to-noise figures. The objective at that time was to confirm, to the best of our knowledge of how each detector subsystem would perform, that the irreducible Dalitz decay and photon conversion backgrounds as well as the limits of the predicted e/π discrimination would not fatally obscure the vector resonance mass signatures. This primary objective was convincingly satisfied in our estimation by this first round of simulation studies.

Nonetheless, we did recognize (see the CDR subsection 3.4) that secondary particle backgrounds from the large quantity of material in and near the central arm acceptance could pose problems. This is a special concern for the performance of the RICH which is the keystone of the e/π discrimination hardware. Indeed, disappointing results reported recently at the QM '93 conference regarding the performance and backgrounds afflicting the double-RICH CERES/NA45 experiment at CERN have made us acutely sensitive to this issue. Moreover, design changes in the PHENIX central arm magnet yokes have brought this steel even closer to the acceptance region than in the CDR. Not surprisingly this change has increased the secondary particle backgrounds into all central arm detectors.

Consequently in the last several months we have engaged in a systematic effort to ascertain the deterioration, if any, in the overall performance of the dielectron program of measurements. This new round of simulations has led us to suggest certain changes in the designs of central arm subsystems (see the updates on the MVD and the Drift Chambers). Given these modifications, our calculated results to date still leave us confident that the dielectron measurements will be successfully accomplished. This is an ongoing process and we accept that there is still a lot of work to be done in order to verify that none of the subsystems will be compromised by secondary particle flux.

We discuss first the results of new simulations on the predicted performance of the RICH where special attention is paid to the effects of the secondary particle backgrounds present in the central arm. In particular we present an in-depth study of the effect of photon conversions by the MVD detector system in comparison with other electron background sources. After that study we describe new simulations on the tracking performance as regards the vector meson mass resolutions and indicate how the track reconstruction performance can be integrated into studies of other detector subsystems such as the RICH and the MVD. A brief discussion of new acceptance calculations by the Muon Arm is mentioned at the end of this section.

2.2.1 Secondary Electrons on RICH

Undoubtedly one of the most severe backgrounds expected to be present in the Ring Imaging Cerenkov Hodoscope (RICH) system is that of secondary electrons and positrons. These are produced by photon conversions at the magnet pole pieces, by the inner tracking chambers (including the chambers themselves and their support structures), and in the RICH gas radiator itself. Since they are “real” electrons/positrons, they produce Cerenkov light and will increase the noise level in RICH system substantially.

We have studied the secondary electron background using PISA, the PHENIX integrated simulation program. We included the magnet pole pieces, the beam pipe, the inner tracking chambers with a somewhat simplified if not pessimistic support frame, and finally the RICH itself with a C_2H_6 radiator gas. The “nose cone” and the MVD detector were not in this particular simulation run. Related results on a modified version of the MVD and also including the nosecone are presented in the following section of this update

The support frame of the inner tracking chambers (DC1, DC2, and PAD1) was represented by a 2 cm thick Aluminum plate, which was thicker in terms of radiation length than the intended support frame to be made of a light composite material. The simulated frame

Figure 1: Hit pattern in the RICH PMT array for a typical Au+Au central collision event (HIJET). The PMTs that detect at least one Cerenkov photon are plotted as squares. The four panels of this figure corresponds to the four sectors of the PMT array. Each sector has $80(\phi) \times 20(z)$ segmentation. The horizontal axis is the ϕ position of the PMTs and the vertical axis is the z position.

was about 10 cm away from the active region of the detector to avoid having converted electrons directly entering the acceptance of the RICH. The PAD1 chamber was taken to be about 0.6% radiation length. We used single density HIJET Au+Au central collision events, and simulated all hadronic and electromagnetic shower development in $10^\circ < \theta < 170^\circ$ in polar angle and 2π in azimuth. The magnetic field map for the single outer coil with full field strength in the new yoke design was used in the calculation. The Z -position of the reaction vertex was fixed at $Z = 0$. Additional studies at $Z \neq 0$ are being analyzed but based on preliminary indications these results are not expected to change our conclusions significantly.

Fig. 1 shows a hit pattern in the RICH for a typical event. The four panels of the figure corresponds to the four sectors of RICH (Upstream and Downstream sectors of East-Arm

Dalitz	1.0
Beam pipe conversion	0.4
Magnet Pole, Decay in flight (Kaon)	0.5
DC active region	0.7
PAD active region	3.7
DC + PAD support frame	1.9
RICH gas volume	1.9

Table 2: Summary of RICH ring sources

and West-Arm). Here we assume that the photon detector will be an array of 6400 PMTs, each PMT having a Winston cone to collect Cerenkov light. Since the Winston cones limit the angular acceptance of the PMTs, only those Cerenkov photons that are accepted by the cones are plotted as in the figure. There are about 10 Cerenkov rings and 100 PMT hits per event. Most of these rings are indeed produced by the secondary background.

Fig. 2 shows the production vertex of electrons/positrons that produce at least 5 PMT hits in the RICH system. A good electron track typically produces 10 PMT hits, and this requirement of 5 PMT hits yields about 90% acceptance for real electron signal. It also required that the timing of PMT hit be within 2 nsec of proper timing for good electron signal. Since the PMTs has good timing resolution (≈ 250 psec in r.m.s), this timing cut is very conservative. The timing cut reduces the amount of background by 20%. From this figure, we can identify the major sources of background:

- there is a concentration at the collision vertex ($R = 0, Z = 0$),
- there is a small amount of conversion in magnet pole surface reaching the RICH,
- there is conversion in DC+PAD region, in particular in the support structure, and
- there is the conversion in RICH gas volume.

On average, there are about 10 Cerenkov clusters per event, of which only 1 cluster is caused by a Dalitz electron from the collision vertex. All others are caused by the conversions. The reason the number of Dalitz electrons is so small is that many of them are cut off by magnetic field. The minimum p_T at $Z = 0$ is about 92 MeV/c, and particles with less than that momentum at the collision vertex ($R = 0$) never reach the RICH detector. This curl-up momentum value becomes progressively smaller for $R > 0$ where structural material is located. Moreover, even if a Dalitz electron from the initial vertex is above the 92 MeV/c curl up momentum value it may still not be registered in the RICH because its trajectory will have been bent too much relative to the Winston cone axis. It is only when the electron's momentum exceeds 150-200 MeV/c that it will fire the RICH. With these facts in mind we quantify the sources of those conversions reaching the RICH in table 2 .

We also studied the secondary electron background for $Z = 30$ and for $Z = 0$ cm at half field strength, and have obtained similar results. Within statistical error, the amount of

Figure 2: A scatter plot of the production vertex of electrons and positrons that produce more than 5 hits in RICH. Thirty events of single HIJET Au+Au central collisions are accumulated. The region occupied by the central magnet, the inner tracking detectors (DC + PAD1), and the RICH gas volume are drawn in dashed lines to elucidate the figure.

background does not depend on the Z-vertex position. In the half field case, the number of Cerenkov clusters increases. This is because more low momentum electron/positrons which had been cut-off by the magnet in full field strength now reach the RICH detector. The background from the other sources did not show any significant increase. We also studied a case when the DC frame was moved another 5 cm away from the acceptance. This change reduced the background from the frame by half to about 1.0 per event.

The secondary electron background will have a substantial effect on the Level I and Level II trigger. In particular, it appears from these simulation results that it will be very unlikely to have any Level I trigger rejection capability for dielectron events in central Au+Au collisions. Moreover, the Level I DAQ hardware will have to contend with processing an average of 10 electron tracks per central collision. The strategy appropriate for the Level II trigger is now being studied. However, the effect on the e/π rejection and the final dielectron

measurement will be much smaller. This is because many of the Cerenkov rings that are produced by the secondary background do not have good reconstructed tracks pointing back to the collision vertex. Hence they will not contribute to the background in the final offline analysis. Even if a secondary electron has a well reconstructed track apparently coming from the vertex, it will generally have a large discrepancy between its real energy (typically less than a few hundred MeV) and its apparent momentum (a few GeV/c or larger). This is because these secondaries are produced just before the first tracking chamber in a region of weak magnetic field, and therefore they are not bent much by the field. Such spurious electrons will be readily removed by the means of the EM calorimeter energy/momentum matching condition.

All of these expectations are borne out by the most advanced PISA simulations done to-date. Namely, these new off-line type calculations do the complete pattern recognition including the full set of primary and the background particles (40% of the primary particle rate). The pattern recognition "starts from scratch" (see the discussion of Fig. 5 section 3.2.2) in that it is based on the simulated TDC responses of the Drift Chambers including multiple hits and is seeded with the the expected primary vertex reconstruction from the MVD and the BBC. Then the momentum reconstruction is done in PISA self-consistently based on this track recovery information. In turn the track recovery information is furnished to the RICH ring-finder algorithm as described in the previous paragraphs. The net result from this sophisticated simulation is that the simulated e/π rejection ratio and the dielectron invariant mass spectrum signal-to-noise ratios should be largely unaltered from what was shown and discussed in Figs. 3.3-3.5 of the CDR. At most (see the next section) there could be a 50% increase in dielectron combinatoric background depending upon the particle momentum threshold taken for invariant mass pairs.

We cannot emphasize strongly enough the difference between the planned use of the RICH in PHENIX and that attempted by CERES/NA45. In the latter experiment, the dual RICH system was designed to function *both* as a tracker and as a particle identifier. Preliminary results indicate that while that system functions well in peripheral collisions with low particle multiplicity, it is plagued by ghost tracks and suspect rings in high background central collisions. By contrast the RICH PHENIX, albeit θ -sensitive, will be operated primarily in a particle identifier mode. The track pointing information, as determined principally by PAD1 and PAD2, will lock in the ring-finder search. Without that independent tracking information our own simulation results shown here indicate that the RICH information would be hopelessly confused in central collisions. Indeed, it is our understanding from the QM '93 conference that is just such an independent tracking capability which will added to CERES/NA45 in future.

2.2.2 MVD Induced Conversion Electrons

The previous section was devoted to a study of the secondary electron backgrounds generated by the magnet yoke steel and the inner tracking chambers including their support structures. That section focussed directly on the number of rings expected to be found by the RICH from these sources which would pass the Level 1 trigger cuts. In the present section we report on the results of a separate study which has been made on the effect of the Multiplicity

and Vertex Detector (MVD). Unlike those electrons coming from the magnet steel and the tracking chamber frame support, the secondary electron backgrounds generated by the MVD cannot be rejected by tracking cuts. At best the track pointing error from the tracking system, on track-by-track basis, is simulated in PISA to be of the order of a few centimeters (see Fig. 5) and that is not good enough to reject conversions occurring in the MVD silicon layers.

Since the MVD offers the possibility of being redesigned, or even eliminated in a worst case scenario, a special study has been made using PISA to ascertain the effect of the $e^\pm$ (“electron”) background in the RICH from the MVD relative to the so-called “irreducible” background from all other sources. This study has aided in the optimization of the design of a new MVD configuration by highlighting the trade-offs and compromises to be made, in addition to emphasizing the need for and value of an integrated simulation program. The new design of the MVD, which resulted from this simulation study, has removed 2/3 of the material in the outer layer. More complete details of the updated design are contained in Chapter 5. Here we present the integrated simulation results using the re-designed MVD.

For this special study the input to PISA was the hadrons produced in Au+Au Hijet events with impact parameters less than 0.12 fm and was thus similar to the RICH ring-finding study conducted above for non-MVD sources. Dalitz decay of the π^0 to $e^+e^-\gamma$ with a 1.2% branching ratio is one source of electron background. Conversion of the photons from the dominant $\pi^0 \rightarrow \gamma\gamma$ decay branch into $e^\pm$ pairs in the material around the interaction region is another important source of background. Other hadrons contribute to the electron background mainly via a two step process. A hadronic interaction produces π^0 's, which then make electrons via the same mechanisms as primary π^0 's. This two-step channel does not give rise to a significant background component in the relatively thin beam pipe or MVD, but is important in the magnet iron and in the muon nosecone. All of the primary and secondary (tertiary and so on) particles are tracked with PISA though the PHENIX detector. The MVD, the combination of drift chambers 1 and 2 (DC1/DC2) and pad chamber 1 (PC1), and the RICH detectors were included in the simulation. The calculation also included the beam pipe (1 mm of Be), the central magnet steel (and the field produced by it), the muon absorber nosecone, and the muon magnet. Information about all electrons entering the RICH detectors was recorded, including the location of the production vertex. This study did not focus on the actual Level 1 rings produced by the RICH, but other studies have shown that about one-third to one-half, depending upon the source position, of the electrons entering the RICH will produce observable rings according to the criteria mentioned in the previous section.

The average number of background electrons entering the RICH ($\langle N(e^\pm) \rangle$) from various sources is summarized in table 3. The row labeled “magnet” includes the magnet poleface and iron plus the muon absorber nosecone. The row labeled “other” includes conversions and other interactions in air along with decay products from particles other than π^0 's. The column labeled “no cuts” includes all electrons entering the RICH detectors, without any further cuts. The background sources near the beamline have a p_T cut of ≈ 100 MeV/c introduced by the magnetic field in the central region – particles at lower p_T values are unable to leave the central region and hit the RICH. The next column includes only those electrons

source	$\langle N(e^\pm) \rangle$ no cuts	$\langle N(e^\pm) \rangle$ $p_T > 200 \text{ MeV}/c$	$\langle N(e^\pm) \rangle$ $\delta z_{vtx} < 5 \text{ cm}$
Dalitz decay	$2.46 \pm .13$	$0.86 \pm .08$	$2.46 \pm .13$
Beam pipe	$0.59 \pm .06$	$0.27 \pm .04$	$0.52 \pm .06$
MVD barrel Si	$0.82 \pm .07$	$0.21 \pm .04$	$0.80 \pm .07$
MVD electronics	$0.50 \pm .07$	$0.00 \pm .00$	$0.49 \pm .07$
DC1/DC2/PC1	$4.26 \pm .17$	$0.39 \pm .05$	$2.42 \pm .25$
magnet	$9.55 \pm .25$	$0.88 \pm .08$	$0.93 \pm .13$
other	$0.87 \pm .08$	$0.15 \pm .03$	$0.19 \pm .04$
total	$19.05 \pm .35$	$2.76 \pm .13$	$7.81 \pm .33$
MVD fraction	$7 \pm 1\%$	$8 \pm 2\%$	$17 \pm 1\%$

Table 3: The average number of background $e^\pm$ entering the RICH per central Hijet event. The background contributions are separated into difference sources. The “magnet” contribution includes the muon nosecone. The last row shows the fraction of the total number coming from the MVD. The error bars are statistical.

with $p_T > 200 \text{ MeV}/c$. The angular acceptance (for Cherenkov light) of the Winston cones in front of the RICH photomultiplier tubes introduces a p_T threshold of $\approx 150 \text{ MeV}/c$. The p_T cut used in table 3 was chosen to be slightly above this threshold.

Figure 3 summarizes some of the information in table 3. Almost all ($\approx 90\%$) background from the beam pipe and the MVD is produced by conversions of photons from π^0 decay. The top plot shows $\langle N(e^\pm) \rangle$ from various sources in the inner region – Dalitz decay, the beam pipe, the MVD barrel Si detector wafers, and the MVD electronics. The numbers with and without the $200 \text{ MeV}/c$ p_T cut are shown. The second plot shows the number of radiation lengths of material (X_0) in each of the elements. For the beam pipe and the MVD Si, this is straightforward. For the MVD electronics, an average number of radiation lengths, calculated by assuming the material in the electronics was distributed in a uniform cylindrical shell at the appropriate radius is shown. The real design will place all of the electronics at the bottom of the detector, out of the azimuthal coverage of the detector arms. The number of “radiation lengths” associated with Dalitz decay is defined as $\approx 1.2\%/2 = 0.6\%$, where 1.2% is the branching ratio for π^0 Dalitz decay. This is the number of radiation lengths of material which would be required to produce the same number of $e^\pm$ conversions from π^0 decay photons. The bottom part of fig. 3 shows the ratio $\langle N(e^\pm) \rangle / X_0$. With or without a p_T cut, the beam pipe gives a few more electrons per radiation length than the the MVD Si. Without a p_T cut, the contribution of the MVD electronics is similar to the MVD Si, but slightly lower. With a $200 \text{ MeV}/c$ p_T cut, the contribution of the MVD electronics is completely eliminated. The slightly reduced number of electrons per radiation length of material from the MVD Si, which has a hole in the upper two-thirds of the outer Si layer, and the more substantially reduced ratio from the MVD electronics demonstrates the clear advantage in putting as much of the MVD material out of the direct path to the two electron arms as possible. The contribution of Dalitz decay is larger than predicted based on the number of “radiation lengths”. The number of these “radiation lengths” was defined

Figure 3: The average number of $e^\pm$ per event from the beam pipe, MVD Si, and MVD electronics (top), the number of “radiation lengths” associated with each of these sources (middle), and the ratio of the two (bottom) are shown. “Radiation lengths” for Dalitz decay is defined in the text

such that the same number of electrons was produced. However, the average electron from Dalitz decay has half of the energy of the original π^0 compared to a quarter for the average conversion electron. This energy difference is reflected in their transverse momenta. The $\approx 100 \text{ MeV}/c$ p_T cutoff imposed by the central magnetic field eliminates a smaller fraction of the electrons from Dalitz decay than from conversions, enhancing their numbers relative to the estimated number of “radiation lengths”.

As noted in the previous section the first problem caused by background electrons is at the trigger level. Large numbers of electrons entering the RICH represent a significant problem for the trigger. The second column of table 3 shows the number of electrons entering

the RICH from the different sources. The largest contributor is electrons produced in the magnet, followed by the contribution from the combination of DC1/DC2/PC1. The triggering challenge is dominated by the need to diminish where possible electrons from these major background sources, but the trigger is not predicted to be limited by the MVD source.

After the data have been analyzed (perhaps including the online analysis in the later stages of the trigger), some sources of background should be easily eliminated. In particular, most electrons originating in the magnets and muon absorber should be easily separated from those originating near the vertex. This is illustrated by comparing columns 2 and 4 of table 3. Column 2 shows the number of electrons entering the RICH without cuts while column 4 shows the number which also traceback to a z position within 5 cm of the vertex. This cut eliminates most of the background from the magnet. Of the total “magnet” contribution about 44% of the electrons in the “no cuts” column are associated with primary π^0 's, falling to 29% when the 200 MeV/c p_T cut is applied. However, of the small fraction of electrons from the magnet which satisfy the vertex cut, $\approx 90\%$ are associated with primary π^0 's. The vertex cut eliminates slightly less than half of the background from the DC1/DC2/PC1 combination. About 90% of the DC1/DC2/PC1 background which survives the vertex cut comes from conversion of π^0 decay photons. Without cuts (column 2), only 62% of the electrons from the DC1/DC2/PC1 combination are from conversion of photons from primary π^0 's. The two step process by which particles other than π^0 's produce background can give rise to numerous electrons, but most of these electrons can be eliminated via a vertex cut.

On the other hand the vertex cut has no effect on the background from conversion of π^0 decay photons in the beam pipe and MVD --- the small number of particles eliminated by these cuts were associated with interactions of primary particles other than π^0 's. No reasonable vertex cut would be able to eliminate the conversion electrons from the inner region of the spectrometer. For practical purposes, the photons from the π^0 decay comes from the vertex ($c\tau = 25$ nm) and the pair production process produces electrons which travel, to a good approximation, in the direction of the incident photon and therefore also appear to have come from the target (to within $\approx 100 - 300\mu\text{m}$ for conversion in the MVD and beam pipe).

Because the background from material near the vertex is so difficult to eliminate, its impact on the pair mass spectrum must be understood. The MVD provides measurements which are important in the overall goals of PHENIX (e.g. $dN/d\eta$, $dN/d\eta d\phi$, multiplicity for the trigger, and the vertex position), but these positive contributions must be compared to the increase in electron background it causes. When considering the impact of the MVD on the background, the appropriate scale for comparison is the irreducible background which comes from Dalitz decay (unavoidable) and conversions in the beam pipe, which is as thin and light as possible (1 mm Be). There are two p_T cutoffs which apply to the inner detectors. First, is the ≈ 100 MeV/c cutoff due to the magnetic field and second is the ≈ 150 MeV/c p_T cutoff introduced by the RICH detector. The comparison of the MVD background to the irreducible background table 3 used a third, slightly higher, p_T cutoff of 200 MeV/c. With this p_T cut, the ratio (MVD electrons)/(Dalitz+beam pipe) is 0.20 ± 0.04 . When constructing a pair mass spectrum for electrons, the contribution of these background particles depends

Figure 4: Simulations of the invariant mass resolutions of the vector mesons to be detected in the PHENIX central arm.

on the square of the total number produced, so the MVD in its current design is expected to increase the background in the pair mass spectrum by $\approx 1.20^2 = 1.42 \pm .09$. About 10% of the material in the MVD barrel has been neglected in this calculation. The increase in background in the pair mass spectrum, compared to that from Dalitz decays and the beam pipe would be $\approx 1.27^2 = 1.61 \pm .10$ with a 150 MeV/c p_T cut.

2.2.3 Mass Resolution in the Central Arm

We are pleased to report that the simulated resolutions of the vector mesons detected in the central arm continue to be within acceptable limits. These new calculations were performed for a magnetic field which is slightly stronger (0.78 T-m vs. 0.70 T-m) than in the previous design. The detector tracking performance (position and angular resolutions) has been modelled here with better accuracy than before. Fig. 4 is a plot of the mass resolution of the PHENIX central tracker shown as a function of p_T , for the detection of these vector mesons. The drift chambers and the pad chambers were the only detectors used in these calculations. Also included in this simulation were the effects of the beam pipe, the intervening helium filler gas, and a realistically thick helium bag envelope. While not included the MVD has been shown in other simulations to have no significant effect on the predicted vector meson resolutions.

The resolutions were calculated in a single particle mode where only one particle of the

species of interest was detected within the spectrometer acceptance. The results shown here indicate that in the K^+K^- decay channel the Φ can be measured with a resolution of about 0.07% for a pair momentum below 1.0 GeV. For decays via electrons, the corresponding resolution is $\sim 0.5\%$. The J/Ψ can be measured with a resolution of about 0.7%. These results are very similar to those presented in the Conceptual Design Report. Additional information about these calculations is given in Chapter 6 describing the tracking detectors.

The PISA/PISORP simulations now include a detailed description of the expected response of the Drift Chambers and that response in turn is coupled to a modelling of the RICH ring finder procedure. An example of this calculation for the analysis of simulated ϕ meson data is shown in Fig. 5.

In the top panel there is presented the electron spectrum from a ϕ resonance event generator [15] as determined by the tracking system, and then as accepted by the RICH electron identification algorithm. This algorithm takes as its starting input the tracking information provided by the Drift Chambers in order to confirm the presence of an electron ring. According to these calculations, the RICH should be 91% efficient with respect to the number of tracks recovered by the Drift Chamber analysis.

In the middle panel is shown the invariant mass spectrum as deduced from the opposite sign pairs tracked by the Drift Chambers and confirmed as electrons by the RICH system. As before these are single meson/event type simulations but the pattern recognition conditions still have to be fulfilled. In this middle panel are listed all the details of the Drift Chamber modeling, essentially the intrinsic noise effects which we can assume will detract from perfect performance. As usual, the tracking and momentum analysis will be done in a “multi-pass” fashion for which in the first pass one is completely ignorant as to the identity and momentum of the particle being tracked. In the second, and higher possibly, passes one can mitigate some of the imperfections of the response function which are known to be momentum or particle dependent, and in that manner achieve an improved mass resolution. The mass resolutions quoted in this figure are essentially the resolutions shown in Fig. 4 integrated over this event generator’s transverse momentum distribution.

Finally, in the lower panel is shown the track pointing accuracy expected from the Drift Chamber system. In this simulation, all the electrons started from $Z = 0$, so the width of the deduced Z origin is a measure of the tracking system’s vertex resolution on a track-by-track basis. It should be pointed out that this spectrum was obtained without the use of the PAD 1 data, and that data should improve the vertex resolution somewhat. Nonetheless, one would not expect that the final resolution would be much better than 3 cm, and that resolution, as has been mentioned in the previous section, is insufficient to tag effectively photon conversion electrons originating from an MVD source. Hence, our effort to minimize the MVD material available for photon conversion into the central arm acceptance.

2.2.4 Dimuon Measurements

In the CDR, the analysis of the acceptance and coverage of the muon arm was carried out assuming “frameless” chambers. Since that time, an analysis of the acceptance has been carried out which uses realistic chamber frame widths. The analysis required that the muons from the vector mesons penetrate to the third layer of the muon identification system and

Figure 5: Simulations of the data quality expected to be available from an analysis of the ϕ mesons thrown by a standard event generator available in PISA. The top panel shows the electron momentum spectrum before and after gating by the RICH ring finder. The middle panel shows the predicted invariant mass resolution with a variety of DC noise contributions included. The bottom panel shows the spectrum of vertex Z position determinations for the electron tracks using only the data from the UV wires of the DCs.

not hit any frames in the tracking system. The fraction of events which survive those cuts are 16 % for the ϕ , 47 % for the J/ψ , and 66 % for the Υ . Drell-Yan and $D\bar{D} \rightarrow \mu^+ + \mu^- + X$ rates will be reduced by about the same fraction as for a resonance of the same mass. There is a rapidity dependence to those acceptance losses, with larger losses occurring at higher rapidity. More detail can be found in the update section for Chapter 10 of the CDR. The chamber design is still being optimized and it is felt that a significant fraction of the above losses are recoverable.

Figure 6: Two photon invariant mass spectra at various photon pair transverse momenta using $dN_{\pi^0}/dy = 375$. The results are shown for the full PHENIX calorimeter detector acceptance for photons with energy greater than 250 MeV.

2.2.5 Revision for Photon Simulations

Invariant mass spectra for two photons under the condition of a realistic case of $dN_{\pi^0}/dy = 375$ is shown in Fig. 6. A similar figure is shown as Fig. 3.10 on page 3-26 of the previous CDR. An obvious mistake was made to create the previous figure at which it was assumed that $dN_{\pi^0}/dy = 95$. Correspondingly, the yield uncertainty when one estimates cross sections of π^0 and η from the two-photon spectrum is higher than that presented in the previous CDR. The correct figure on the yield uncertainty is shown in Fig. 7. This figure is the replacement of the previous CDR Fig. 3.11 on page 3-27. Yield extraction uncertainty is defined as statistical uncertainty only: systematic errors are not taken into account.

If π^0 and η peaks are identified in the two-photon spectrum, the next step is to evaluate the spectrum of single photons by using these π^0 and η . This spectrum is shown in Fig. 8b.

Figure 7: PHENIX calorimeter detector performance for $dN_{\pi^0}/dy = 95$ (squares) and $dN_{\pi^0}/dy = 375$ (circles), the multiplicity anticipated at RHIC. Top: π^0 (open points) and η (solid points) measurement showing the transverse momentum dependence of the peak-to-total ratio (Q). An asymmetry cut of $\alpha \leq 0.4$ is applied. Bottom: The statistical uncertainties in the meson yield extraction. Solid points: π^0 , open points: η . Systematic errors are not taken into account.

On the other hand, the actual photon spectrum recorded on the detector is given in Fig. 8a. If the reconstruction procedure is perfect, Fig. 8a must be identical to Fig 8b. In fact, these two seem identical.

Figure 8: Measured single photons as compared with the reconstructed single photons from π^0 and η for two days runs at RHIC for central Au + Au collisions. An electromagnetic calorimeter resolution of 7% at 1 GeV is assumed.

However, if one takes the ratio between the two spectra, Figs. 8a and 8b, the ratio deviates from 1 at $p_T < 1$ GeV/c, as seen in Fig. 8c. This deviation would originate for two reasons: (a) The signal-to-noise ratio of π^0 becomes worse as p_T decreases and, therefore, the yield ambiguity of single photons from π^0 increases. (b) The opening angle of 2γ from π^0 increases as p_T decreases, so that the contribution from π^0 's produced in the rapidity region outside the detector coverage becomes stronger as p_T decreases.

As described in Section 3.1., our conclusion is, therefore, that the direct photon measurement is possible at $p_T > 1$ GeV/c, if an enhancement of the direct photon is well above a

few percent of the single photons from π^0 .

2.2.6 First Studies of the QED Background into the BBC

The Beam-Beam Counter (BBC) determines the time zero T_0 when an interaction occurs in a beam bunch crossing (2 ns traversal time) and provides the first estimate of the vertex point Z_0 along the beam axis. The BBC consists of two sets of identical counter arrays installed on both sides of the interaction region. One set is in the muon plug on the Muon detector side, and the other is in free space. By measuring a pair of arrival times T_1 and T_2 of the fastest particle which intercepts the counter array on each side, the time zero T_0 and the interaction point Z_0 will be obtained as the average and the difference of T_1 and T_2 , respectively.

If there were no backgrounds nor any slow particles, the resolutions of the extracted T_0 and the Z_0 would be affected only by the intrinsic time resolution of the counter elements. However, all interactions do produce slow particles, even at very forward angles, and there does exist a significant amount of background particles scattered from the central spectrometer structures and from the Muon detector. Therefore an examination of the BBC performance with a Monte Carlo simulation is mandated. The specific results of this simulation of the intrinsic BBC performance is detailed in Chapter 5. We choose to show here the first results of a study of the *physics* background into the BBC, namely that coming from Quantum Electrodynamical Pair production.

In a relativistic heavy-ion beam crossing one will have copious creation of energetic electron and positron pairs due to QED processes. Hence the BBC subsystem risks being exposed to an enormous amount of QED electrons and positrons. These events occur independently of the nucleus-nucleus strong interaction. Their backgrounds would affect the performance of the T_0 and the Z_0 determinations in the nucleus-nucleus interaction of our interest, if both of the QED and strong nucleus-nucleus processes occur in the same beam bunch crossing. The majority of such QED electrons and positrons are expected to be of low total momentum and would be curled up in the axial magnetic field, absorbed in the beam pipe or an absorber in front of the BBC, and thus will not be detected. However, some energetic electrons or positrons could reach the detector and produce misleading TDC data.

To evaluate the yield of QED backgrounds which might contaminate the BBC, a simulation study was made. This study used the PISA/PISORP program chain and is described more fully in Chapter 5. Briefly, one thousand electrons with various P_t momenta were thrown at a fixed angle $\theta = 4^\circ$ from the $Z = 0$ position, and the number of events with any hit in the counter array was counted. Most of the hits originated in showers created at the beam pipe or absorbers. The result is shown in Fig. 9. We found the P_t cut-off momentum of electrons to be around 4 MeV/c. A theoretical P_t spectrum of the QED pair creation[16] indicates that roughly 98%¹ of QED backgrounds will be cut off. A more quantitative study is in progress with a specially developed QED pair event generator from which results should be available by year's end.

¹The P_t spectrum at 4° was not available, therefore used the total P_t spectrum integrated over all the kinematical region to get this value.

Figure 9: The P_t cut-off momentum of electrons at the BBC.

2.3 Presentation to the TAC Cost and Schedule Review

- 1) What is simulation and why have it in **PHENIX**?
- 2) What's new in simulation since the CDR?
 - RICH at Level 1
 - MVD at Level 2
 - DC/RICH combination at Levels 2 and 3²

²Shown previously

- PAD Electron Backgrounds at Levels 0, 1, and 3
 - Muon ID at Level 1
 - BBC at Level 1
- 3)** PISA/PISORP 2 prototype performance
 - 4)** WBS Summary of PISA/PISORP 3 development

What is ... ?

- **Simulation** is the computerized modelling of the *real* detector in response to *real* events in as *realistic* a manner as possible.
 - **Stand-alone Simulation** is the modelling of a single detector subsystem in a detailed manner while making more or less realistic assumptions about the effects of all other detector subsystems.
 - **Integrated Simulation** includes *all* detector subsystems modelled in equally detailed manners and under the same event conditions. Integrated simulation requires an agreed upon method of “data” exchange between detector subsystems.
- Simulation should encompass all aspects of the data flow from the lowest to the highest trigger conditions and on into the off-line analysis.

Why have ... ?

Simple answer: Does this device measure the physics signatures it is claimed to do, and under what assumptions are these claims valid and when do they become invalid such that the detector inexorably fails?

Detailed answers (partial list):

- **Initial design stage** where one scopes out a single subsystem and eventually the whole detector – 1992
- **Re-design stage** where a subsystem optimized in stand-alone is found to be “unneighborly”, or else costs have to be cut, *etc.* – 1993-94
- **Data reduction stage** where using software strategies one coaxes the best technical performance out of the detector once the designs have been frozen – 1995-98
- **Physics analysis stage** where one sorts out the spurious signals from the real signals – 1999-?

Purposes of an INTEGRATED simulation

- QGP Signatures proposed PHENIX invariably involve the participation of several of the major detector subsystems:
 - Interesting signals typically associated with highest particle densities where modeling of the subsystems is most difficult.
 - Extraordinary limits, *e.g.* 10^4 e/π separation in central arm and 10^4 $\pi^\pm$ suppression in muon endcap, are demanded.
 - Stringent energy resolution goals, *i.e.* $\Delta M/M < 0.5\%$ in central arm and $\Delta M/M < 3.0\%$ in muon endcap, are mandated to achieve acceptable signal-to-background.
- Subsystem design decisions rely crucially on simulation results:
 - Each subsystem must be meet its objectives under a consistent set of event characteristics.
 - Each subsystem must be compatible with every other subsystem in direct view of the collision region → *First Rule*
Every perfectly working subsystem is, at some level, another subsystem's background generator.
 - Every signal and background simulation must be performed under consistent assumptions of subsystem performance and mutual interaction.

⇒ **PISA PHENIX Integrated Simulation Application**

General overview

- The **integrated** simulation is more **integrated** than before.
- The **realistic** events are more **realistic** than before.
- The simulation spans a **wider path** across the dataflow than before.

Details

- The **RICH** subsystem performance exhaustively simulated down to Level 1 trigger stage
 $\Rightarrow e/\pi$ discrimination factor of $RICH \geq 10^3$, remains keystone of dielectron physics program
- The **MVD** subsystem carefully scrutinized for impact on the dielectron background
 $\Rightarrow$ a new MVD design is optimized preserving needed physics function
- The **DC** chambers rigorously simulated down to “scratch” (TDC drift times, basic intra-cell level)
 $\Rightarrow$ complex events reconstructed, tracks momentum analyzed, and RICH's electron ID algorithm successively engaged
- New simulations of **Muon ID** subsystem pad detectors
 $\Rightarrow$ pad design enhances true pair signal rate at earliest trigger level
- New **BB** subsystem straightforwardly incorporated into PISA
 $\Rightarrow$ simulations underway to confirm its performance facing secondary and real (QED) backgrounds

There are TWO electron background issues: on-line and off-line

RICH rings at Level 1 for one event, and their (Z, R) origins for 30 events

Dalitz	1.0
Beam pipe conversion	0.4
Magnet Pole, Decay in flight (Kaon)	0.5
DC active region	0.7
PAD active region	3.7
DC + PAD support frame	1.9
RICH gas volume	1.9

Summary of RICH full ring sources

source	$\langle N(e^\pm) \rangle$ no cuts	$\langle N(e^\pm) \rangle$ $p_T > 200\text{MeV}/c$	$\langle N(e^\pm) \rangle$ $\delta z_{vtx} < 5\text{cm}$
Dalitz decay	$2.46 \pm .13$	$0.86 \pm .08$	$2.46 \pm .13$
Beam pipe	$0.59 \pm .06$	$0.27 \pm .04$	$0.52 \pm .06$
MVD barrel Si	$0.82 \pm .07$	$0.21 \pm .04$	$0.80 \pm .07$
MVD electronics	$0.50 \pm .07$	$0.00 \pm .00$	$0.49 \pm .07$
DC1/DC2/PC1	$4.26 \pm .17$	$0.39 \pm .05$	$2.42 \pm .25$
magnet	$9.55 \pm .25$	$0.88 \pm .08$	$0.93 \pm .13$
other	$0.87 \pm .08$	$0.15 \pm .03$	$0.19 \pm .04$
total	$19.05 \pm .35$	$2.76 \pm .13$	$7.81 \pm .33$
MVD fraction	$7 \pm 1\%$	$8 \pm 2\%$	$17 \pm 1\%$

The average number of background $e^\pm$ entering the RICH per central Hijing event.

The average number of $e^\pm$ per event from the beam pipe, MVD Si, and MVD electronics (top), the number of "radiation lengths" associated with each of these sources (middle), and the ratio of the two (bottom) are shown.

MESSAGE: MVD not a problem on-line; off-line MVD raises electron background $\approx 25\%$ inclusives $\Rightarrow 60\%$ pairs.

Central arm (Z,R) origins of background electrons entering PAD 2

Momentum spectra of background electrons at various levels in the central arm

PISA Simulation of Muon ID Trigger Algorithm

Muon ID Level 1 Trigger Algorithm Simulation

- Complete absorber configuration with full HIJET events
- Muon ID subsystem response implemented realistically in PISORP
 - Road starts with hit in layer 1
 - Road continuation in subsequent layers if subsequent hit bin within ± 1 bin numbers (both theta and phi) of previous layer bin numbers
 - Road continuation in subsequent layers if subsequent hit bin within ± 2 bin numbers (both theta and phi) of first layer bin numbers
 - Road termination layer recorded
- Road algorithm results
 - 80% of events have at least one road from layer 1 to layer 2
 - 45% of events have two roads both from layer 1 to layer 2
 - 20% of events have two roads both from layer 1 to layer 3, $\Rightarrow$

80% event rejection attained simply at Level 1

consistent with $\geq 89\%$ J/ψ relative acceptance

PISA Simulation of Muon ID Trigger Algorithm

Muon ID Level 1 Trigger Efficiency Calculation

- R. Vogt J/ ψ event generator called 7494 times
- 403 muon pairs reach layer 2 (same number for layer 1 also)
- 398 muon pairs reach layer 3
- Assume 95% efficiency in layer 3 for each muon
- $\Rightarrow \epsilon = 398 * (0.95)^2 / 403 = 0.89$ *relative efficiency*
- Absolute efficiency = $398 * (0.95)^2 / 7494 = 0.048$ (ignoring μ -tracker, etc.)
- More sophisticated algorithm could allow for missing layer 3

PISA Simulation of BB Counter Electron Acceptance

- BB Counter Subsystem Introduced into PISA in May, 1993
- Simulations of performance and background effects are underway
- Possible impact of QED electrons being investigated
 - First step is simulation of transverse momentum acceptance as a function of electron's P_T (shown above for $\theta = 4^\circ$)
 - Second step is use of realistic QED event generator to get electron rate into BB subsystem for Au+Au at RHIC
 - Third step is to mix QED and central Au+Au events in a single simulation run to determine if there is a background problem
- Total QED P_T spectrum $\Rightarrow$ 98% of electrons ≤ 4 MeV/c

PISA: Past and Present

March 23, 1992 DC Meeting: *We need an integrated simulation !*
J. Harris at QM'93, June 24

FOPI for GSI becomes PISA for RHIC

May 15, 1992 through August 15, 1992

PISA 1.0 for the pCDR simulations: VAX first then UNIX

Muon Tracking, Muon ID, Muon Resolution, Electron Tracking, EMCal clusters/TOF, RICH performance

October 15, 1992 through April 15, 1993

PISA 2.0 for the CDR simulations: VAX and UNIX equivalent

PISORP 2.0 released: enables full exchange of data between subsystems

CMZ framework for installation and maintenance (provisional choice)

August 27, 1993 through present

PISA/PISORP 2.03 for CDR update/TAC review

Expanded use of KUIP interface, realistic pattern recognition and momentum analysis

Full integration of inner central detectors (MVD, DC, RICH) and the Muon Arm

PISA/PISORP 2.03 now contain 70,000 lines of code (120 lines/day @ \$0.0)

PISA/PISORP 2.03

Three Performance Criteria

1) Execution Speed (quoted for a 25 megaflop RISC unit)

- ≈ 10 HIJET events/hour into central arm (almost all particles)
- ≈ 40 HIJET events/hour into muon arm (higher momentum filter)
- 100 - 500 events O.K. for simple background and trigger studies
- Require ≈ 100 hours CPU and event mixing for signal/noise studies such as the ϕ and the J/ψ plots in the CDR.

2) Consistency of Results

- Several independent groups in different institutions are achieving comparable results (for example in electron backgrounds, mass resolutions, and tracking performance) using PISA on different UNIX platforms and comparing PISA to stand-alone simulation programs

3) User-friendly and productive?

A Delphic oracle's answer:

“People still talk to me about PISA, but not as much as they used to”

*S.H.A. riposte: “Be careful that you ask
the right question to a simulator”*

– San Ramon, October 24

- PISA/PISORP 3 Development builds on existing prototype
 - Approximately 20 FTE-years allocated, about 25% of the total off-line allocation, and with \$0.2K real expenditure
 - Core group to do the infrastructure design and code generation
 - Detector group contact persons to do subsystem specific coding
 - Professional software specialist to assist in database and graphics interfaces, similar to off-line WBS scenario
- PISA/PISORP 2 prototype development to cease in Q1 of 1994. It will serve as the interim simulation facility during PISA/PISORP 3 program production
- PISA/PISORP 3 envisions a hierarchy of data structures ranging from **Level 0** to **Level 3**, with all of these data structures aligned with the overall on-line/off-line database management technology
 - **Level 0** from PISA 3 is essentially the raw output of GEANT at the subevent level (no analog in the actual data stream)
 - **Levels 0.2–1.0** from PISORP 3I simulates the detector subsystem data at various stages in the DAQ culminating in the **Level 1** data structure simulating what is archived to tape from the Level 1 trigger
 - **Levels 2–3** from PISORP 3II simulate the processing of the data (eq. track stubs in the DCs) first on an isolated detector subsystem basis, and then on a subsystems integrated basis
 - All data structures to be graphically accessible and summarizable
- Milestones according to the generation of the data structures – first **official** release of PISA/PISORP 3 on July 1, 1996

3 RD45 Experiment Progress

Last year after coordinating the summer run for the RD-10/45 experiment shown in Figure 10, the VU group began the data analysis of the data from this experiment. This year we continued with this data analysis and also used GEANT 3.14 to simulate the experimental setup so that the experimental results could be compared to those of GEANT.

The first step in the data analysis was to fine tune the particle identification. Next the various alternatives for the definition of hits for the calorimeter, the hodoscopes following the calorimeter, and the wire chambers were considered and the one that gave the best efficiency to noise ratio was chosen for each of them. Both the particle identification and the definition of hits went through several iterations before all the bugs were worked out.

The RD-10/45 experiment was run with 1–8 GeV/c single particle beam from the AGS consisting of protons, pions, muons, electrons and kaons. Of particular interest was the range of pions (protons) as a function of momentum. This was determined by measuring the fraction of incident pions (protons) with hits in the n th scintillator plane of the calorimeter where $n = 1 \dots 39$. The tail of the distribution of fraction of incident pions (protons) is linear on a log scale (see figure 11) and can be fit with an exponential to give a formula for fraction of events with hits as a function of range in iron for each of the momenta used in the experiment.

Also of interest is the distribution (lateral and angular) of hits at a given range. This was measured after 80 cm and 135 cm of iron (the two calorimeter sizes used in the RD-45 experiment) by a combination of the wire chambers and the hodoscopes (T1 and T2 in figure 10) following the calorimeter. Figure 12 shows a typical lateral distribution of hits for muons and for protons. In addition to measuring the distribution of hits the wire chambers and leakage hodoscopes were used to evaluate the effect of a 10 cm lead wall which was placed between the calorimeter and the first leakage hodoscope for some of the runs. The effect of the lead wall on the fraction of events with hits in the leakage detectors and on the distribution of these hit was determined.

The calorimeter was also studied in terms of energy resolution for the various particles as a function of energy. This is of interest because there is very little data of calorimeter resolution in the energy range of 1–10 GeV/c.

In addition to the data analysis mentioned above the VU personnel spent about 3 weeks at BNL helping with the setup and running of the PHENIX μ -Id experiment. We assisted with the setup of the second level trigger, the strategy for particle identification, general grunt work of laying cables, etc.

4 The Soft Photon Experiment

**R. Clark, C. Erd, J. Gomez del Campo, A. Ray, J. Schukraft, D. Shapira,
M. Tincknell, and C. Woody**

Experiment E855, a search for new sources of “soft” photons (transverse momentum < 50 MeV), was conducted at Brookhaven in March of 1990. A beam of protons of energy 10

Figure 10: RD-10/45 experimental setup

Figure 11: Fraction of events with hits versus range for 8 GeV/c protons.

Figure 12: Plot showing the difference between the muon and proton lateral distributions for leakage from 80 cm Fe calorimeter for 6 GeV/c particles.

and 18 GeV was used to bombard Be and W targets at the AGS. Some theorists claim that partial or complete quark deconfinement would lead to a slight excess of just such photons and, hence, provide supporting evidence for the existence of a quark-gluon plasma.

To see the predicted signal one has to remove the known sources of photons in this energy regime, which include hadronic decays, bremsstrahlung, and the decay of excited nuclei. Of the hadronic decays, the overwhelming contribution is due to π^0 's, each of which decays into 2 photons. Because of the abundant amount of progress which has occurred in the analysis in the past year and which this report addresses in some detail, the reader is referred to the previous progress reports on this experiment or reference [1] for a more thorough discussion of the theoretical considerations as well as a discussion of the detector layout.

Bremsstrahlung photons are created as a consequence of the primary proton-nucleon interaction. In this interaction many charged particles are spontaneously created with rapid velocities, which thereafter produce bremsstrahlung radiation. This is similar to the case of bremsstrahlung production following the spontaneous creation of an electron during β -decay.

Since charged particles weren't measured during the experiment, a method of their estimation was necessary. The LUND Monte Carlo provided the charged particle distribution from which the bremsstrahlung yield was calculated. Previously, the calculation had been performed only at $y_{cm} = 0$. During the past year the calculation has been extended to all the other rapidities at which our photon detectors were placed.

Another calculation which was completed recently was the CFD trigger efficiencies for the two photon detectors. Each of these consisted of an array of 19 hexagonal BaF_2 crystals in a close packed arrangement. (In this report the array located at forward rapidities will hereafter

be referred to as BAF1 and the one placed at wider angles BAF2.) This calculation was needed in order to correct the low p_T portion of the spectra. To do this a series of GEANT simulations were run for monoenergetic photons which varied from 3 MeV in energy up to 2.048 GeV. In all 30 different energies were used in the simulations, which were repeated for each of the two photon detectors. From the energy deposition patterns and the known CFD efficiencies for *each crystal* of the photon detector, a determination of the probability of, say, a 20 MeV photon of firing a CFD was possible. This work has been completed for both photon detectors.

These monoenergetic GEANT simulations were also used to study energy leakage out the back and sides of the crystals. It turns out that the amount that the monoenergy peak is shifted is easily parameterized in energy. It was hoped that it would be enough to assign an energy shift for each measured energy, which would correspond to the most probable energy.

Because the dimensions of BAF1 and BAF2 are different, treatment of leakage had to be done separately for each detector. Although this method worked fine for the photon detector which was located at forward angles (BAF1), it was found to be inadequate for BAF2. The reason for this is that the crystals of BAF2 are shorter than those comprising BAF1, so more energy leaks out the back. As a result, not only are the most probable energies shifted more for BAF2, the *spread* of the energy shift is greater for BAF2.

Figure 13 illustrates the different results for BAF1 and BAF2. The solid curve is a hypothetical input distribution which was made to mimic the real data. The dotted curve is the uncorrected detected spectrum, and the dashed curve has been corrected for CFD trigger efficiency and leakage using the methods described above. The detected curves also have the effects of position resolution and photostatistics in them. A pileup of low p_T events (< 100 MeV/c is noticable in BAF2. It is evident from the figure that BAF2 needs a more elaborate method which takes into account the distribution of leaked energies, not just the peak of that distribution. Such a treatment is now being developed.

Within the past year progress has also been made on the absolute normalization of the data. Although this has yet to be finalized because various detection efficiencies have not been estimated, two of the figures in this report plot absolute cross sections as they stand now. These values are not expected to change much when all detection efficiencies are factored into the normalization.

Another aspect of the analysis which was completed in the past year was a study of the effect of multi-photon events in a single detector contaminating the data. This analysis makes no attempt to distinguish these events. It is simply assumed that all neutral events not believed to be neutrons are single photons. If there is an appreciable probability that an event contains more than one photon, then the spectra will be affected. To study this phenomenon the LUND Monte Carlo was used as input. It turns out that even at 11° , where more photons hit the detector than at any other position, the probability is no more than a few percent.

Also studied this year was the class of events in which one photon was deposited in BAF1 and one photon into BAF2. There are of the order of 2000 such events in all of the data. These events were looked at in an attempt to reconstruct the invariant mass of the π^0 . This is possible because a subset of these photon coincidence events will be from a single

Figure 13: The effects of energy leakage, trigger efficiency, position resolution and photo-statistics on transverse momentum spectra: solid curves, input; dotted curves, uncorrected detected spectra; dashed curves, corrected detected spectra. a: BAF1, b: BAF2.

π^0 decay. The purpose of doing this was to check the energy calibration in a manner which was completely independent of the previous method, which was using minimum ionization events. The results of this effort are shown in Figure 14. The distinct peak at a mass of 134.98 MeV, as determined from a gaussian fit to the peak, is within 2 parts in 10000 to the published value for the π^0 mass.

To have any hope of seeing an excess signal it is critical to accurately estimate the contribution to the spectra due to the decay of π^0 's. By measuring the photon spectrum as a function of rapidity, it is possible to infer the original π^0 p_T spectrum. This involves a parametrization of the π^0 p_T spectrum and allowing it to decay via a Monte Carlo program. One systematically varies the parameters of the π^0 spectrum, minimizing the χ^2 of the difference between the measured *photon* spectrum and the one produced by the π^0 Monte Carlo.

Since the bremsstrahlung, nuclear γ 's and the purported anomalous signal for which this experiment searches are significant only at low p_T , the effect of these on our π^0 photon spectral fit is removed by fitting only for $p_T > 50$ MeV. To carry out this minimization process, the MINUIT minimization package of the CERN program libraries was used [18].

These fits of the data have been substantially improved within the last year. This has been accomplished primarily by altering the π^0 parameterization in order to take into account

Figure 14: Reconstruction of the π^0 invariant mass from photon coincidence events. a: solid curve, data; dotted curve, a fourth degree polynomial fit to the background continuum; dashed curve, continuum fit plus gaussian fit to the peak. b: solid curve, data with the continuum subtracted; dashed curve, gaussian fit to peak.

that the spectra become steeper at wider rapidities. This phenomenon is due to the fact that such rapidities are closer to the edge of phase space.

Figure 15 shows the fitting procedure applied to the LUND data, which includes not just π^0 decays but all hadronic decays. In the interest of space only four rapidities are shown although data was taken at 9 different ones. It is worth pointing out that the increase in the p_T slope is evident in the LUND data in this figure. It is also worth noting that the results of the fit with LUND are exceptional and provide evidence that the overall methodology is sound.

Figure 16 shows the same fitting procedure applied to the pBe data. Also shown in the figure is the bremsstrahlung estimation as well as the sum of these two contributions. In this figure and the next, the spectra of the data turn over at the low p_T end because weighting due to trigger efficiency is turned off when greater than 5. This was done to avoid giving unreasonably high weights to the data, which would necessarily make it less reliable. It can be seen from the figure that no excess signal of any sort is evident.

Figure 17 shows both the Be and W data at $y_{cm} = 0$. A significant excess is apparent in the W data. An excess is also seen at the other rapidities in tungsten. An attempt was made recently to correlate this signal with the charged particle multiplicity in the event in

Figure 15: Photon p_T distributions for LUND data compared with π^0 decay contribution derived from fit (solid curve). a: $y_{cm} = +0.5$, b: $y_{cm} = 0$, c: $y_{cm} = -1.28$, d: $y_{cm} = -1.83$.

order to determine its production mechanism. This correlation can be used to distinguish purely hadronic sources of soft photons, such as meson decays and bremsstrahlung, which vary linearly with the charged multiplicity, and a thermal source of soft photons, which would exhibit a quadratic dependence on the charged multiplicity [19]

No correlation was observed at all. Since it was believed that the hadronic decay and that the bremsstrahlung contribution due to particles produced in the primary interaction were correctly estimated, the question of the origin of the excess signal naturally arises. Originally, it was believed that the source of these photons might be the decay of excited nuclei, in which case they would not surprisingly be absent in the Be data.

Figure 16: Photon p_T distributions for Beryllium data compared with π^0 decay and bremsstrahlung contributions. a: $y_{cm} = +0.5$, b: $y_{cm} = 0$, c: $y_{cm} = -1.28$, d: $y_{cm} = -1.83$.

Because a linear least squares extrapolation of data from targets of various thicknesses to an empty target (target out) spectrum does not work for tungsten (Figure 18), it is now believed that the excess seen in W is due to *secondary* interactions in the W target. The thickness of the W target, 1 mm, was chosen to be 1% of a proton interaction length. However, 1 mm is a much more significant fraction of the photon radiation length in W, which is .35 cm. In the energy regime of the experiment the most probable situation is for a relatively high energy photon to pair produce on its way out of the W target and for the resulting charged particles to emit low energy photons via bremsstrahlung.

To study the effect of these types of interactions, the oft used GEANT program was

Figure 17: Photon p_T distributions for Beryllium and Tungsten data at $y_{cm} = 0$ compared with π^0 decay and bremsstrahlung contributions. a: Beryllium, b: Tungsten.

again employed. However, due to reasons of file format, LUND was not used as the GEANT input. Another Monte Carlo event generator called ARC (A Relativistic Cascade) was used in its stead [20]. Figure 19 shows some very preliminary results from this study.

This figure requires some explanation. In panels a: and b:, all photons within a rapidity range were accepted. This assures maximum statistics. On the other hand, in c: and d: only photons which hit the BaF₂ photon detector were accepted. This criterion was used in order to study the effect of charged particle vetoing of an event. The secondary bremsstrahlung photons are typically accompanied by the parent electron or positron.

However, in the analysis of the real data, all events with charged particles entering the photon detector are thrown away. Therefore, only secondary photons which are not in close proximity with their parent particles would have contaminated the data. All other secondary photons would have been thrown away. It is readily apparent from panel c: of Figure 19 that this makes a huge difference.

One piece of the data analysis which remains is to quantify the information in Figure 19 with that of the real data in Figure 18. Ultimately it will be desirable to overlay a secondary source contribution in panel b: of Figure 17. Also yet to be completed is implementing a better method of treating energy leakage in BAF2 as well as the error analysis. It is expected that all data analysis will be finished within the next few months.

Figure 18: Extrapolation to empty target thickness from a bin to bin linear least squares extrapolation. Upper solid curve, 5% interaction length; dashed curve, 2% interaction length; dotted curve, 1% interaction length; dot-dashed curve, extrapolated empty target spectrum; lower solid curve, actual empty target spectrum. a: and b: Beryllium, c: and d: Tungsten.

References

- [1] T. Matsui and H. Satz, Phys. Lett. **B178**, 416 (1986).
- [2] C. Lourenco (for NA38), Talk at QM'93 (to be published).
- [3] D. Lissauer and E.V. Shuryak, Phys. Lett. **B253**, 15 (1991).
- [4] K. Kajantie, J. Kapusta, L. McLerran, and A. Mekjian, Phys. Rev. **D34**, 2746 (1986).
- [5] E. Shuryak and L. Xiong, Phys. Rev. Lett. **70**, 2241 (1993); K. J. Eskola and M. Gyulassy, Phys. Rev. **C47**, 2239 (1993).
- [6] L. Van Hove, Phys. Lett. **B118**, 138 (1982).

Figure 19: Effect of secondary interactions in the tungsten target. a: dashed curve, ARC input spectrum; solid curve, output spectrum; dotted curve, photons due to secondary interactions. b: solid curve, spectrum of photons due to secondary interactions for a target thickness of 5% interaction length; dashed curve, 2% interaction length; dotted curve, 1% interaction length. c: solid curve, photon spectrum due to primary plus secondary photons hitting detector; dashed curve, same as solid curve except requiring no accompanying charged particles. d: solid curve, photon spectrum due to primary plus secondary photons when hitting detector and no accompanying charged particles for 5% interaction length; dashed curve, 2% interaction length; dotted curve, 1% interaction length.

- [7] M. Kataja, P. V. Ruuskanen, L. McLerran, and H. von Gersdorf, Phys. Rev. **D34**, 2755 (1986).
- [8] F. Wilczek, Talk presented at QM'93 (to be published).
- [9] B. Müller and X.-N. Wang, Phys. Rev. Lett. **68**, 2437 (1992).
- [10] M. Gyulassy and M. Plümer, Phys. Lett. **B243**, 432 (1990).

- [11] S. Pratt, Phys. Rev. **C33**, 1314 (1986); G. F. Bertsch, M. Tohyama and M. Gong, Phys. Rev. **C37**, 1896 (1988).
- [12] J. D. Bjorken, Phys. Rev. **D27**, 140 (1983).
- [13] D. K. Srivastava, J. I. Kapusta, NUC-MINN-93/3-T; also Talk presented at QM'93 (to be published).
- [14] A. Chilingarov *et al.*, Phys. Lett. **B83**, 136 (1979); K. Kodama *et al.*, Phys. Lett. **B263**, 579 (1991).
- [15] R. Vogt, Atom. Nucl. Data Tabl. **50**, 343 (1992).
- [16] J.-S. Wu, M.J. Rhoades-Brown, C. Bottcher and M.R. Strayer RHIC Detector Note 4. May 1992
- [17] C. Woody *et al.*, "Status of Soft Photons in Experiment E855," from the Proceedings of the Pittsburgh Workshop on Soft Lepton Pair and Photon Production, J.A. Thompson, editor, Nova Science Publishers, Inc., New York, 1992.
- [18] F. James and M. Roos, CERN Program Library D506, MINUIT-Function Minimization and Error Analysis, 1986.
- [19] V. Cerny, P. Lichard and J. Pisut, *Z. Phys.* **C31**, 163.
- [20] Y. Pang, T. J. Schlagel and S. H. Kahana, *Nuc. Phys.* **A544**, 435c (1992).

The 4π CsI-Ball

R.Tezkratt, C.F. Maguire
Department of Physics and Astronomy
Vanderbilt University, Nashville TN 37235

K.Hagel, B.Xiao, R.Wada and J.B.Natowitz
Cyclotron Institute, Texas A&M University
College Station, TX 77843

I. Introduction.

In the past year we have focused most of our effort on the construction of our 4π CsI Ball [1]. This detector will be used in conjunction with the HILI [2] counter and the Texas A&M University Neutron Ball. The combined devices will be dedicated to the study of heavy ion collisions at intermediate energies between 10 - 60 AMeV.

In this report we will focus on the progress made in the construction of the CsI Ball. Before this, we will give a detailed description of the device which is reported in the section 2. In the sections 3-5 we will summarize the detector design the photomultiplier tube base and the light collection efficiency in the CsI(Tl) crystals. The technique for the fabrication of uniform thin scintillator foils will be presented in section 6. The tests results for the particle identification and the data acquisition electronics will be detailed in the last two sections.

II. Description of the 4π CsI Ball..

The CsI-Ball consists of 96 phoswich detectors. A schematic three dimensional view is shown in fig.1. The light guides and the phototubes are not included in this picture. The device consists of 7 independent rings with azimuthal symmetry around the beam axis. For ease of assembly the frame of the Ball is divided into three pieces, the first piece, in clockwise direction, holds four rings, the second one holds one ring the last piece holds two rings. The frame is made of aluminum. The individual detectors mounts are designed to allow the remouval of any detector without interfering with the alignment of the neighboring detectors.

Fig 2. shows the half-plane section of the Ball in the vertical plane which contains the beam axis. For each ring the polar coverage angle and the number of the detectors are given in table 1. For a given ring the CsI(Tl) pieces are identical in shape and have the same polar angle coordinates with respect to the beam axis. In order to have high granularity at the forward angle, the solide angle subtented by forward detectors are smaller than for backward detectors.

The CsI-Ball will cover approximatively 92% of 4π solide angle. The loss in solide angle reflects in : the back hole for beam entrance and the front exit hole, the gaps between individual detectors and finally the removal of one detector at 90° to allow the target insertion, the resulting solid angle loss is on the order of 8%.

III. Detector design.

The whole set of detectors are composed of thin plastic scintillator NE102A (2.4 ns rise time) of typical thickness : 50 μm , and 2 cm CsI(Tl) scintillator cristal. A schematic view of the detector design is given fig. 3. The thin plastic layer is placed in the front face of the CsI(Tl) crystal with out bonding material. The back face of CsI(Tl) crystal is glued with optical cement to a light guide made of plexiglas. This light guide has the shape of the CsI(Tl) crystal on its front face and a circular shape on its back face in order to fit the cylindrical shape of the phototube. The lenght of the light guide dependent from ring position. The front face geometries of the individual crystals in different rings are shown in figure 4. The front and side faces of the CsI(Tl) are polished. The scintillator and the light guide are wraped with a white teflon tape, which is a good reflector of UV light emitted during the scintillation process. The back face of the light guide is glued via optical greace to the entrance window of the photomultiplier tube (PMT) (Hamamatsu 1924). The PMT and the light guide are surrounded by a cylindrical μ -metal shield. The front face of plastic scintillator is coverd by aluminised mylar foil (200 $\mu\text{g}/\text{cm}^2$). The resulting detection thresholds for particle identification range from $E/A \simeq 2$ MeV for alpha particles to $E/A \simeq 4$ MeV for Ca ions.

The photomultiplier tube and its voltage divider are designed to operate at atmospheric pressure, while the plastic and the CsI(Tl) are in a vacuum vessel.

IV. Photomultiplier Base.

A considerable efforts have been made in order to design our own photomultiplier voltage divider. Starting our search from existing ones in the market we finally found

is a clear separation of the $Z = 2$ isotopes. The data shown in this spectrum are the product at 20° of the $^{40}\text{Ar} + ^{197}\text{Au}$ reaction at 20 MeV/A.

For higher Z particles, the phoswich identification mode ($\Delta E - E$) is used. Identification results are shown in Fig. 8 whose event sample comes from the same test run as used in Fig. 7. One clearly sees high Z resolution up to $Z = 16$ over a considerable dynamical range of particle energies.

Particle identification can be improved by increasing the thickness of the plastic foil, but this has the inconvenient to increase the detection threshold particularly for heavy fragments.

IX. Summary and schedule.

We have nearly finished the construction of the CsI Ball. This detector is dedicated for the detection and measurement of the light charged particles as well as intermediate mass fragments with nearly 4π coverage. It consists of 96 phoswich detectors arranged in 7 coaxial rings. Each detector is made of $50\ \mu\text{m}$ thick plastic scintillator foil and 2 cm thick CsI(Tl) crystal. Good element identification up to $Z = 16$ is reached.

Together with the forward wall of the HILI hodoscopes (192 detectors, 2.5° opening angle each), this device will bring an excellent resolving power with a total of nearly 300 detectors in all. Finally the combination CsI-Ball-HILI-Neutron ball will be dedicated to the study of the hot nuclear matter and its decay modes. The combined capabilities have been made for this physics in such way that the recent theoretical developments can be confronted directly to the experimental results in order to answer some of the questions in this exciting domain of the nuclear physics.

The first data taking is expected for the beginning of the next year (1994).

References

- [1] – C.F. Maguire, *et al.*, Proposal of A Comprehensive Detector of Heavy Ion Reaction Products, 1989.
- [2] – D. Shapira, *et al.*, NIM A301 (1991) 76.

after several test the good values of the resistor chain divider which gave us the better particle identification in the beam particle tests. Figure 5 shows the diagram for the voltage divider we finally adopted.

V. Light collection efficiency.

Considerable attention was paid to the light collection efficiency in the CsI(Tl) crystals. Alpha particle tests were performed on one the largest crystals which belongs to the 6th ring shows that a good light collection efficiency was achieved (figure 6). Indeed this results shows no dependence of the amplitude the light pulse as a function of the position. The different position are illustrated in the top right of this figure.

VI. Fabrication of the scintillator foils.

The scintillator foils were spread from Betapaint Bicorn BC-448 plastic scintillator dissolved in xylene. The solution was diluted until it had the desired viscosity than spread on a glass plate which was maintained horizontal until the solution dries. The resulting thicknesses is a function of the viscosity of the solution. Typical thicknesses we could make are ranging between 30 to 200 μm . We obtained a good and reproducible results with good thickness uniformity (less than 10 %).

VII. Data acquisition electronics.

The electronics of such a detector is a very important part of the project. Both CAMAC and FASTBUS standards are used. Because of the cost of this project part we choose the cheapest solution everywhere.

In order to reduce the ratio signal/noise level and dispersive losses for the fast anode current pulse representing the response of the plastic scintillator, the whole data acquisition electronics will be settled next to the reaction chamber. Discriminator thresholds and photomultiplier high voltage supplies are adjusted via remote computer control.

VIII. Modules test results.

The results of the beam tests are very successful. As shown in Fig. 7, the CsI pulse shape discrimination (PSD) mode of identification easily resolved the light charged-particles. We can see that all three of $Z = 1$ isotopes are cleanly identified, and there

Figure 1. A schematic three dimensional view of the CsI-Ball.

Figure 2. Half-plane section of the Ball in the vertical plane which contains the beam axis.

Figure 3. A schematic view of the detector design.

Figure 4. The front face geometries of the individual crystals in the different rings.

Figure 5. Photomultiplier voltage divider. $R1 = R10 = R11 = 160K\Omega$; $R3 = R7 = R8 = 60K\Omega$; $R2 = R4 = R5 = R6 = 41K\Omega$; $C1 = C4 = 0.1\mu F$; $C2 = 0.2\mu F$; $C3 = 0.3\mu F$.

Figure 6. Test result for light collection efficiency in the CsI crystal with the light guide.

Figure 7. Two dimensional identification spectra of the gamma-rays, p, d, t, ^3He and alpha particles, obtained during a test run of one module of the CsI-Ball.

Figure 8. Scatter plot of the slow part of the CsI response versus the plastic response obtained during a test run with one module of the CsI-Ball. 57

DATE

FILMED

5/13/94

END