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Author

Schroeder, L.S.

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DETECTORS FOR HIGH ENERGY NUCLEUS-NUCLEUS COLLISIONS*

L. S. Schroeder
Nuclear Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

Invited paper presented at the Fourth International Conference on
Ultra-relativistic Nucleus-Nucleus Collisions, Helsinki, Finland,
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L. S. Schroeder
Nuclear Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

1. Introduction

In this talk I want to review the recent Workshop on Detectors for Relativistic Nuclear Collisions, held last March 26-30, 1984, at the Lawrence Berkeley Laboratory. For a complete summary of the meeting consult the Proceedings of the Workshop.¹ Besides providing you with an overall impression/flavor of the Workshop, I also hope to instill in you a sense of the considerable strides that have been made in coming to grips experimentally with the very complex collisions that we will encounter at higher energies. But at the same time, it must be realized that we still have a long way to go to fully exploit the potential of this new domain of high energy and baryon density.

2. Reasons and Goals for the Workshop

There were several reasons for having the dedicated Detector Workshop. As we proceed into the mid-1980's and beyond, the prospects for higher energy nucleus-nucleus collisions are quite promising. Specifically, at Brookhaven a transfer line between the Tandem Van de Graaff and the AGS will provide light ions ($A \leq 32$) at energies up to 15 GeV/nucleon in 1986.² At the same time, an upgrade of the PS injector by the GSI/LBL collaboration will provide ^{16}O ions in the CERN SPS at energies of 15-225 GeV/nucleon beginning in 1986.³ In late 1983, the Nuclear Science Advisory Committee of the Department of Energy and the National Science Foundation recommended⁴ that the next major nuclear physics facility in the United States should be a relativistic nuclear collider to explore the domain of high energy densities and hopefully the production of deconfined hadronic matter--the quark-gluon plasma. Finally, several national laboratories in the United States have active programs underway to look at collider options, including RHIC at Brookhaven,⁵ the Mini-Collider at Berkeley,^{6,7} and a 10 GeV/nucleon on 10 GeV/nucleon

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Since new fixed target heavy-ion facilities will be available by 1986, only two years away, we felt that it was both timely and necessary to start looking at the detector requirements imposed by these much higher energies well in advance of their ability to deliver beam on target. With the somewhat more distant future for colliders, an early start on detectors is also called for. Specifically, the goals of the Workshop were:

- o Build on the substantial base of information generated for detectors at the previous Quark Matter meetings,^{9,10} fixed target detectors discussed at Bielefeld and at an SPS fixed target workshop¹¹ in December 1982, and collider detectors at Brookhaven (QM'83).
- o Consider detectors for both geometries, i.e.,
fixed target: spanning energies from 15-225 GeV/nucleon
collider: covering the range from $2 + 2$ to $100 + 100$ GeV/nucleon
- o Want to identify any detector elements thought to be on the critical path for investigation of the quark-gluon plasma which require an R&D effort.

3. Structure of the Working Groups

In order to provide a central focus for the Workshop it was decided to concentrate on the detection of the quark-gluon plasma as our theme. However, it should be remembered that the conclusions arrived at for detectors are really in the context of high energy and baryon density achievable in central high energy nucleus-nucleus collisions and apply to a potentially broader and richer range of phenomena than just the quark-gluon plasma per se.

The individual working groups (five in all) were roughly set up along lines of observables of the quark-gluon plasma.^{12,13} Figure 1 is the now familiar representation of the evolution of a central nucleus-nucleus collision in the temperature (T) and relative baryon density (ρ/ρ_0) plane. Two imagined trajectories, one emphasizing the baryon-rich plasma, the other the meson-rich (so-called "transparency") regime are shown. In order for a detection scheme to be sensitive to the presence of the quark-gluon phase, measurements of direct radiation from the plasma itself (region 1) or from the re-hadronized phase (region 2) will be required. Since the plasma is not thought to be stable, radiation from both regions could be present in each event. A device measuring hadrons in the final state would

Phase Diagram With Nuclear Collision Trajectories

Experimental Signatures

- Region 1: Direct radiation from plasma (photons, leptons, lepton pairs)
- Region 2: Recondensed hadronic matter (π , K, p, $\bar{p}$, ...)
Possible free quarks, diquarks

Figure 1: Phase diagram for nuclear matter showing trajectories corresponding to the "transparency" (baryon-free) and "stopping" (baryon-rich) zones of the nuclear collision process.

detect hadrons arising from ordinary hadronization processes found, for example, in nucleon-nucleon collisions, and hadrons produced by quark and gluon recombination processes in the plasma phase. Theoretical guidance will certainly be required to differentiate between these sources.

For the Workshop we identified three areas of detector measurement or technique which were used as the focus for individual groups. These were:

- o Hadrons--generally thought to include detection of strange particles and antibaryons, i.e., few particle measurements, often with a reduced solid angle detector system.
- o Event parameters--experiments with large ($\sim 4\pi$) solid angle coverage, measuring many of the final state particles in order to determine such experimental observables as the average charged particle multiplicity $\langle M \rangle$, the pseudo-rapidity ($dn/d\eta$), or rapidity (dn/dy) distributions as function of multiplicity, fluctuations in particle density, etc.
- o Penetrating probes--experiments involved in measuring photons, leptons, lepton pairs, etc., which are thought to be useful in probing the hot, compressed stage of the collision process.

For each of these categories, there was a separate working group for fixed target and collider geometries. Each working group had conveners who organized and guided the work of the group. The conveners were:

	<u>Hadrons</u>	<u>Event Parameters</u>	<u>Penetrating Probes</u>
Fixed Target:	C. Gruhn (LBL) I. Otterlund (Lund)	K. Foley (BNL) A. Poskanzer (LBL)	J. Carroll (UCLA) M. Goldberg (Syracuse)
Collider:	$\left\{ \begin{array}{l} \text{W. Carithers (LBL)} \\ \text{T.J.M. Symons (LBL)} \\ \text{G. Young (ORNL)} \end{array} \right\}$		T. Ludlam (BNL) L. Madansky (Johns Hopkins)

These are the people who did the work and are the ones who made the Workshop a success.

4. Background Information--A Starting Point

Before proceeding to the results, I first want to illustrate some of the experimental problems and discuss related instrumentation

questions that we know will have to be dealt with to unravel the dynamics of central nucleus-nucleus collisions.

The first and most obvious fact is that central nucleus-nucleus collisions (always assume the heaviest nuclei for maximizing production of the plasma) will yield very high multiplicities of final state particles. Already at Bevalac energies the GSI/LBL Plastic Ball experiment observes ≈ 100 – 200 charged particles being produced. This is shown in Figure 2 for the case of Au + Au collisions at a laboratory kinetic energy of 1.05 GeV/nucleon (0.234 GeV/nucleon in the c.m.). In this energy range the final states are still dominated by nucleons. At about 10 GeV/nucleon in the laboratory, roughly the energy available at the AGS, we expect several hundred mesons (mostly pions) will be created, comparable to the number of nucleons. At the energies of the now famous Si + Ag JACEE event,¹⁴ ≈ 4 – 5 TeV/nucleon in the laboratory, we expect a thousand or more mesons to be created and are in a "meson-dominated" regime. The multiplicities described above have been observed! Recent event simulations are also finding similar numbers.¹

The large multiplicities that will be present naturally lead us to ask instrumentally oriented questions. These include:

- o To what extent will tracking of individual particles still be possible (useful) in such a high multiplicity environment?
- o As the multiplicity increases, do we eventually just rely on calorimetry for our event information?
- o How to receive and process the large amount of information associated with these events?
- o How to trigger on central collisions?
- o Are there existing detector designs that can do (almost do) the job?
- o Does experience with big high energy detectors such as UA1 or UA2 provide some of the answers to our questions?
- o Finally, what are the signatures of the quark-gluon plasma?

Having formulated these questions, we hoped to provide some but not all of the answers.

5. General Comments on Detectors in Fixed Target and Collider Geometries

As pointed out previously, the individual working groups divided into separate categories (hadrons, event parameters, penetrating probes) and concentrated on detectors in either a fixed target or collider geometry. Before discussing the highlights of the working groups, I want to discuss some general features of detectors which

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Figure 2: Charged particle multiplicity distribution for Au + Au collisions studied by the GSI/LBL Plastic Ball collaboration at the Bevalac.

are intrinsic to: i) the geometry of the experiment (fixed target or collider) and ii) the energy range associated with these geometries.

The fixed target groups considered experiments spanning the energy range of $E_T = 15\text{--}225$ GeV/nucleon. This corresponds to a rapidity interval between target and projectile of $\Delta y \approx 3.5$ at 15 GeV/nucleon, and $\Delta y \approx 6.2$ at 225 GeV/nucleon. Figure 3 indicates the present concept of the collision process, where the regions are divided into spectator and participant zones. For $E_T \leq 225$ GeV per nucleon no clear baryon-free central region will be developed. An additional feature of event detection in the fixed target mode is the strong kinematic focussing of particles in the forward direction. In particular, the spectator nucleons associated with the projectile will be emitted into a narrow cone of $\Delta\theta < 1^\circ$ about the beam axis at 15 GeV/nucleon, and $\Delta\theta < 0.1^\circ$ at 225 GeV/nucleon. This means that one will be able to measure particles emitted in the target and central rapidity regions, but that the projectile associated nucleons will be much harder. However, this focussing does have one major advantage: a lack of fast forward-going projectile fragments within the interval $\Delta\theta$ can be used as part of a central collision trigger (e.g., use in veto mode--if projectile spectator fragment observed, veto event--not central). The strong center of mass boost experienced with fixed target geometry is also advantageous to short-lived particles such as K_S^0 , Λ^0 --greatly improves their detection efficiency. Finally, in the fixed target mode the "effective luminosity" (event rate = $\sigma\mathcal{L}$) can be made large, just by using a thicker target; this enhances the possibility of observing processes with very low cross-sections. The thickness must of course be chosen to accommodate other considerations such as keeping the conversion of γ -rays (mostly from $\pi^0, n \rightarrow \gamma\gamma$) under control.

In collider geometry the particles are emitted over the complete 4π solid angle. This greatly reduces the number of particles per unit solid angle, but does place an added burden of requiring a much larger detector system (therefore more expensive) if one is interested in obtaining information on the complete event. For colliding beam experiments the interaction region can be up to a meter in length. With such an extended source and assuming high interaction rates (i.e., high luminosity) some tracking of the particles will be required just to guarantee that they come from a single vertex. Since one can not place a counter directly in the beam, other methods of selecting central collisions than the one discussed above for the fixed target mode will have to be developed (e.g., large multiplicity, high transverse energy or momentum, etc.).

Figure 3: Characterization of the collision process showing spectator and participant regions.

Figure 4: (a) Charged particle multiplicities for $^{16}\text{O} + \text{A}$ and $^{40}\text{Ca} + \text{A}$ collisions obtained by extrapolation of pA data, where k = number of participant nucleons/number spectator nucleons. (b) Expected number of charged particles per steradian.

Now we turn to a review of the results from the individual working groups. I will try to cover the highlights of each group and again refer you to the Workshop Proceedings for a much more complete version.¹

6. Hadrons-Fixed Target

This group considered those fixed target experiments involving measurements of the single-particle or few-particle inclusive type. Experiments of this genre would generally be restricted to reduced solid angle coverage (i.e., not 4π) with associated detectors (e.g., multiplicity array, calorimeter, etc.). Examples of the experiments considered by the group were: i) measurement of strange particles and antibaryons for flavor tasting of the plasma, ii) Hanbury-Brown/Twiss (HBT) like-particle interferometry to extract information on the space-time evolution of the system, and iii) production of heavy flavors such as $\phi(1020) = \phi(s\bar{s})$, $\psi(3100) = \psi(c\bar{c})$ as a probe of the quark content of the plasma.

Considerable attention was paid to the question of how to trigger on central collisions. One possibility is the so-called "spectator veto" where one vetos events which produce near beam-rapidity particles in the projectile fragmentation region. In order to understand the influence of such a central collision tag, extrapolations based on proton-emulsion data¹⁵ have been performed for nucleus-nucleus reactions considered by the hadron group. Figure 4 shows the results of these extrapolations for charged particle multiplicities (4(a)) and the number of particles expected per steradian (4(b)) as a function of the laboratory emission angle, Θ . In each case, the distributions were calculated for the spectator veto.

Figure 5 shows a relatively large solid angle spectrometer being designed by Gruhn et al.¹⁶ for the detection of strange baryons and antibaryons. Particular attention is being given to Ω production since being an (sss) system it could be a very sensitive probe of the plasma phase of the collision. The main elements of the detector are: a superconducting magnet (3.5-7 T) to sweep away low momentum particles from the forward cone, a multiplicity array for centrality tagging, and a downstream projectile calorimeter in which low energy deposition would be used to signal a central event. The heart of the apparatus is a micro-TPC (μ TPC) which will be used to recognize and identify both the initial strange particle decay (e.g., $\Xi^- \rightarrow \Lambda^0 \pi^-$) and the subsequent decay ($\Lambda^0 \rightarrow p \pi^-$). Three planes of drift chambers are used in front of the μ TPC to increase momentum resolution.

Figure 5: Proposed layout of an experiment to study strange baryon and antibaryon production with 160 beams at the CERN SPS (Ref. 16).

SINGLE ARM SPECTROMETER

Overall length 12 m, $\theta: 5^\circ - 20^\circ$ Typically 10-15 particles to track

Figure 6: Single arm spectrometer being considered for possible use at the AGS (15 GeV/nucleon) with light ion beams ($A \leq 32$).

Small solid angle devices were also considered. They offer several advantages, including: i) excellent particle identification, ii) good momentum resolution, $\Delta p/p \lesssim 1\%$, and iii) are capable of taking high beam intensity. Figure 6 shows an example of an inclusive small solid angle ($\Delta \approx 10$ msr) spectrometer being considered for studying charged particle spectra ($\pi^\pm, K^\pm, p, \bar{p}, \Lambda$ decays) in the central rapidity region ($5^\circ < \theta_{\text{Lab}} \lesssim 20^\circ$ for $^{32}\text{S} + \text{Au}$ collisions at 15 GeV/nucleon). For 10^7 particles on target per sec up to 10 particles per event could be tracked and identified in the spectrometer. The main elements of the detector are the track segment projection chamber (TSPC) for tracking, a large aperture vertical deflection magnet, followed by several arrays of threshold Čerenkov and aerogel counters. A lucite multisegmented Čerenkov multiplicity filter would be used to tag central events. The device would be employed to measure inclusive spectra of strange and non-strange particles. Comparison of these spectra at several beam energies would provide information on the "nuclear temperature" of the participant zone and the strange particle yields have of course been suggested as a probe of the plasma phase.^{12,13,17} This spectrometer could also be used for interferometry measurements (HBT) of π 's and K's. In this context, W. Zajc led a small working group which considered interferometry in detail.¹⁸ The good news appears to be that rates for HBT studies will be large (one gains as the square of the multiplicity). But the high multiplicities present as yet unsolved tracking problems. This group estimated the time needed to reach 10^5 events as summarized below:

	<u>2π pairs</u>	<u>2K pairs</u>
15 GeV/nucleon	10 hr.	1000 hr.
200 GeV/nuclon	1 hr.	100 hr.

These estimates are for ^{16}O collisions on a heavy (Pb or U) target.

The hadron group also considered streamer chambers,^{1,3} solid state nuclear track detectors¹ and emulsion chambers¹ as suitable detectors for fixed target nuclear collision studies. The group raised the following detector issues which need further study: i) at high multiplicities secondary interactions in detector material can cause a problem for pattern recognition, ii) reduced coverage ($\Delta\Omega$) at forward angles may be necessary to accommodate large particle fluxes--impacts detector segmentation, and iii) groups using streamer chambers need to look further into CCD and holographic read-outs ($\sim 40 \mu\text{m}$ resolution needed). Finally, they identified the following areas as

needing R&D: i) particle identification (RICH's, etc.) and ii) $\check{C}$ segmentation required due to density of final state particles (how best to do it? how to focus $\check{C}$ light?).

7. Event Parameters--Fixed Target

This group concentrated on detectors for fixed target work which have nearly 4π solid angle (i.e., complete azimuthal coverage). The four types of detectors and the range of physics that each would cover is indicated in Table 1. Beams of both 15 GeV/nucleon ^{32}S at the AGS and 225 GeV/nucleon ^{16}O at the CERN SPS were discussed.

Table 1

<u>Event Parameter</u>	<u>Idealized Detector</u>	<u>MPS III</u>	<u>Non-Magnetic</u>	<u>Streamer Chamber</u>
Multiplicity:				
Neg	X	X		X
Total	X	X	X	X
dN/d η	X	X	X	X
dN/dy:				
Neg	X	X		X
Others	X			
$\pi^\pm$ energy	X			
π^0 energy	X		X	
E_T	X		X	
P_T	X	X		X
Shape: equilibration	X	X	X	X
flow	X	X	X	X
jets	X	X	X	X
Particle corr: π^-	X	X		X
K, $\bar{p}$	X	X		
Others	X			

I will only review their results for the so-called "idealized" detector. The MPS III is being described elsewhere in these proceedings,² and the non-magnetic detector and streamer chamber are closely related to the detectors being designed by the GSI/LBL PS 190 collaboration and are described elsewhere in these proceedings.³

The idealized dipole detector conceived by this group is shown in Figure 7. It consists of a target surrounded by a cube of CCD detecting planes which act as vertex detector and multiplicity counter inside the uniform magnetic field region. Three-dimensional tracking chambers are spread throughout the volume of the magnet, with electromagnetic and hadronic calorimeters (located inside return yoke of dipole coils) and time-of-flight counters providing angular coverage (down to $\theta_{\text{Lab}} \approx 20^\circ$). Downstream of the magnet are additional tracking chambers, possible RICH detectors for particle identification and more time-of-flight and calorimetry.

Figure 7: Idealized detector.

Figure 8: (a) 15 GeV/nucleon $^{160}\text{Pb} + \text{Au}$ central collisions tracked in the non-bend plane of the idealized detector.

(b) Same event in the bend plane with a field of 0.5T.

As suggested earlier, the numbers of particles will be large. For example, the results of a HIJET calculation¹⁹ for $^{16}\text{O} + \text{Au}$ at 15 GeV/nucleon for impact parameters $b \leq 4$ fm, suggests several hundred particles. To see what this means for a detector like the idealized system of Figure 7, the group has simulated what a typical central event at 15 GeV/nucleon would look like. Figure 8(a) shows the event in the non-bend plane where pattern reconstruction is easier (tracks are straight lines). Figure 8(b) shows the same event in the bend plane (assume 0.5 T field). Clearly at 225 GeV/nucleon, due to the larger number of particles and their stronger forward focus, it will be even harder. The group suggests that a system like the European Hybrid Spectrometer which uses a series of dispersing dipoles spaced along the beam line would possibly be a better solution. They further concluded that heavy beam ($\text{Au} + \text{Au}$) fixed target experiments look very difficult at 15 GeV/nucleon and only calorimetry at 225 GeV/nucleon looks feasible, even for ^{16}O .

They identified the following areas as requiring substantial R&D: i) CCD vertex detectors are completely untested for heavy ions, ii) RICH detectors have been built but not proven in high multiplicity environment, iii) three-dimensional tracking chambers, iv) new development in calorimetry of soft hadrons needed, v) thin μTPC 's, Si-beam anti's and time-of-flight barrel arrays, and vi) pattern recognition problems require much more software development.

8. Petrating Probes-Fixed Target

This group considered systems designed to detect directly produced electromagnetic probes (photons, leptons, lepton pairs) in light ion collisions from 15-225 GeV/nucleon. In looking at the physics addressed by such detectors, they followed a rough set of guidelines provided by L. McLerran^{1,13}:

Transverse Mass ($m_T^2 = m_{\text{pair}}^2 + p_T^2$)

Possible Source

1) $m_T \lesssim 50$ MeV	coherent emission from local charge fluctuations
2) $50 \lesssim m_T \lesssim 500$ MeV	hadronic decays; some coherent effects
3) $500 \lesssim m_T \lesssim 3$ GeV	direct emission from plasma
4) $3 \lesssim m_T \lesssim 10$ GeV	approach to equilibrium; structure function of quarks and gluons (perturbative QCD)
5) $m_T \lesssim 10$ GeV	Drell-Yan

Although several different detectors were identified by the group, I will only mention plans to measure high mass muon pairs using a combination (NA34) of a spectrometer (first discussed at the Bielefeld meeting⁹ by W. Willis and collaborators) designed for proton-nucleus experiments and the existing NA3 spectrometer to be used as the downstream muon spectrometer. Its elements are shown in Figure 9. Their approach employs strong filtering (≈ 10 interaction lengths) after the target to remove hadrons and limit decays of π 's and K's into muons. In this way they hope to get around problems arising from high multiplicities, lepton identification and combinatorics. Multiple scattering in the filter will of course impose limits on the mass resolution and p_T of the dimuon pair. The front-end of the detector consists of a vertex detector and hadron calorimeter. In addition, they will also incorporate electron identification in the front-end so that the low-mass spectrum ($m_{ee} < 1000$ MeV) can be studied. However, at the time of the Workshop, studies indicated that due to the large multiplicities expected (they quote ~ 300 charged particles within a 5° core for $^{16}O + ^{195}Pt$ at 225 GeV/nucleon), individual electron tracking and identification may not be possible. Furthermore, the 150 π^0 's expected/central event will yield between 1 and 2 e-pairs via Dalitz decay alone--complicating the process. A possible future development is the addition of a pair spectrometer (placed in an opening in the calorimeter section) to measure soft photons and electrons.

The group developed Table 2, to assess whether experiments are do-able; and if so in what kinematic domains; and if proposed.

Figure 9: NA34 detector being proposed for light ion experiments at CERN. (a) Full detector, (b) expanded view of the near target detector.

CODE: DO $\equiv$ DO-ABLE
 PROP $\equiv$ existing PROPOSAL
 DET $\equiv$ existing DETECTOR
 Y = YES N = NO R = RUMORED

Accelerator	AGS			SPS		
Probe	DO	PROP	DET	DO	PROP	DET
Hard Gamma (same info as D-Y pairs but higher yield)	NO (π^0 reject too hard)			MONEY (low yield requires dedicated mach. then OK for $p_T > 2.5$ GeV/c)		
Medium Backward Gamma	Y	R	N	Y	R	UA1
Soft Gamma, $X_f \sim 0$	Y	N	N	Y	N	N
<u>Lepton Pairs</u>						
Large Mass	Y ($M_{e^+e^-} > 1$ GeV)	N	N	Y R	Y	NA3($X_f \sim 0$) NA10($X_f \sim 1$)
ϕ, ψ	(conclusions same as for large mass pairs directly above)					
Low Mass, 0.4-1 GeV	Y (if $N_{ee}/N_\pi > 10^{-5}$)	R	N	MONEY Y	N N	N($X_f \sim 0$) N($X_f \sim 1$)

9. Penetrating Probes--Collider

This group employed the same criteria for the physics and kinematic regimes of interest as described in section 8, the difference being that they were concerned with experiments done in the colliding beam mode, where the particles of interest spread out over 4π . Figure 10 shows us a picture of the geometry and kinematics in the collider frame of reference (positions of detector elements are shown). The average momenta associated with different rapidity values are not large ($< 1-2$ GeV/c) for values of y near midrapidity. Note that the extended source present in the collider will require some close-in tracking capability in order to differentiate between multiple event vertices. For purposes of their work, the group considered collider detectors at $3 + 3$ GeV/nucleon ($\Delta y = 2.8$) and at $100 + 100$ GeV/nucleon ($\Delta y = 10.6$), with luminosities rising from $\mathcal{L} \sim 10^{24} \text{ cm}^{-2}\text{sec}^{-1}$ at the lower end to $\mathcal{L} \sim 10^{27} \text{ cm}^{-2}\text{sec}^{-1}$ at the upper end. Fig. 11 shows results of a HIJET calculation¹⁹ of the number of particles per unit rapidity (as function of y) at three different collider energies for central Au + Au collisions.

The group did not undertake the design of a specific apparatus;

Figure 10: Schematic layout of the forward half of a collider detector showing the angular correspondence with pseudorapidity ($y = -\ln(\tan \theta/2)$); this corresponds to the rapidity of particles whose $m \ll p_T$. The approximate average momentum, $\langle p \rangle$, is given for each rapidity interval.

Figure 11: HIJET predictions for central Au + Au collisions at three different CM energies.

however, they did conclude that a device like that shown in Figure 12 (a symmetric version of the Bielefeld detector⁹) had many of the features required to make it a useful dimuon detector. That is, it should be compact (to filter out hadrons) and be able to detect muons with $p_{\mu} > 5 \text{ GeV}/c$ (momentum needed for effective hadron filtering). Also if one is interested in studying the small pair mass and transverse momentum characteristics of the plasma, one is restricted to $|y| > 2$, where the geometry and kinematics are similar to fixed target experiments, consistent with the design in Figure 12. The practical limit for pair mass muons in the central region in a collider would be $M_{\mu\mu} > 3 \text{ GeV}$ --not the region most strongly populated by a thermalized quark-gluon plasma.

Low-mass electron pairs for probing the plasma will be hard due to the high multiplicities expected. The group suggested that any electron detector should exploit the reduced numbers of particles expected at midrapidity. Difficulties arise due to tracking in this environment, and an electron/hadron rejection of $\geq 10^5$ is needed to be able to identify direct electrons. A specialized detector with relatively small aperture at $\theta_{c.m.} = 90^\circ$ appears to be the best choice. They noted that electron identification techniques are not easily incorporated in a large acceptance system, such as the one shown in Figure 12.

High p_T photons ($p_T \gtrsim 8 \text{ GeV}/c$) are rare processes in hadron-hadron collisions and require high luminosities to be seen. However, they may be enhanced in central nucleus-nucleus collisions and should be looked for (again, luminosity will be the dominant issue). Shower counters, capable of resolving individual photons, will be required, all in a high multiplicity environment. They conclude that much work remains in this area before experiments are undertaken.

One final point worth noting: they discussed the possibility that jet-production²⁰ may be an interesting new signature for the plasma. Collider energies in excess of 50-75 GeV/nucleon will be required before such studies can even be started.

In the area of R&D the group identified: i) charged particle tracking and high resolution wire chambers capable of resolving individual particles in high track density and multiplicity environment, ii) vertex detectors (e.g., silicon strip detectors), iii) techniques of particle identification in the background of many particles, and iv) more information needed on effects of radiation damage in nuclear beam experiments (including effects of slow neutrons and heavy fragments).

Figure 12: A 4π detector for high energy colliding beam operations derived from a workshop study for a fixed target device at the CERN SPS (Ref. 10). To make this detector, two of the SPS fixed target designs were placed back-to-back.

This group considered detectors that could address the broad range of needs of both hadron and event parameter experiments. For hadron studies they considered detection of baryons, mesons and their anti-particles with the idea of obtaining information on: i) strange/nonstrange and baryon/antibaryon production ratios, ii) relative yields of particles with $|s| = 0, 1, 2, 3$, iii) $\pi\pi$, KK , pp intensity interferometry, and iv) studies of multipion and multikaon systems. Event parameter measurements include: i) multiplicity and energy and momentum flow as functions of rapidity and azimuthal emission angle, ii) correlations between dN/dy and $\langle p_T \rangle$, and iii) fluctuations in these observables. Also considered were the similarities and differences for collider detectors operating between $2 + 2$ GeV/nucleon and $100 + 100$ GeV/nucleon. One immediate comment is that if the plasma is characterized by a temperature of, say $T = 200$ MeV, the average energies of particles emitted from such a thermal source will be relatively low (e.g., π 's ≈ 500 MeV, K 's ≈ 400 MeV). This means that the detector (particularly at midrapidity) will generally be sampling soft hadrons. This puts an added burden on calorimetry for these particles and on the survival probability for those particles which are unstable (e.g., $\approx 88\%$ of the π^+ 's produced from a 200 MeV plasma will survive a 3 meter flight path, and $\approx 52\%$ of the kaons).

Their general aim was to define a relatively simple collider detector, one which employs tracking over a limited solid angle while providing calorimetry over the remaining nearly 4π . In this scheme, the target/projectile fragmentation regions were not considered, since at collider energies most of the fragmentation products remain inside the beam pipe. Figure 13 shows the general layout of such a detector. It consists of the following elements: i) a multiplicity barrel surrounding the interaction region capable of measuring $dN/d\eta$ with good accuracy, ii) electromagnetic and hadronic calorimetry over at least the central two units of rapidity ($40^\circ \leq \theta_{c.m.} \leq 140^\circ$), and iii) an open region into which one could place either a visual detector like a streamer chamber or a charged particle spectrometer with the ability to track up to 20 particles. Thus, the general philosophy was to use the calorimetry section for triggering (high p_T or E_T) and the streamer chamber or spectrometer arm for measuring single and few particle correlations. The capabilities of a streamer chamber are well known for relatively high multiplicities and for observing decays of unstable particles like $\Lambda^0 \rightarrow p\pi^-$. The magnetic spectrometer arm would have to possess good tracking and

Figure 13: General layout for a collider beam detector with nearly 4π calorimetry and tracking capability at midrapidity.

Figure 14: Layout of the zero degree photon detector to measure bremsstrahlung at a collider.

particle identification capabilities. Note that the bending will be in the vertical plane, allowing equal acceptance for positive and negative particles. Such a device, concentrating on the physics of the central region, should have a large dynamic range of operation, i.e., work as well at a few GeV/nucleon as at tens of GeV/nucleon; since the plasma once achieved should be characterized by a single temperature (relatively independent of incident energy).

The group performed a simple Monte Carlo study of the magnetic spectrometer arm's acceptance for HBT experiments. They assumed: i) 10^5 pairs needed to provide a sensitivity of Δ (radius) ≈ 0.2 fm, Δ (lifetime) ≈ 0.7 fm/c and Δ (intercept-degree of coherence) ≈ 0.1 , ii) luminosity of 10^{24} cm $^{-2}$ sec $^{-1}$ for uranium-uranium collisions, and iii) rate $\propto \mathcal{L}(dn/dy)^2$. From the Monte Carlo they obtained 1.5×10^4 like sign π -pairs/day, so that about one week's run would provide detailed HBT information.

Since one cannot place a detector directly in the beam for collider experiments (as is done for fixed target work) other ways of defining centrality are needed. Following the suggestion of Bjorken and McLerran²¹ that bremsstrahlung photons emitted as two nuclei pass through each other, could be used as an indicator of the number of charged participants $\left(N_{\text{tot}} \approx \frac{Z^2 \alpha}{\pi} \ln \frac{\omega_{\text{max}}}{\omega_{\text{min}}}\right)$, one finds that $N_{\text{tot}} \sim 50$ photons can be expected in the energy interval of 100-1500 MeV at a mean angle of $\sim 0.6^\circ$, at 100 + 100 GeV/nucleon for a Au + Au collision. The neutrons from projectile break-up are well inside this cone (i.e., at $\sim 1/10$ its value). Figure 14 shows such a photon detector, downstream of the interaction region. A lead-glass array, consisting of ~ 250 cells (to reduce double-hit probability), located ≥ 30 meters from the interaction point, would be suitable.

The group identified the following areas for R&D: i) studies of calorimeter responses to intense fluxes of soft photons and hadrons, ii) issues related to machine design--identifying backgrounds for 0° photons and access to 0° for both charged and neutral particles, and iii) more thinking about what to do with several hundred fully identified tracks, if you have them.

11. Summary

A number of lessons were learned from the Workshop, including:

- o Experiments appear do-able, but
 - i) in high flux environment one will probably have to give up tracking all particles and go to calorimetry
 - ii) selective tracking will often be required (e.g., to

distinguish between multiple vertices in collider mode).

- o R&D issues identified
 - i) particle identification (thin TPC's, RICH, TRD, ...)
and the related question of segmentation of detectors
 - ii) low-mass detectors needed to reduce delta rays,
conversions of γ 's, secondary interactions, ...
 - iii) use and development of high-technology items (e.g., Si
strip detectors)
- o Need for high energy physics input
 - i) interest and participation (the quark-gluon plasma is
both an intellectual and instrumental challenge)
 - ii) experience and expertise (e.g., use experience with
large detector like UA1 as a guide post)
- o More theoretical work/input on question of signatures of
quark-gluon plasma (theorist's R&D).

Much work has occurred since the time of the Bielefeld and Brookhaven Quark Matter meetings on the question of detecting high energy central nucleus-nucleus events. Many new proposals for experiments are being submitted to the new high energy facilities. The message is clear: there is a community of particle and nuclear physicists who want to use nuclear beams to probe the new phenomena expected in the high energy density environment of nucleus-nucleus collisions. The experiments are do-able, but if history teaches us any lessons (and if we are willing to listen), the process of unraveling the signal from the background will not be an easy one. It will tax our ingenuity as experimentalists--but it is a challenge we will be happy to accept.

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