ORNL/TM-11179

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MARTIN MARIETTA

Detectors for Relativistic Heavy-Ion Experiments

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OPERATED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
NTIS price codes—Printed Copy: A03; Microfiche A01

ORNL/TM-11179

Physics Division

Detectors for Relativistic Heavy-Ion Experiments

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Prepared as Supplemental Material
for the 1989 Report of the NSAC Instrumentation Subcommittee

DATE PUBLISHED — April 1989

Prepared for the
Office of High Energy and Nuclear Physics

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
operated by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-84OR21400

CONTENTS

ABSTRACT v
1. EXPERIMENTAL PROBES FOR NEW STATES OF MATTER FORMED IN ULTRARELATIVISTIC HEAVY-ION COLLISIONS 1
2. SURVEY OF PRESENT DETECTORS USED IN RELATIVISTIC HEAVY-ION EXPERIMENTS 4
2.1 PARTICLE IDENTIFICATION 4
2.1.1 Lepton Identification 5
2.1.1.1 Electron Identification 5
2.1.1.2 Muon Identification 5
2.1.1.3 Neutrino Identification 6
2.1.2 Photon Identification 6
2.1.3 Pion/Kaon/Proton Separation 7
2.1.3.1 Time-of-Flight Measurements 7
2.1.3.2 Cerenkov Counters 7
2.1.3.3 Ionization Measurements 8
2.1.4 Hyperon Identification 9
2.2 CHARGED-PARTICLE TRACKING 9
2.3 EVENT CLASSIFICATION AND GLOBAL EVENT PARAMETERS . . 10
2.3.1 Energy at "Zero Degrees" 10
2.3.2 Calorimetric Energy Measurement 11
2.3.3 Multiplicity Measurement 12
2.4 ELECTRONICS ISSUES 14
3. NEW PROJECTS UNDERWAY OR NEEDED IN INSTRUMENTATION FOR RESEARCH WITH ULTRARELATIVISTIC HEAVY IONS 16
3.1 PARTICLE IDENTIFICATION 16
3.1.1 Lepton Identification 16
3.1.2 Photon Identification 17
3.1.3 Pion/Kaon/Proton Identification 17
3.1.3.1 Ionization Measurements 17
3.1.4 Hyperon Identification 17
3.2 TRACKING 18
3.3 EVENT CLASSIFICATION 19
3.3.1 Calorimetry 19
3.3.2 Multiplicity Counters 20
3.4 ELECTRONICS 21

ABSTRACT

We present in some detail an overview of the detectors currently used in relativistic heavy-ion research at the BNL AGS and the CERN SPS. Following that, a detailed list of R&D projects is given, including specific areas of work which need to be addressed in preparation for further experiments at the AGS and SPS and for the upcoming experiments at RHIC.

1. EXPERIMENTAL PROBES FOR NEW STATES OF MATTER FORMED IN ULTRARELATIVISTIC HEAVY-ION COLLISIONS

The present interest in heavy-ion collisions at ultrarelativistc energies stems from the idea that a state of matter may be created in the laboratory in which the quarks and gluons making up the familiar nucleons of nuclear physics become deconfined from their parent nucleons and free to travel over a large volume. It is thought that such a state of matter existed in the period roughly one microsecond after the *Big Bang*. This "quark-gluon plasma" then ceased to exist as the universe cooled and the quarks and gluons were "frozen" into the protons and neutrons that we know. Because the conditions for creating such a state of matter in the laboratory appear to require that large amounts of energy be deposited over an extended volume, it has been proposed to build a dedicated colliding-beams machine to be able to investigate this physics. The proposed Relativistic Heavy-Ion Collider (RHIC), to be built at BNL, would collide beams of up to mass = 200 nuclei at energies of up to 100 GeV/nucleon per beam (equivalent to a 20 TeV/nucleon fixed-target accelerator) in order to achieve the conditions thought to be needed to create a quark-gluon plasma.

The final state created in collisions of such high-energy nuclei is much more complex than that encountered in accelerator experiments to date. This is so principally because of the multiplicity of final state particles produced, which may reach 20,000 in gold-gold collisions at top energy at RHIC. It is thus crucial to find efficient means of sorting through these complex final states for evidence for creation of a quark-gluon plasma. It is also crucial to identify signals giving information about whether the quarks and gluons are truly deconfined and about the conditions of the state created.

The methods used to characterize these collisions may be divided into three broad categories:

a. penetrating probes, giving direct information from the plasma,

b. indicators of a phase transition,

c. global event parameters.

Penetrating probes include direct photons, lepton pairs, and high-p_T jets of particles. The number and p_T spectra of these reflect directly the conditions in a plasma and depend on the entropy density and initial temperature of a system and on the thermal history of the plasma. Information on structure function changes is contained in the real and virtual photon spectra. The properties of the "real sea" of quarks and gluons will be reflected in the hadronization of high-p_T jets.

Indicators of a phase transition include production of strange particles and antibaryons (indicates attainment of chemical equilibrium), local charge correlations and heavy vector-meson suppression (indicates a change in color screening relative to normal matter), and production of stable multiquark states (indicates ease of assembling multiquark final states.)

Global event parameters include correlations of multiple particles in space-time (which could signal the long-range correlations and macroscopic fluctuations characteristic of a first-order phase transition), measurements of inclusive particle spectra and particle distributions in phase space (which give information on the final state of the event and any large-scale phenomena), and measurements of energy flow in the final state (which gives information on the centrality of the event and the total transverse energy production, which may characterize the energy density attained.)

A short list of detector techniques useful in performing experiments concentrating on these methods follows.

General Category	Specific Probe	Detector Capability
Penetrating Probes	Lepton pairs	Electron identification over large solid angle
	" "	Muon identification over large solid angle
	Direct photons	Single photon identification over large solid angle
	High p_T jets	Particle ID and tracking in jet cores, plus large solid-angle calorimetry to tag jets
Phase Transition Indicators	Strange particles and antibaryons	$\pi/K/P$ separation "Vee" identification Tracking in magnetic field, especially near the target
	Charge correlations	Tracking in magnetic fields over large areas
	Vector meson spectra	Electron and/or muon identification
	Multiquark states	Full particle ID and momentum measurement, possibly over small solid angle
Global Event Parameters	Space-time correlations	Precise momentum measurement and particle ID over several regions of limited solid angle
	Spectra of particles	Tracking in magnetic fields and/or neutral particle identification (e.g., by calorimetry)
	Multiplicity of particles, in θ and ϕ	Tracking with or without magnetic field, with excellent angular resolution
	Transverse, forward, and total energy	Electromagnetic and hadronic calorimetry over large solid angle

There is a need, in designing instruments to carry out the above measurements, to have high levels of segmentation and "pixel-oriented" readout schemes. The need for development of such techniques becomes obvious when the present vs future particle multiplicities are considered, as shown below.

Facility	Date	Beam and Energies Employed	Multiplicity of Particles in Final State
BNL AGS	present	^{16}O, ^{28}Si, 15 GeV/A	50-200
CERN SPS	present	^{16}O, ^{32}S, 60 and 200 GeV/A	150-950
BNL AGS	1992	^{197}Au, 12 GeV/A	up to 1000
CERN SPS	1993	^{208}Pb, 160 GeV/A	up to 4000
RHIC	1995	$^{197}Au + {}^{197}Au$, 100 GeV/A each	up to 20,000

The needs of RHIC thus diverge from those of the SSC on three important points. The SSC will need to identify a few hundred particles per event but with a high probability of event overlaps, with emphasis on very energetic particles. RHIC will need to handle over ten thousand particles per event, at modest event rates, with a need to keep information from the many soft particles.

2. SURVEY OF PRESENT DETECTORS USED IN RELATIVISTIC HEAVY-ION EXPERIMENTS

We divide the following discussion into categories concerned with various types of measurement needs. Examples are drawn from the experiments in operation at the BNL AGS and the CERN SPS as of 1988.

All experiments include some global measurements such as zero-degree calorimetry, transverse energy, and/or multiplicity to characterize the events. Each experiment then typically concentrates on one or two methods of characterizing the final state in some specific way. The methods discussed in Section 1 usually involve some level of particle identification in order to be sufficiently selective. The several experiments include, in addition, differing levels of tracking ability, depending on which method of probing the final state has been selected.

2.1 PARTICLE IDENTIFICATION

All the heavy-ion experiments presently running at the AGS and SPS have particle identification incorporated for a limited selection of particle types. This identification is typically done over a restricted range of solid angle, as the devices required are often more complex and thus more expensive per unit solid angle than the "global" devices such as mid-rapidity calorimeters or multiplicity counters used to measure global characteristics of heavy-ion collisions.

An abbreviated list of the particles identified by the various groups is as follows:

— NA34:

Electrons at backward rapidity using ring-imaging Cerenkov counters (RICH counters - under development).

Muons at mid-rapidity using absorber + dipole spectrometer.

Hadrons using a slit-spectrometer at backward rapidity.

Photons using a conversion method in the slit-spectrometer and a movable BGO array for low p_T photons.

— NA35:

Hyperons at mid- and backward rapidity using kinematic identification in a streamer chamber.

— NA36:

Hyperons at mid- and backward rapidity using kinematic identification in a TPC.

— NA38:

Muons at mid-rapidity using an absorber + toroidal spectrometer.

— WA80:

Photons and neutral mesons near mid-rapidity using highly segmented lead glass.

Light baryons and pions at target rapidity using phoswich detectors.

— WA85:

Hyperons at mid-rapidity using a dipole spectrometer.

— E802:

Charged hadrons at all rapidities using a single-arm spectrometer with good time-of-flight capability.

Photons at mid-rapidity using lead-glass.

— E810:

Hyperons at mid- and backward rapidity using kinematic identification in a TPC.

— E814:

Charged and neutral hadrons, particularly projectile fragments as well as $\pi/K/p$, at forward rapidities

A short discussion of the techniques presently employed is given in the following sections.

2.1.1 Lepton Identification

2.1.1.1 Electron Identification

The NA34 group at CERN has investigated the problems involved in electron detection in relativistic heavy-ion collisions over the past several years. The principal problems to be surmounted are production of secondary electrons, either by Bethe-Heitler conversion of any of the numerous photons present or by Dalitz decays of neutral pions. They have developed and tested a spectrometer for soft electrons whose principal elements are two RICH counters which measure the direction of electrons before and after traversing a magnetic field. The RICH counters" thresholds are set high enough that the counter is "blind" to the much greater flux of hadrons. In order to image the Cerenkov rings without an excessive number of noise hits, this group has developed an optical readout scheme that looks at the visible light when secondary electrons cause an avalanche near an anode wire. These secondary electrons are created when the original UV Cerenkov photons are absorbed in a UV-sensitive gas such as TMAE. This entire technique demonstrates excellent hadron rejection in mixed test beams. The rings can be located to an accuracy of on the order of 1 mm, which means that the electron directions can be measured with a precision of 1 mrad for an optical system of 1 meter focal length. First experiments using this apparatus in runs with heavy beams are expected to occur in 1990.

The NA34 group has also developed a transition radiation detector (TRD) for detecting high-energy electrons at forward rapidities. This device was developed for use with their proton-beam program. It has been operated successfully at thresholds as low as 3 GeV/c. The development of a TRD which could operate at thresholds as low as 500 MeV/c is being pursued by the E802 group. This threshold would make observations of electron-positron pairs possible even below the rho meson mass at mid-rapidity at RHIC.

2.1.1.2 Muon Identification

The only experiments presently engaged in muon detection are NA38 and NA34 at the SPS. Both are using muon spectrometers built by earlier collaborations, the NA10 group for NA38 and the NA3 group for NA34. Both spectrometers are conventional in that they consist of a thick hadron absorber between the target and spectrometer, a set of tracking chambers and trigger scintillators, an analysis magnet (toroid for NA38, dipole for NA34), another set of chambers and trigger scintillators, a final absorber wall (e.g., of 50 cm of iron), and a final set of trigger scintillators. The NA34 group uses a second target located just ahead of their zero-degree calorimeter to provide a source of muons, while the NA38 experiment is dedicated to muon detection. The acceptance of the NA34 experiment is broader because it uses a dipole and thus does not lose pairs when one member goes down the toroid axis, as happens in the NA38 setup. The absorber in the NA38 experiment is carbon to minimize multiple scattering of the muons, while muons in NA34 must penetrate uranium-based calorimeters. Since both experiments concentrate on forward angles, NA38 has the better invariant-mass resolution as it has less multiple scattering. In both cases the muon identification is done solely on the basis of the ability of muons to penetrate large thicknesses of matter without showering or reacting. Charged particles that pass cuts on multiple scattering, vertex, and momentum are identified as muons.

Because the principal interest in detecting muons is to look for opposite-sign pairs of muons which result from virtual photon exchange or vector meson decay, background can be rejected by constructing invariant mass spectra for like-sign pairs and subtracting these appropriately from the corresponding spectra for unlike-sign pairs. NA38 has demonstrated that for 200-GeV/c/nucleon ^{16}O incident on ^{238}U, a very clean invariant-mass spectrum is obtained for unlike sign pairs above an invariant mass of about 2.0 GeV/c^2. The invariant mass spectrum has a signal to noise of only 1:1 when pairs as light as the rho mass are selected. For heavier projectiles, the signal/noise is expected to worsen linearly with the increase in projectile mass, A, because the signal only increases as A but the combinatorical background increases as A^2. NA38 has made a study of the decay background sources and will shorten their target-to-absorber distance for future experiments. They will also employ a copper/scintillating-fiber EM calorimeter instead of the lead/scintillating-fiber EM calorimeter they use presently (see Section 2.3.2) in order to have a shorter interaction length for hadrons entering the absorber. These measures should reduce the number of decay muons present in the spectrometer.

2.1.1.3 Neutrino Identification

To date, no attempts have been made to identify neutrinos in relativistic heavy-ion-induced reactions. This partly reflects the difficulty of detecting neutrinos and partly reflects the lack of theoretical motivation for searching for them. The most likely technique seems to be detection by transverse energy imbalance, as employed for example in UA1 and UA2 to search for W mesons. To date, only the NA34 group has constructed a calorimeter that is hermetic and has sufficient granularity to attempt this task. They do employ a missing energy trigger. However, they have only used this for proton running, as it is difficult to correct the missing energy for muons in the heavy-ion case.

This may be a feasible thing to try at central rapidities at RHIC, although the problem of detecting a few GeV to a few tens of GeV of missing transverse energy in events that can generate up to 5 TeV of transverse energy for "ordinary" central collisions seems technically daunting.

2.1.2 Photon Identification

Four groups presently attempt photon detection in ultrarelativistic heavy-ion experiments. The NA34 group uses a conversion spectrometer in the gap of their slit spectrometer, the WA80 and E802 groups use large-area arrays of lead glass as electromagnetic calorimeters, and the E814 group uses an array of NaI(Tl) crystals.

The segmented EM calorimeter technique is inherently more efficient as it does not pay the detection efficiency penalty that the NA34 device suffers due to a conversion probability much less than one. The conversion technique has the advantage that it can localize the showers in space using proportional chambers. In order to obtain shower localization using their technique, WA80 and E802 must segment the glass into a large number of towers, each of which must have a not-inexpensive readout including a good-quality phototube to see the modest amounts of Cerenkov light generated in the lead-glass. A tower size of 15 cm x 15 cm is used by E802 while a tower size of 3.5 cm x 3.5 cm is used by WA80. E814 uses vacuum photodiodes to readout their NaI(Tl) crystals individually. All setups use proportional chambers in front of the photon detectors in order to tag and reject charged particles. Neutral hadrons are rejected by an analysis of the transverse shower size in WA80; the NA34 technique has a very low probability of triggering on neutral hadrons.

The fine segmentation and large distance from the target of the WA80 calorimeter also allow it to be used to reconstruct π^0's and η's by calculating the invariant mass of photon pairs falling within its acceptance. A mass resolution of about 6% is achieved for the π^0. By obtaining good measurements of the invariant cross sections for π^0's and η's, it is possible to subtract, in a statistical manner, the contribution of decay photons from the measured inclusive photon spectrum and thus obtain a measurement of the photon spectrum emitted directly from the reaction. Such measurements are greatly aided by having large solid-angle coverage for the original photon measurement in order to obtain the most reliable measurement of the neutral meson decays. None of the present setups covers 2π in azimuth or more than one unit in pseudorapidity. Future setups would benefit from such coverage.

Detection of neutral mesons is complicated at forward rapidities and large values of the transverse momentum, p_T, of the parent meson, as in both cases the decay photons have a small angular separation. Because the electromagnetic showers produced in a detector have a finite transverse size, a given detector can only separate photons some minimum distance apart. This value is 5 cm for the WA80 lead glass. For the present WA80 setup this corresponds to a maximum p_T of about 4 GeV/c for π^0's at rapidity = 2 before the two photons start to become indistinguishable. Detectors with shorter radiation lengths than lead glass and better two-shower separation than lead glass are needed before single photon detection in reactions involving mass $\sim$ 200 projectiles appears feasible.

2.1.3 Pion/Kaon/Proton Separation

2.1.3.1 Time-of-Flight Measurements

The present state-of-the-art in time-of-flight walls is exemplified by the E802 wall used in their single-arm spectrometer. A somewhat similar wall of more modest performance is employed by the NA34 group in conjunction with their External Spectrometer. The E802 TOF-wall consists of a large number of long narrow slats viewed from each end by fast phototubes. With attention to noise and electronics performance, this group has been able to achieve rms time resolutions of 75 ps for all the narrow slats in the wall. A somewhat larger value, 100 ps, is obtained for the double-width slats. In conjunction with their magnetic spectrometer they are able to achieve K/π separation up to 2 GeV/c over a rather short path length without using their Cerenkov counter information. This performance would be ideal for a central region spectrometer at RHIC.

2.1.3.2 Cerenkov Counters

The E802 group employs a large complex of segmented Cerenkov counters in their experiment. These include low- and high-pressure gas Cerenkov counters and aerogel Cerenkov counters as part of their spectrometer. The indices of refraction have been selected to enable the spectrometer to separate pions, kaons and protons up to momenta of 5 GeV/c when operated in conjunction with the time-of-flight wall. These Cerenkov's handle multiple particles by the classic technique of segmentation into many cells with independent mirrors and phototubes for readout.

At present none of the other heavy-ion groups have attempted the construction of a Cerenkov complex for particle ID, with the exception of a set of aerogel counters in the slit-spectrometer of NA34 and of the RICH counter under development by the NA34 group for the specialized job of electron identification only. There is as yet no development of devices such as the large RICH counters used in the CERN Omega spectrometer or to be used in the DELPHI collider experiment at LEP and the SLD experiment at the SLC. Discussions, modelling, and initial development work have occurred for proximity-focussed Cerenkov counters for use with the planned lead beams at the SPS. The principal barrier to using Cerenkov counters in collisions involving two very heavy nuclei is the problem of handling the large particle multiplicities. At present the only ideas under consideration are RICH and proximity-focussed Cerenkov counters. Both these ideas need work mainly in the area of readout methods and speed.

The development of CCD readout by the NA34 group for their RICH counters (see Section 2.1.1.1 above on electron identification) is promising in terms of the number of readout pixels which may be obtained. However, this particular technique needs a large increase in speed before it is useful in experiments other than those with quite selective triggers.

2.1.3.3 Ionization Measurements

This category is understood to include measurements of the specific energy loss due to atomic ionization in gaseous, liquid, or solid media. The most common use of the technique is in ΔE measurements either in the front section of a phoswich-type detector or in a gas-sampling volume such as a TPC.

The WA80 group uses the Plastic Ball Detector, constructed earlier by the group of the same name. This detector has 655 phoswich elements consisting of 4-mm-thick CaF_2 ΔE sections followed by 35-cm-deep plastic scintillator E elements. The elements are only thick enough to stop protons of 200-MeV kinetic energy or below, making the Plastic Ball useful only for studying the target fragmentation region in fixed-target experiments at the AGS or SPS. The resolution of the device is sufficient to resolve individual isotopes of light nuclei once they are energetic enough to penetrate the ΔE section. Heavier elements up to about Z = 10 can be resolved by appropriate choice of gains in the electronics. Positive pions are separated from protons by observing the delayed signal from their decay muons.

At present the groups (NA36, E810) developing TPCs which can handle the large final-state multiplicity of heavy-ion reactions have not incorporated the capability to make energy-loss measurements into their devices. The standard in this area still remains the PEP-4 TPC at the PEP electron-positron ring at SLAC. Several of the LEP experiments will also measure multiple samplings of ionization loss in their central tracking chambers; DELPHI and ALEPH are building TPCs, while OPAL is building a more conventional cylindrical drift chamber. The technique of measuring multiple ionization samples in a gas is also used by the MUSIC detectors at the Bevalac to identify heavy ions in the forward direction. Projectiles and projectile fragments in the range of Z = 26 have been detected with much better than unit charge resolution. Such a technique might find application in the very forward regions at RHIC.

The discrimination of electrons, pions, kaons, and protons using the multiple-ionization-sampling technique does suffer from ambiguities in the numerous regions where the various specific ionization curves for the above particles cross each other as a function of momentum. This is particularly severe in the region near minimum ionization for kaons and protons, i.e., for momenta of 0.8 to 4 GeV/c. For the central rapidity region at RHIC, most of the particles are expected to fall below this range; and for rapidities forward of mid-rapidity at the SPS, most particles are in the relativistic rise region, so that measurements of magnetic rigidity and specific ionization will be sufficient to identify these particles. For rapidities in the range of about 1 to 3, however, the confusion becomes maximal and additional information, as provided by TOF or RICH counters, will be needed to identify particles.

2.1.4 Hyperon Identification

Three groups presently identify hyperons produced in ultrarelativistic heavy-ion collisions at the AGS and SPS. The NA35 group uses their streamer chamber to identify neutral vees and measure momenta while the NA36 and E810 groups use TPCs to perform the same function. All three groups have reported the identification of the decay $\Lambda^0 \rightarrow p + \pi^-$. The NA35 group has also reconstructed cascades. The vees are straightforward to see at rapidities that are not too forward; the pion and proton are identified by the usual kinematic hypotheses as were used in bubble chamber work. All three groups use a target placed upstream of a large spectrometer magnet. NA35 covers 2π in azimuth for polar angles forward of 35 degrees, while NA36 chooses to place their TPC to one side of the beam axis. The NA36 group expects to be able to take advantage of the much lower density of tracks and to see decays of the more massive hyperons such as the Cascade and Omega.

All these techniques for spotting hyperon decays in heavy-ion collisions depend on finding the decay vertex. This greatly decreases the combinatorial problem which would be encountered if, for example, one attempted to identify Λ^0's solely by forming the invariant mass of all pairs of negative pions and protons. It also has the obvious advantage of immediately determining the three-momentum of the parent for the decay at hand. In the case of just looking at combinatorial pairs, the momentum distribution of the parent can only be determined in a statistical manner. This method will become more difficult in the central rapidity region at RHIC, however, simply because the parent hyperons will receive a smaller boost, meaning that the opening angle of their decay products will be much larger than it is at the AGS or SPS and that their decay vertex will be much closer to the interaction point. This can be countered by having additional information than that from tracking alone to help in the search. Particle identification for the final state particles will help narrow the range of candidate tracks considerably when a specific decay is being searched for.

2.2 CHARGED-PARTICLE TRACKING

There are at present three main lines of development in this area. The use of "imaging chambers," such as streamer chambers and TPCs, is mentioned below in Section 2.3.3 on multiplicity. The E802 group has chosen to use multiple planes of projective readout drift chambers for the tracking through their single-arm spectrometer, while the E814 group has chosen to use proportional chambers with small pads coupled together to form resistive readout chains in their forward-angle spectrometer. The E814 design thus yields also the orthogonal coordinate to the one obtained by conventional drift techniques.

The solution chosen by E802 has the advantage the existence of a considerable body of expertise and lore on the design, construction, and operation of such projective chambers. Spatial resolutions on the order of 100 microns may be obtained with careful construction and data analysis. It has the strong disadvantage that the pattern recognition and hit-to-track association problems become severe, if not insurmountable, in truly high multiplicity environments (say, 100 particles or more hitting the chamber). This restricts their use to moderate acceptance spectrometers or to areas in a detector where the overall particle count is small, such as in a muon spectrometer behind a thick absorber.

The "pad-chambers" developed by E814 offer the advantage of pixel-type readout so that space points are obtained along each particle's trajectory. A spatial resolution of about 200 microns is obtained along each wire; in the other direction, the resolution is determined by the wire spacing (in the other direction). This helps in pattern recognition simply by decreasing the number of possible other hits that a given hit may be associated with. One is still left with the problem of obtaining enough space points on each track to render complete pattern recognition possible. The pad chambers make this possible in principle (if not yet in practice due to electronics costs) in that a large number of planes may be set up to cover a given solid angle. If this is done with a small distance between planes compared to the range of possible displacements of a particle in traversing this distance between adjacent planes, then nearby hits can be easily grouped into candidate track segments. A clear area for R&D is obviously development of dedicated monolithic electronics for these chambers in order to make truly large-area coverage feasible.

The TPC and streamer chamber solutions represent the obvious evolution of the above method to nearly continuous sampling of tracks. Their principal disadvantage lies in their rate capabilities, as discussed in Section 2.3.3. The pad chambers used by E814 can be built with short gas drift distances, enabling them to be used in a high rate environment.

A device which holds promise for development is the silicon drift chamber. This can provide pixel type readout with extremely high resolution, on the order of 5-10 microns. Present devices are quite modest in size, meaning they need to be operated near a target in order to cover significant solid angle. The use of such devices for accurate vertex detectors at RHIC merits particular investigation, as it appears they can provide the needed rate capability and multiple-hit capability needed in that environment. The devices to be developed for RHIC do not need to have the extreme radiation hardness that SSC devices will need. Thus, development for RHIC can concentrate on increasing the pixel count.

2.3 EVENT CLASSIFICATION AND GLOBAL EVENT PARAMETERS

2.3.1 Energy at "Zero Degrees"

It is thought that the most likely place to search for creation of a quark-gluon plasma is in central collisions of very heavy ions. This requires having some method for selecting central collisions on an event-by-event basis. All members of the present generation of experiments have reported that placing cuts on large missing energy in the beam direction or on large values of transverse energy or on large values of the charged particle multiplicity at mid-rapidity tends to select always the same class of central events. The correlation is strong among these variables, although not completely sharp. Given the large difference in solid angle that must be covered by the first method compared to the last two, the easiest method to implement in a fixed target experiment is the first one.

Accordingly, the NA35, WA80, E802, and E814 groups all employ "beam" or "zero-degree" calorimeters for measuring the energy at zero degrees to the beam axis in heavy-ion experiments. This energy is usually carried by the nonreacting portion of the projectile; observation at zero degrees of no more than a few percent of the incident beam energy indicates at particularly violent collision has occurred. All the calorimeters employed are of the sandwich type, with depleted uranium used by WA80 and steel used by E802 and NA35 for the absorber. The E814 zero-degree calorimeter will be a modified version of their uranium/scintillator calorimeters with a larger tower size. Scintillator coupled to fast waveshifters and phototubes completes the readout chain. The WA80 device, for example, has demonstrated its ability to operate at rates in excess of 10^6/second while maintaining linearity to 1% and resolution as good as $\sigma/E = 2\%$.

The zero-degree calorimeter solution cannot be used in all experiments planned for the future, however. Experiments designed to look for relatively rare signals in fixed target geometry want to use large beam currents, often approaching 10^9 particles/second. No known calorimeter can operate at such rates without experiencing such severe problems due to pileup of different events as to render the information from the calorimeter devoid of meaning. Those experiments will need to adopt one and/or the other of the latter two methods above to provide for event classification. Such an approach is already followed by the NA38 group, who operate at beam currents up to 2×10^7/second and who have eschewed the use of a zero-degree calorimeter in favor of a mid-rapidity calorimeter designed to measure predominantly the transverse energy carried by photons resulting from π^0 decay.

In the geometry imposed by a collider, such as RHIC, use of a zero-degree calorimeter is *a priori* ruled out by the requirement that the path for the circulating beams be kept clear. It may be possible to take advantage of the existence of beam-merging and separating magnets in the machine lattice to install devices similar in purpose to a zero-degree calorimeter. This idea takes advantage of the fact that fragments of the projectile will travel with the same momentum per nucleon but will typically have a different charge-to-mass ratio, meaning they will not follow the orbit defined by the machine dipoles, but will exit the beam pipe at some point. Given the very large differences in charge-to-mass ratios among neutrons, protons, and most heavy ions, it does appear feasible to place calorimeters on both sides of the merging magnets that will intercept all single nucleons resulting from disruption of a beam nucleus. This still leaves unanswered how to select events that are strictly peripheral — does lack of activity in these near-zero-degree calorimeters signal a violent or a grazing collision? It would seem that information from such devices must, therefore, be supplemented with that from other sources.

2.3.2 Calorimetric Energy Measurement

The use of calorimeters in heavy-ion experiments is at present somewhat different from their use in particle physics experiments. In the latter, the particle densities in phase space are sufficiently low that calorimeters can be used to measure the energies of individual particles and isolate the energy flow in single jets. In heavy-ion experiments, the particle densities are sufficiently high that a single section, or "tower," of a calorimeter is often struck by more than one particle. The measured quantity is then the summed energy of all the particles emitted within a given solid angle. This is still of considerable utility, however, because a good measure of the transverse energy generated in a reaction or of the energy depletion in the beam direction in the same reaction can be obtained.

The calorimeters used by the NA35 and WA80 groups at CERN are designed to cover mid-rapidities with moderate segmentation for reactions induced by 60- and 200-GeV/c/nucleon projectiles. The calorimeters for both experiments are segmented longitudinally into electromagnetic sections, made of lead-scintillator sandwiches, and hadronic sections, made of steel-scintillator cells. The transverse segmentation in obtained by dividing the cells into square towers in WA80 and into r-theta segments in NA35. Light is coupled out to phototubes in both cases using waveshifters. WA80 uses plate-type shifters placed on opposite sides of a tower, while NA35 uses waveshifter-doped rods inserted into the centers of the towers. Both calorimeters are designed to give moderate resolution, on the order of $\sigma/\sqrt{(E)} = 15\%$ for electromagnetic showers and 50 to 60% for hadronic showers. The resolutions are better than average for hadronic showers and routine for electromagnetic showers.

The use of sandwich-type calorimeter for rapidities in the range of 0 to 1.7, as NA34 uses them, results in some difficulties. The energies of hadrons in this rapidity interval are not large, typically falling below 1 GeV for pions, which is the range where the operation of present-day hadron calorimeters starts to be problematic, both from a standpoint of energy resolution and from a standpoint of linearity and response. This will be an important area for study in designing calorimeters for use in the central-rapidity region at RHIC, where over 1000 such soft pions will appear.

A specialized version of the NA34 calorimeters is used by the E814 group at BNL to detect products of projectile fragmentation at very forward angles. This group needed good angular resolution and the ability to separate particles, particularly neutrons, that are close together in phase space. They have, therefore, further segmented the readout of the original 20 x 20 cm^2 towers of the NA34 uranium-copper-scintillator by a clever technique of milling grooves into the scintillator and filling them afterwards with optically reflecting epoxy. This effectively establishes 10 x 20 cm^2 cells, adequate for analyzing the products of fragmentation when the calorimeters are placed 40 meters from the target. These calorimeters are operated in conjunction with upstream spectrometer magnets, high resolution scintillation counters, and tracking chambers, resulting in precise identification of forward angle products by mass, charge, and momentum.

The NA34 group uses a highly segmented calorimeter for their coverage of forward rapidities, where the number of particles per unit solid angle becomes very large. They employ a cryogenic-liquid type calorimeter, with depleted-uranium absorber plates and liquid argon ionization cells for the active medium. The EM section of this calorimeter has a 2 x 2 cm^2 segmentation. The hadronic part is read out using 5-cm-wide strips with horizontal and vertical strips interleaved. This arrangement samples the developing hadronic showers on a fine scale. Although the hadronic showers still overlap in this device, a good measurement of the energy flow with angle is obtained, particularly at forward angles where the secondary particle flux becomes quite concentrated in a small solid angle.

A different approach to the entire problem of measuring energy flow at mid-rapidities was adopted by the NA38 group at CERN. This group needed to design a calorimeter to operate upstream of the absorber for their muon spectrometer. They operate at beam currents typically 10 to 50 times those used by NA34, NA35, and WA80 and use targets typically 10 times thicker. They also can afford to allow only a little space for any devices before the absorber so as not to have large backgrounds of decay muons in their spectrometer. These considerations led them to use electromagnetic calorimetry only. Speed requirements ruled out the use of ionization-type readouts, such as liquid argon. To avoid "cracks" due to readout sections, they chose to use a novel construction in which thin layers of lead are alternated with rows of optical fibers that have been doped with scintillating agent. This construction can be read out from the back using light guides and phototubes and is compact and fast. Its resolution is similar to that exhibited by the EM calorimeters of the three other groups above. The intense radiation levels experienced by NA38 led to the need to replace the inner section of this device once a week during heavy-ion running. Investigation of this problem pointed to the need to use more radiation-resistant epoxies to bond the fibers to the lead.

This "fiber calorimeter," in principle, can be read out with quite fine transverse segmentation, as its intrinsic radiation length can be made to approach that of lead itself (5.6 mm) by using very thin fibers. The present limits to such a transverse segmentation are presently imposed by costs and sizes of available optical sensors and associated electronics. Development of inexpensive optical readout schemes would help realize the full potential of this type of calorimeter.

2.3.3 Multiplicity Measurement

Two basic approaches have been used to date to obtain measurements of the charged-particle multiplicity as a function of pseudorapidity and azimuthal angle in ultrarelativistic heavy-ion reactions. The first involves counting the track segments in a "visual" tracking chamber, such as a streamer chamber or a TPC, and the second involves counting hits on a planar detector with some type of pixel-oriented readout.

Two groups have pursued the development of TPCs for use in heavy-ion work, the NA36 group at CERN and the E810 group at BNL. Both groups use highly segmented readout planes with a large number of short wires to minimize the double-hit probability. Both chambers are operated in magnetic fields to provide momentum analysis. They must handle upwards of fifty tracks over a small volume. Operation with mass ~30 beams on mass ~200 targets has been demonstrated, as has track reconstruction in the resulting dense environment of hits. These groups plan future upgrades involving the addition of more TPC modules to improve their solid angle coverage. By keeping the individual TPCs of a modest size, they will retain the present level of capability in handling dense distributions of tracks. The rate capability of these TPCs is dictated by their drift distances and the gas drift velocities (~5 cm/microsecond). This makes it difficult to handle more than 10^3-10^4 events per second without having pileup of tracks from different events become a severe problem. The long electronics readout times needed to handle the large volume of data generated in a high multiplicity event further constrain the accepted event rate to a much smaller number, of the order of 1 to 10 events/second recorded to tape.

The NA35 group employs a large volume streamer chamber in a 1.5-Tesla magnetic field. The streamer chamber is loaded with a He-Ne mixture and operated at a deliberately low voltage to minimize flaring and size of the streamers. The main readout is onto three 70-mm film cameras which are coupled to large image intensifiers. The image intensifiers provide sufficient optical gain to overcome the loss in streamer intensity caused by operation at reduced voltage. Tracks can be reconstructed in three dimensions by using the stereo information from the film cameras. This chamber has also been equipped with a novel readout system involving three 1000 x 1000 pixel CCDs which also view the chamber through an image intensifier system. This CCD system provides digitized pictures of the entire event in 0.5 second. On-line software can then scan cuts through the pictures to give fast calculations of charged-particle multiplicity. Fitting routines can analyze these results to extract momenta.

The principal difficulty encountered in dealing with the resulting images of the streamer chamber concerns the extremely dense forward-angle distribution of tracks. For 200-GeV/c/nucleon incident beams, roughly half of the produced particles lie inside a cone of half angle 5 degrees. A large number of overlapping tracks results, yielding a "zone of confusion" at the most forward angles. The use of such chambers becomes quite problematic for fixed-target experiments with mass ~200 projectiles; however, they could be operated easily in the central rapidity region at a heavy-ion collider. Streamer chambers are inherently slow devices (NA35 only triggers theirs once per second), meaning that a highly selective trigger would be needed for the collider environment.

The second general approach to multiplicity measurement is employed by the NA34, WA80, E802, and E814 groups. The two basic techniques employed are pads coupled to limited streamer tubes (used by WA80 and E802) and silicon wafers read out via several hundred contact pads on their surfaces (NA34 and E814).

The WA80 and E802 groups use pad arrays capacitatively coupled to arrays of limited streamer tubes of the Iarocci type. A single wire in the center of a 1 cm x 0.8 cm cross-section cell is held at 4 to 5 kV to provide charge amplification of the track segments left by through-going charged particles. Printed circuit boards with pads etched onto the sides facing the streamer tubes are used to couple the charge signal capacitatively to onboard electronics. Pad sizes as small as 1.5 cm x 2 cm and as large as 5 cm x 5 cm have been used. The WA80 group operates their tubes at 4.9 kV, which provides sufficient signal to avoid the need for a preamplifier on the readout boards. However, this also causes limitations in the number of reactions per second which can be tolerated ($\sim$ few $\times$ 10^4) due to excessive current drain from the HV supply, which causes voltage droop and loss of efficiency. The E802 group operates their tubes at a lower voltage than does WA80, meaning that a preamplifier is needed on the readout boards but that the resulting rate capability and efficiency stability are better.

This technique is well suited for placing large numbers of pixel elements into an experiment at moderate cost. The WA80 arrangement has 45,000 readout pads arranged in a double layer configuration, yielding over 20,000 pixels. Typical measured multiplicities range up to 600, showing the modest occupation probability per cell with such devices.

The NA34 and E814 groups use small silicon wafers a few cm^2 in area and placed within a few cm of the target. Through-going charged particles create particle-hole pairs which drift under the influence of the applied reverse-bias. Signals are collected on small pads on the surface of the detector; these pads are made by masking the detector before the gold electrode is evaporated on. Conventional preamplifier/amplifier chains are used to process the resulting signals. Because accurate pulse-height information is available via this technique for each "pixel," it is possible to determine if more than one particle has traversed a cell under the assumption that all particles are minimum ionizing; the NA34 group has, in fact, used this to advantage. This pulse-height capability makes it possible for them to tolerate the inevitable multiple hits in the cells. These detectors have many fewer cells than do the streamer tube arrays, typically having only ~500 pixels. Several layers are used: NA34 has 3 x 400 pixels and E814 has 2 x 512 pixels.

The present techniques will all experience problems in handling the sixfold increase in multiplicities which will occur when mass 200 beams become available at the AGS and SPS in a few years. Handling the large increase in final state multiplicities presents a formidable challenge. It seems obvious that R&D work on fast pixel detectors will need to be done in the near future. A clear area where R&D is needed is in dedicated integrated circuits capable of reading out ~100 pixels each from such detectors. Development of circuits is essential to be able to handle the large number of channels needed ($> 10^5$) at reasonable power and cost.

2.4 ELECTRONICS ISSUES

The present heavy-ion experiments at the AGS and SPS have followed a course similar to high-energy physics experiments at the same machines in regard to electronics for detector readout. For devices which can be handled by up to a few thousand channels of commercial power supplies, discriminators, TDCs and/or ADCs, such as the readout of calorimeters and phototubes used in TOF walls or Cerenkov counters, the course followed has been to purchase the commercial devices. In the case of specialized needs or where a fairly large number of channels must be handled, say of the order of 10^4 or more, most groups have constructed their own circuits, usually taking advantage of the present state-of-the-art in hybrid and monolithic electronics technology. For example, the multiplicity counters mentioned above are all readout by custom circuits: hybrid latches and shift registers for the streamer tube pads in WA80, the same plus preamplifiers for the streamer tube pads in E802, custom preamplifiers and shapers for the silicon wafers in NA34 and E814, and custom hybrids and monolithic circuits for the TPC readouts of NA36 and E810. Custom circuits for reading out the large number of signal pads in the E814 multiwire pad chambers are also under development and test.

The electronics needs anticipated for the future at the AGS and SPS and at RHIC tend to be grouped into two areas at present. These areas can be described by the questions:

1. How can inexpensive and low-noise circuits be developed so that it becomes possible to instrument 10^5 channels or more at a feasible cost?
2. What methods can be used to store and process these large amounts of data during the trigger-decision process?

An example of a need in the first area would be a circuit designed to read out a calorimeter segmented into 50 to 100 thousand cells. If the calorimeter were read out by photodiodes viewing scintillator or by pads sensing ionization in liquid argon, a useful circuit would need to incorporate a low-noise preamplifier, a shaping amplifier, a storage element, and possibly a local ADC. A similar circuit would be useful for large-area pad chambers which had several hundred thousand pads. A more ambitious request comes from those wishing to read out several hundred thousand pads on a TPC with full dE/dX information recorded in narrow time slices. In that case, the above circuit would also need to include a good quality flash ADC and associated timing circuitry to keep track of the necessary time coordinates for the pad to which it is connected.

The needs summarized by the second question deal with temporary storage of data, either in analog or digital form, during a trigger-decision period and the provision to the trigger circuitry of information from a specific detector system. The typical solution used at present to store analog information while awaiting a trigger decision is to use a delay cable on the order of 100 meters in length, which provides a 500-nsec delay time. Similar methods can be used to store hit information from pad arrays or multiwire proportional counters. The number of cables needed to adopt this solution for next-generation experiments is worrisomely large; the space, cost, and drive-power requirements for this technique render it most unattractive. Development of a low-power monolithic analog storage unit would be a very attractive alternative, provided the cost and power consumption per channel can be kept low. The circuits used presently to provide information to first- and second-level triggers are often fast analog sums, in the case of calorimeter inputs, or fast digital sums followed by some type of majority logic, in the case of multiplicity counters. Some type of provision to do this on a large scale is needed for next-generation experiments. The power consumption of circuits will, to large extent, be dictated by the speed needed to make trigger decisions. and this latter quantity is partly controlled by how much delay can be imposed on the several signals from the detector before a decision to keep or reject the event is made.

3. NEW PROJECTS UNDERWAY OR NEEDED IN INSTRUMENTATION FOR RESEARCH WITH ULTRARELATIVISTIC HEAVY IONS

A number of research and development needs involving detector techniques of use in ultrarelativistic heavy-ion experiments are discussed briefly below. A few of these areas are presently under investigation. New efforts need to be undertaken in most cases. The interested reader is referred to the workshops which have been held over the past 4 years on the subject: 1984, Berkeley; 1985, Brookhaven; 1987, Berkeley; 1988, Brookhaven.

The following lists emphasize projects of particular interest for RHIC. The large and parallel R&D effort for the SSC will, of course, yield many useful techniques which can be used at RHIC. The projects below tend to emphasize the extreme segmentation needed for RHIC, the soft particles which must be dealt with at RHIC, and development of slower or less radiation-hard technologies which could be used at RHIC but which are not likely candidates for the SSC environment.

3.1 PARTICLE IDENTIFICATION

Most of the techniques discussed presently are tailored to the specific problems encountered in identifying a given type of particle. Tradeoffs made in designing a RICH counter to be an accurate tagger for electrons would not be appropriate in designing a general-purpose device for use in hadron identification, for example. Some of the areas needing investigation are listed below, grouped by the type of particle to be identified.

3.1.1 Lepton Identification

<u>RICH counters (particularly for "hadron-blind" operation for electrons)</u>

UV sensitive gases — is TMAE the best/only choice? Conversion lengths?
Is EF (Ethyl-Ferrocene) a better gas?
Two-dimensional readouts — development of optical imaging vs pad chambers
Speed of readouts, particularly CCDs
Merits of spherical imaging vs proximity focussing for specific cases
Control of background "speckle"
Pattern recognition algorithms
General triggering techniques (e.g., separation of visible Cerenkov photons for self-triggering via phototubes)

<u>TRD counters for electrons</u>

Known to work for $\gamma > 1000$, need tests for γ=500-1000 range
Delta-ray problems from through-going charged particles
Design of radiator foils — thickness, number, material, processing
Readout chambers, arranging for sensitivity only to X-rays
Two-dimensional readout, with emphasis on possibilities for triggering

<u>Muon identification issues</u>

Optimum balance between hadronic shower punchthru and muon multiple scattering for muon absorbers
Instrumentation of return yoke for further muon/hadron rejection, check of momentum

Development of fast two-dimensional hodoscopes for road-finding
Trigger processor for non-bend plane association, imposition of P_{min} cuts in bend-plane

3.1.2 Photon Identification

High resolution EM calorimeters (see 3.3.1 below, also)

Development of "spaghetti" and "lasagna" type calorimeters, i.e., short radiation length/small Moliere radius devices for largest effective number of pixels/unit area
Fast, inexpensive readouts suitable for 10^5 channels
High spatial resolution devices for resolving high p_T neutral meson decays
High-energy resolution devices for resolving low p_T neutral meson decays
Coupling to BaF_2, CsI inexpensively
Suitability of BGO for collider beam-crossing times

3.1.3 Pion/Kaon/Proton Identification

Time-of-flight counters

Mechanical design, operation of "flashlight" vs "picket fence" geometries
Separation of Cerenkov from scintillation light
Multithreshold constant-fraction discriminators, multihit high-resolution TDCs
Development of monolithic circuit including CFD, delay, precise TDC, readout logic
(The next four areas are obvious areas for industrial collaboration)
- Large-area, multianode fast phototubes
- Large-area microchannel plates coupled to scintillating optical fiber matrix
- Fast scintillation materials
- Very thin phototube windows

RICH counters (also see above under 3.1.1 for electron ID)

Pattern recognition problem: density of ring hits at RHIC is similar to that in a jet at the SLC → smaller rings eases the problem, but require higher resolution on ring centroid and radius

3.1.3.1 Ionization Measurements

Most of the issues needing investigation are discussed below under the sections dealing with TPC design and Si drift-chamber design. The use of phoswich detectors for identification of target-rapidity hadrons in fixed-target experiments is a relatively mature technology. Most of the issues to be dealt with in designing a detector for this region have to do with segmentation, punch-through, and desired dynamic range and can be dealt with using present experience with such devices and Monte Carlo calculations.

3.1.4 Hyperon Identification

Hyperon identification first requires having sufficiently accurate tracking and decay product identification (pions, kaons, protons, photons) to find decay vertices and test decay hypotheses. There is a clear need for work on fast track finders if one desires to trigger on observation of vees or decay vertices. This work will be influenced by what is feasible at the second and third level trigger stage and will itself influence the needed trigger decision times. One likely possibility is to move likely events to an on-line microprocessor farm and do a considerable amount of computing before deciding to move an event to tape.

3.2 TRACKING

The issues in tracking presently divide into two broad groups. The first group deals with design of TPCs for operation in either a fixed target or collider environment, and the second deals with the development of drift and multiwire chambers yielding space-point information. There are a number of related issues dealing with magnet construction and calibration of chambers. The large issue of track reconstruction also needs development to handle the large track densities expected for ultrarelativistic heavy-ion collisions. A central issue for all detectors depending on gas drift will be event pileup: for a pileup probability of 10^{-4}, one pileup event appears per second even for the low luminosities for mass ~200 ions at RHIC.

It is doubtful that drift chambers will find wide applicability for the SSC due to the long readout times imposed by the gas drift velocity. RHIC will present low enough rates that the use of gas drift counters can be considered, but central issues of space-charge limitations and of handling high track densities over all space must be addressed.

TPC design and operation

Optimization of gas mixtures for speed, low diffusion, and dE/dX information
Optimization of pad sizes for two-track resolution, dE/dX resolution, and overall readout load
Design of monolithic electronics for on-chamber mounting and digitization
Space-charge limitations and gas gain, distortions of drift paths
Segmentation of drift distances: tradeoffs between overall drift time, and thus rate and confusion from overlapping events, and overall chamber and electronics cost

Multiwire chamber design and readout

Development of chambers with highly segmented pad readout over large areas, and study of position resolution vs pad size and shape
Uniformity of response and efficiency for pad chambers
Development of coupling of dense pad arrays to readout electronics
Development of low-noise, large dynamic range front-end and charge division electronics
Usefulness of projective readout, for example, for muon tracking

"Straw" chambers

Usefulness for heavy-ion collisions
Construction of pads on "straw" body
Readout of pads, electronics development

Si drift chambers

Demonstration of working model in beam
Electronics monolithic with detector, readout speeds
Attainable resolutions, two track separation, possibility of dE/dX information
Uniformity of response over whole area
Radiation damage — rads allowable

3.3 EVENT CLASSIFICATION

The three methods mentioned in Section 2.3 for event classification all depend on having adequate calorimetric coverage and/or multiplicity coverage. The related detector hardware questions are listed in Sections 3.3.1 and 3.3.2 below. It will remain for specific experiments to decide, based on simulation calculations, what degree of precision they wish to implement in their measurements to provide event classification. For example, a large tracking spectrometer might provide sufficient multiplicity information itself at mid-rapidity that only modest calorimetry at forward rapidities is deemed necessary in addition.

3.3.1 Calorimetry

The work needed in this area can be grouped into three general areas. The first is basic calorimeter construction; the second is readout; and the third is response under the conditions of particular applications. A number of topics have been suggested for investigation in these general areas. These include:

Calorimeters involving optical fibers either as active elements or as readout elements

Coupling to readout devices with high segmentation
Ratio of scintillator to absorber thicknesses and absolute thicknesses
New scintillation materials, such as PMP
Light output, attenuation length of fibers
Fiber orientation relative to particle incident direction
Energy and position resolution
Energy and position linearity

EM calorimeters using crystals

Properties of undoped CsI (speed, resolution) including lab and test beam work
Speed and cost issues for BGO to assess suitability for collider use
Response of scintillating glass to soft hadrons
Hadron response of BaF_2, work on availability and cost of BaF_2

Silicon readout

Is this technique too expensive for general use?
Are there areas where space and density needs merit its use?

General response issues for all techniques

e/h relative response, especially for low-energy hadrons
Shower profiles for electrons, photons, hadrons
Position resolution for electrons, photons, hadrons
Energy resolution for electrons, photons, hadrons
Linearity for electrons, photons, hadrons
Angle dependence for electrons, photons, hadrons

Readout techniques

Readout electronics for PIN photodiodes development of compact monolithic devices with low noise and low cost
Sensitivity of all solid state optical sensors to charged particles
Methods for reducing charge transfer time for ALL liquid ionization calorimeters
Dynamic range of readouts — soft hadrons to jets
Studies of rate dependence of the gain of photomultiplier tubes

Application-specific issues

Optimum balance between hadronic shower punchthru and muon multiple scattering for muon absorbers, particularly for the high charged-particle multiplicity per event at RHIC
Segmentation for event characterization in compact geometries
Construction of pole-tip calorimeters — should silicon or scintillating fiber be used?
Can time-of-flight and fast EM calorimetry be combined in one device?
How finely segmented can EM calorimeters be made (to do single photon detection)?

3.3.2 Multiplicity Counters

Most of the issues related to constructing multiplicity counters are part of the larger issue of building tracking detectors and are thus mentioned in that section. There are a few areas specific to just counting particles in a given solid angle. These are mentioned here.

Streamer tube arrays

Development of monolithic preamp + latch for pad readout
Gain and efficiency stability in high-rate conditions
Development of smaller gas cell sizes to decrease overall drift time
Recording of time of arrival and pulse-height information

Hodoscopes

Development of two-dimensional readout methods
Coupling via waveshifter-doped optical fibers to multianode phototubes or image intensifier + CCD readouts
Construction methods to realize small cell sizes over large areas
General development of two-dimensional optical imaging devices other than CCDs — sensitivity to few photons, approximately ns range response times

Si pad detectors

Multiplexing of analog signals to reduce number of cables and cable-drivers
Development of high-density low-power discriminators and logic to provide signals for triggering

CCD multiplicity counters

Development of parallel readout schemes to obtain readouts in 100 microseconds

3.4 ELECTRONICS

Many of the electronics devices needed for the various detector projects are listed above under the specific detector to which they would be coupled. There are some general areas which will need development work. Some of this work will form the basis of the specific developments needed for individual detectors. There is a pressing need for the development of workable low-noise "standard cells" for use in designing analog circuitry in monolithic form. A large number of cells exist in the libraries of chip manufacturers for the needs of digital design, but few exist for analog work. An effort to develop a good working set of standard analog cells would pay great dividends in the future ability to design application specific integrated circuits (ASICs) for use in reading out large-scale detector systems. A few examples are listed in the following.

Standard cells for monolithic design

Preamplifiers
Shaping amplifiers — integrators, unipolar and bipolar shapers, differentiators
Storage cells; e.g., capacitor arrays
Comparators, particularly with multiple references
Timing discriminators, constant-fraction discriminators
Time-to-voltage converters

Functional units

Analog pipelines
ADCs
TDCs
Waveform recorders

General needs

Radiation-hardened electronics
Investigation of various chip technologies other than CMOS — NMOS, SOS, Ga-As, BiMOS

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