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PARTICLE IDENTIFICATION IN ULTRARELATIVISTIC NUCLEAR COLLISIONS

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The role of particle identification (PID) in both fixed-target and colliding-beam studies of ultrarelativistic nuclear (URN) collisions is examined. The demands placed on the PID systems by peculiarities of URN collisions, such as large multiplicities and the need for simultaneous measurement of a number of observables, are discussed. A variety of PID techniques are reviewed, with emphasis on their applicability and efficiency in the environment of such collisions. Two examples of PID as incorporated into existing fixed-target nuclear-beam experiments are presented.

1. INTRODUCTION

What follows is an attempt at a general discussion — an overview as it were — of PID in URN physics experimentation. The design of a specific detector or experiment is not the aim of this paper. Space constraints also require that some topics remain untouched, such as the role of PID in the trigger system. Rather, the reader is offered one view of the overall demands URN collisions will place on detector systems and the utility of presently available PID techniques in such environments.

In order to diagnose the space-time evolution of the high energy density hadronic matter formed in URN collisions, one must study the changes in flavour composition, transverse-momentum distributions, and correlations of produced particles as a function of observables such as transverse-energy flow and available centre-of-mass (c.m.) energy on an event-by-event basis. The need for particle identification in such experiments is quite apparent if one accepts the above as an operational definition of the problem. One can loosely group the specific measurements that should be made (simultaneously, as we shall see) in the following way:

- The *STANDARD* measurements such as inclusive species identification and transverse-momentum distributions

- The *TOPICAL* measurements such as the production rate of strange antibaryons[1]. Such signals rest on theoretical assumptions (e.g. thermalization of energy) that have not yet been justified by experiment.
- The measurements that will make experimenters *RICH AND FAMOUS*, namely the observation of exotica (e.g. stable or quasi-stable quark matter[2], fractionally charged objects or, better yet, something totally unanticipated).
- The *DIFFICULT BUT NECESSARY* measurements such as low-mass lepton pairs, multi-(charged) particle correlations, direct photons and photon-photon correlations.

The nature of URN interactions and the physics that one hopes to extract together place demands on detector systems that are rather different from those that have led to the classical collider detectors of modern particle physics. It is instructive to discuss some of these peculiarities and investigate their manifold implications. But first, let us examine the particle composition of multiplicity as a function of distance from an URN collision in order to better appreciate the problem at hand.

2. COMPOSITION OF THE MULTIPLICITY

In Fig. 1 a schematic view is given of the relative composition of multiplicity at various distances from the vertex (or, if one prefers, as a function of time after the interaction). Immediately after the collision a zoo of charged and neutral

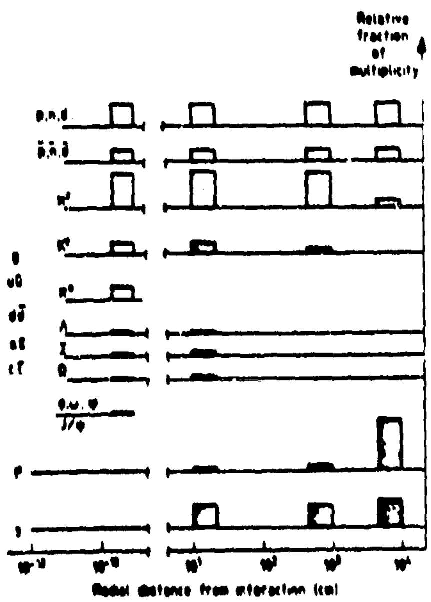

FIGURE 1
Schematic view of the composition of multiplicity in URN collisions as a function of distance from the interaction vertex.

particles emerges into the detectors. Shown in Fig. 1 are a variety of ejected particles that reflect interesting aspects of the space-time evolution of the interaction, e.g. real and virtual photons that retain an as yet unadulterated memory of the highest energy density phase of the collision and the hyperons that are believed to retain some memory of the strange quark–antiquark production in the early stages of the interaction. On the scale of a few centimetres from the interaction vertex one sees a photon signal that has long been swamped by π^0 decay photons. Lepton pairs from vector meson decay have already joined the direct lepton pairs. Hyperons are still detectable if tracked in the large pion, kaon, and hadron background. On the scale of a metre or so one sees that all signs of the hyperon content of the multiplicity are lost into the pion, kaon, and nucleon hordes, and that kaons are beginning to contribute to the pion and lepton multiplicities. On the scale of metres, all kaons and most pions have decayed away, creating an enormous lepton background in which the direct lepton signal is buried.

It appears, then, that any detector designed to infer backward from observed ejected particles to the high-energy density phase of the collision must have the requisite PID ability incorporated into the tracking and energy-flow measurement throughout the detector. It is this interweaving of PID, tracking, and calorimetry that we identify as one of the paramount considerations in the design of URN detectors.

There are more specific lessons to be drawn from this exercise.

i) Lepton-pair measurements require that the large pion flux be absorbed out as close to the vertex as possible. This is obviously inconsistent with tracking close to the vertex in the same rapidity intervals.

ii) The identification of short-lived particles (e.g. hyperons) will involve tracking in a very dense background of other particles.

iii) Measurement of direct photons will be if anything an even more difficult problem than usual in particle physics[3], given the combinatorial limitations on π^0 reconstruction in high-multiplicity environments and the photon backgrounds expected near calorimeter slits.

iv) The need to maintain sensitivity to new particles implies some charge and mass resolution close to the interaction vertex, placing strong constraints on tracking devices in this region.

v) Finally, we note that there will be additional modification of the relative mix of multiplicity and thus an increase in difficulty of measurement due to the detectors themselves, for example photon conversion electrons produced by tracking-chamber material that will further pollute the direct electron pair signal.

3. PECULIARITIES AND IMPLICATIONS

Let us elaborate a little on what distinguishes URN collisions from more classical elementary particle interactions.

HIGH MULTIPLICITY: Total multiplicities to 10^4, distributed rather uniformly in the c.m. frame, are anticipated in colliding-beam experiments with very heavy nuclei. Global tracking of such events presents a significant technical challenge, to say the least. Before undertaking such efforts, one must first present a plausible physics case for tracking all charged particles. One presumes that 'sampling' (i.e. in solid angle) tracking in conjunction with global energy-flow measurement will constitute the first step. However, the question of global versus sampling tracking will probably persist well into the second round of collider experiments.

Not only is the average multiplicity large in such collisions, but one also expects strong fluctuations. One will study, then, the tails of such distributions for indications of unusual behaviour (see below). Thus, detectors must be able to function in multiplicity environments many times the mean multiplicity.

High multiplicity means fine segmentation of detectors. The multiplicity per unit solid angle in the centre of mass expected in URN collisions is, it is interesting to note, similar to that expected in the dense centres of jets in very high energy proton-antiproton collisions. The difference, of course, is that in the former the density is rather uniform over the whole solid angle. The segmentation question in URN collisions is, then, not unrelated to that in conventional jet physics.

It is quite important to note that combinatorial constraints will quickly become a limiting factor in high-multiplicity environments. Low-mass electron pair measurements, for example, in the moderate multiplicity environment of fixed-target experiments at SPS energies are already known to be limited by combinatorial background from pion Dalitz decays[4]. This is not a background that can be overcome by more or better detectors, but a fundamental limitation on the physics that can be extracted from URN collisions.

LACK OF A CLEAR SIGNAL: It is generous to say that there are few signals that one can presently point to as unequivocally indicative of interesting new physics in URN collisions. As mentioned above, tails of the multiplicity (or transverse energy) distributions offer an interesting class of events to look at. However, one must examine a variety of observables simultaneously in order to infer the space-time evolution of the interaction and corroborate the unusual behaviour of any one observable. This is an important point and makes an experimentalist's life rather difficult. Not only is one facing measurements that are sometimes physically incompatible (e.g. the aforementioned muon/hyperon problem), but one must measure a wide variety of particles over a broad dynamic range at the same time in order to obtain information from all stages of the interaction. One aspect of the above that relies strongly on particle identification is the search for exotic particles or new quasi-stable to stable forms of hadronic matter produced in URN collisions.

The lack of clear signals implies also that one will perform scans in likely observables (such as transverse energy and total available c.m. energy) in order to search for thresholds. The latter is particularly relevant to the collider mode of operation.

BROAD RANGE OF KINEMATICAL CONDITIONS: It is often said that the study of URN collisions is facilitated by the fact that the transverse momenta expected are rather moderate (i.e. a few hundred MeV/c). In fact, this helps only some measurements and then only in a narrow kinematical regime: for example, in the central region in a collider, momentum measurement is made simpler by the low lab momentum of the particles. However, calorimetry becomes problematic in this same region owing to non-linearities in the response of calorimeters to particles in the range of 1 GeV/c and below. In addition, one is interested in not only the central region (the so-called baryon-free region) but also the fragmentation (or baryon-rich) region. Add to this the fact that a number of complex fixed-target experiments will be built before a collider begins to operate and it becomes clear that the dynamic range over which particle identification must operate in URN physics is enormous, ranging from slow nuclear fragments to multi-hundred GeV muons.

4. PID TECHNIQUES

Let us now turn to the available PID techniques and examine them with an eye towards their utility and efficiency in the URN collision environment. In this 'guide Michelin' we list the pluses and minuses of each technique, with sufficient references to allow the interested reader to pursue any given technique in more depth. Where we refer below to particles as identifiable, we implicitly include their antiparticles unless otherwise noted.

TIME OF FLIGHT USING SCINTILLATORS π/K/p [5]

- Low-momentum range (< 2 GeV/c). Limited potential for segmentation due to bulky readouts. Magnetic field shielding problem for photomultiplier (PM) tubes.

+ Mature technique.

TIME OF FLIGHT USING PLANAR SPARK COUNTERS π/K/p [6]

- New technology. Segmentation potential unclear.

+ Better momentum range (few GeV/c).

IONIZATION ENERGY LOSS π/K/p, high-Z particles[7]

- Measurements using both β^{-2} and relativistic rise are possible, but there are ambiguous regions in momentum that require use of other techniques in conjunction with dE/dx. Measurement of dE/dx in tracking chambers places demands on gas and pressure that can compromise tracking ability[8].

+ Good momentum range (tens of GeV/c) using the relativistic rise of energy loss in gases. Ability to contribute to identification of heavier particles is important. Energy resolution from 7% to 15%.

THRESHOLD CHERENKOV π/K/p [7,9]

- Very limited segmentation ability. Limited operating range for a given detector owing to fixed threshold/index of refraction. Becomes technically difficult if pressurized gases on cryogenic liquids are required, though advent of aerogel simplifies design. Photomultiplier tube problems here also.

+ Mature technology. Good momentum range (to 10 GeV/c) in conjunction with time of flight (TOF), dE/dx.

RING-IMAGING CHERENKOV DETECTOR e/h, π/K/p [10]

- Complex, new technology: photon detection involves multistep chambers with low-pressure photosensitive vapours to obtain the high gains necessary for ~ 10 photoelectrons per ring.

+ Excellent momentum range (1-35 GeV/c with two-radiator system). Excellent segmentation; overlapping rings can be resolved. Ring-imaging Cherenkov (RICH) detectors can be used as an element of a tracking system (i.e. centre of rings). Compact construction possible. Can be operated in threshold mode for e/h separation.

TRANSITION RADIATION DETECTOR e/h [11]

- New technology. Compact transition radiation detector (TRD) difficult owing to low photon yield per unit length of radiator. Number of readout channels becomes quite large in finely segmented device.

+ Excellent range ($2 < p_e < 100$ GeV/c) for electron identification. Segmentation limited only by that of proportional chambers; as such TRD fits well into tracking/calorimeter system as both a PID and a tracking element.

CALORIMETRIC PARTICLE IDENTIFICATION γ/e/h [12]

Full energy measurement (NaI, BGO, BaF_2, CsI, lead-glass) PID via comparison of measured energy and independently measured momentum. Energy resolution: $dE/E = (2\text{-}8)\%/\sqrt{E}$. Good segmentation possible, but costly. Photodiode readouts can reduce cost, eliminate PM tube problems.

Sampling calorimeter γ/e/h [13]

Sampling calorimeters with separate electromagnetic and hadronic parts exploit large differences between radiation length and interaction length for high-Z materials. Good segmentation possible, but only moderate energy resolution: Electromagnetic $dE/E = (14\text{–}25)\%/\sqrt{E}$, hadronic $(25\text{–}90)\%/\sqrt{E}$.

Calorimetric particle identification π/K/p

Use of lateral and longitudinal hadronic shower development and hadronic stopping characteristics in calorimeters is potentially a powerful PID technique. The utility depends on lateral and longitudinal segmentation, and detailed knowledge of the shower development and calorimeter response to all particles in the shower. Identification of antiprotons annihilating in a U/scintillator calorimeter has already been demonstrated by the Axial Field Spectrometer (AFS) Collaboration at the CERN Intersecting Storage Rings (ISR)[14]. The possibility of using finely segmented (both longitudinal and transverse directions) calorimeters[15] to identify low-energy hadrons by their ionization and stopping characteristics should be investigated.

KINEMATICAL TUNING IN COLLIDING BEAM-MODE

While not a PID technique *per se*, one can nonetheless contribute significantly to the PID problem in colliding-beam experiments by colliding beams of two different energies in order to compress or expand (in the lab) regions of interest in the c.m. frame. This is of particular interest in the fragmentation region where one might want to work at lower c.m. energies. For example, 100 GeV/A on 5 GeV/A (equivalent of a 22 GeV/A symmetric beam energy collision) puts Y_{cm} = 4.75 at 4° in the lab as opposed to 1° in the symmetric case.

ABSORPTION AND RANGING

As noted earlier, one uses dense absorbers to range out, as close to the vertex as possible, pions and kaons that otherwise would decay and generate an undesirable background for the direct muons. The absorber should, of course, be calorimetrized in order to provide transverse-energy flow measurements for both trigger and off-line analysis purposes.

PHOTON CONVERSION[16]

Measurement of photons in the range above tens of MeV via conversion into e^+/e^- pairs is a well-established technique. It can be implemented in conjunction with a general-purpose charged-particle spectrometer, but implies constraints on the magnetic field (owing to the low rigidity of the electrons) and the thickness of chambers and interspersed material (to minimize multiple scattering and energy loss).

5. PID IN EXISTING FIXED-TARGET NUCLEAR-BEAM EXPERIMENTS

Turning now to the question of integrating PID detectors into experiments, we begin with what exists. The CERN Super Proton Synchrotron (SPS) ion-beam programme is well along at the present moment, with six experiments preparing for ion beams in November-December 1986. We choose as examples two elements of the High Energy Lepton and Ion Spectrometer (HELIOS) (née NA34) experiment[17]. HELIOS combines full solid angle (in the centre of mass) electromagnetic and hadronic calorimeter coverage with an external magnetic spectrometer for charged particles and photons, a superconducting muon-pair spectrometer, and a powerful forward spectrometer for single-lepton measurements.

We concentrate first on the HELIOS external spectrometer as an example of how a variety of conventional PID techniques can be associated with drift chambers, a magnetic field, and calorimetry, to make a 'sampling' measurement of the flavour composition, transverse-momentum distributions, and correlations of particles emanating from the central rapidity region in light-ion nucleus collisions at $\sqrt{s}$ = 20 GeV (fixed target). The external spectrometer views the target through a small solid angle (20 msr) slit that extends from 15° to 45° lab (approximately 2.0 to 0.9 in lab rapidity) and ±1.2° in azimuth in the uranium/scintillator wall. The slit size is chosen small enough not to compromise the energy flow measured by the calorimeters and large enough to allow an average of one charged particle into the acceptance for central oxygen-uranium collisions at 200 GeV/A (based on HIJET simulations). The spectrometer can handle larger multiplicities, the limit being related to the granularity of the TOF

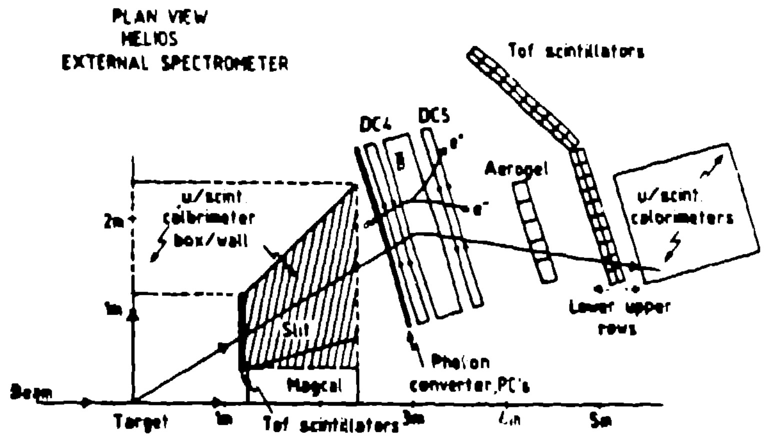

FIGURE 2
A plan view of the HELIOS external spectrometer. The spectrometer looks at the target region through a narrow (in azimuth) slit in the calorimeter wall. See text for details.

elements (40 at the present time). A plan view of the spectrometer is given in Fig. 2. There are TOF elements, aerogel threshold Cherenkov detectors, ionization energy-loss measurements in drift chambers and in scintillators, calorimetric PID in external calorimeters, and a photon-conversion device based on a thin converter and proportional chambers.

The spectrometer represents a synthesis of standard techniques into a device that can handle moderate multiplicities over a limited solid angle. Its use in the multiplicity environment of much heavier incident ions (e.g. a factor of 8 increase in multiplicity could easily be seen with incident Au ions) or in a collider environment is obviously not possible. Modifications and extensions that would allow such operation are possible and will be discussed. Let us first comment on the performance of the present device.

Using the TOF and threshold Cherenkov detectors one has 3σ separation of π/K/p up to 2.5 GeV/c and π–K/p up to 3.5 GeV/c, based on use of aerogel with an index of refraction of 1.028 and a TOF resolution of 0.7 ns. Ionization measurements in the drift chambers and scintillators will be useful in identifying heavier particles (and changes in ionization as a function of distance from target), though there are only 16 dE/dx samples in the chambers. The photon-conversion detector consists of two proportional chambers, one on each side of the thin converter, that provide a conversion trigger. The electrons are momentum analysed in the drift chambers and magnet.

The segmentation is adequate for the proton and light-ion physics to be tackled by HELIOS in the immediate future. Nonetheless, in the context of this paper we must address the possibility of upgrading the device for heavier ions and colliding-beam operation. One could, to some extent, increase the segmentation (and performance) of the scintillator TOF and threshold

Cherenkov. It would seem more sensible, however, to consider employing TOF spark chambers and ultimately a RICH to improve PID and segmentation. Similarly, use of a TPC with good ionization measurement nearer the target could provide additional tracking and good vertex measurement for hyperon identification. Indeed, such a device becomes the prototypical colliding-beam 'slit spectrometer'. We note that the shape of the HELIOS external spectrometer slit was essentially dictated by the mechanical construction of the existing calorimeter modules. At the slit, the upper calorimeter wall is supported by a thin structure of aluminium Hexcel with a total thickness of 0.8 g/cm^2. In collider experiments one would design in the slits from the beginning, allowing reduction of both the mass of the supporting material filling the slit and the leakage from energy deposited in the calorimeters that define the slit[18], and perhaps some of the elements could be built into the slit volume itself for compactness in order to back up the whole slit by additional calorimetry.

6. TRANSITION RADIATION DETECTORS

We discuss now a novel TRD[11] that plays both PID and tracking roles in the electron spectrometer of HELIOS[17]. This spectrometer (Fig. 3) consists of high-precision silicon-pad detectors and drift chambers, a highly segmented

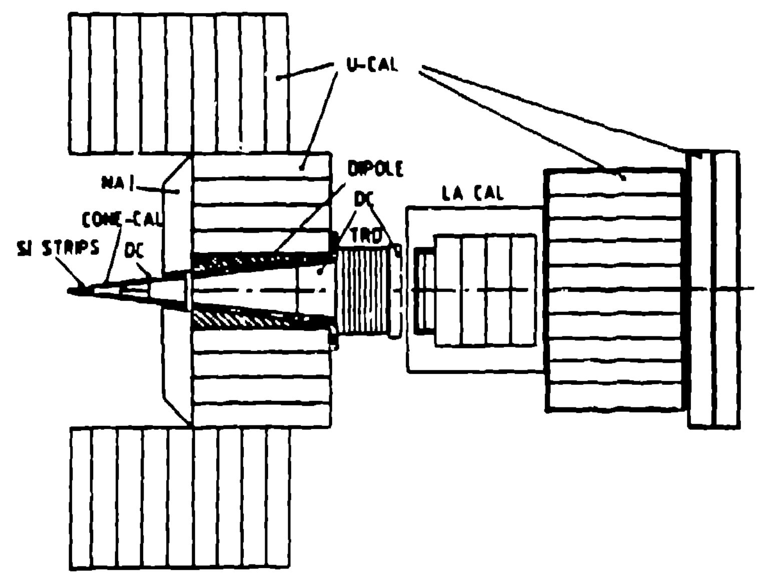

FIGURE 3
A plan view of the HELIOS electron spectrometer. In this view the external and muon spectrometers are not shown. The elements of the electron spectrometer are the silicon pads near the target, DC1, 2 and 3, the calorimetrized magnet or MAGCAL, the TRD and the uranium/liquid argon calorimeter.

U/liquid-argon electromagnetic calorimeter, a calorimetrized magnet, and a segmented TRD. The system is designed to reject pions in favour of electrons at a level of better than 10^{-3} at the trigger level via the silicon pads, the electromagnetic calorimeter, and the TRD. The rejection factor is defined as

$$R_{\pi/e} = e_\pi/e_e, \qquad \text{where } e_e = 90\%$$

and e is the efficiency in detecting a pion or an electron. Momentum analysis (off line) of the electrons in conjunction with calorimeter information (i.e. neutrinos via missing energy and improved pion rejection) provide the means to quantitatively understand prompt lepton production in high-energy pp collisions. Its relevance to the subject at hand derives from the potential utility of such a system of electron identification in the intense pion environment of URN collisions.

Transition radiation occurs when a relativistic charged particle crosses the interface between media with different dielectric constants. The yield of TR photons saturates for $\gamma > 5000$ and thus is ideal for electron/hadron differentiation. The TR photon spectrum spans the region between 3 and 20 keV, with the peak at about 10 keV. The absolute yield is quite low for realistic radiators (the yield at each interface being proportional to the fine structure constant), with approximately 0.1 photon per cm in 'compact' TRDs. The emission angle of TR is proportional to γ^{-1}, implying that the TR is detected along with a particle ionization energy loss. The Landau tail of the ionization loss is then the main background to the TR. Two techniques have been developed to cope with this difficulty: the total-energy deposition method and the cluster-counting method (i.e. clusters of photoelectrons due to absorption in the gas of a TR photon). The reader is directed to references 11 for details of the two methods. It suffices here to say that, because one is generally interested in involving the TRD in the trigger, the cluster method is preferred because it does not require the use of FADCs. Rejection power appears to be similar for the two methods, however. We note that TRD construction is made difficult by the requirement that it be quite low in mass in order to minimize nuclear reactions by hadrons and electron conversions.

The HELIOS TRD contains eight modules, each of which consists of hundreds of very thin CH_2 radiators followed by a 2 cm thick proportional chamber (PC) (Xe/C_4H_{10}) with finely segmented anode and cathode sectors aimed at the target. In this way, the PID information from the TRD is associated with specific tracks that can be correlated with segments from other tracking elements of the electron spectrometer. The TRD then significantly improves the electron identification by rejecting candidates that are in fact charged pions that happen to coincide with electromagnetic energy (e.g. from a neutral pion) in the appropriate calorimeter sector. A schematic representation in one dimension of the way the TRD cluster counting distinguishes electrons, photon conversions, and pions is given in Fig. 4.

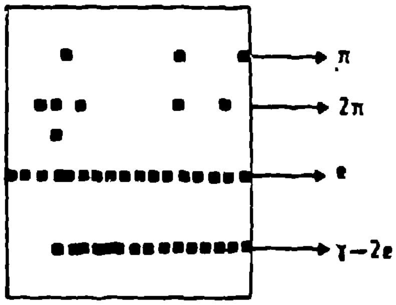

FIGURE 4
A schematic representation in one dimension of the identification capability of the HELIOS TRD using cluster counting.

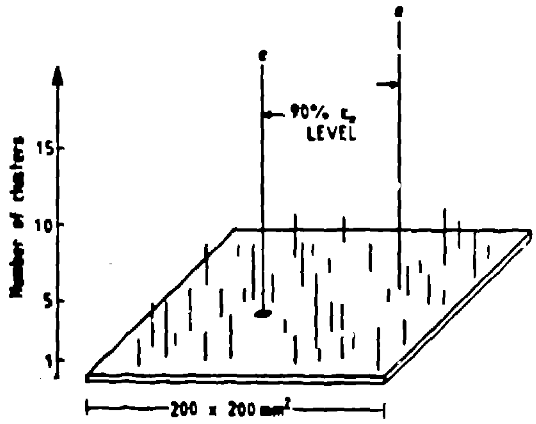

FIGURE 5
The predicted electron identification capability of an 'ultra-sampling' TRD (see text) in a background of 1000 pions per m^2.

In order to make use of tracking TRDs in the URN collision environment, one must appreciably increase the rejection power while maintaining segmentation adequate for the expected electron densities. Dolgoshein et al. have developed and tested (at Serpukhov) a small prototype[11] of an 'ultra-sampling' TRD that appears to justify constructing a full-scale device for use in the next generation of fixed-target nuclear-beam experiments at CERN and BNL. The device would have rejection power at the level of 10^{-3} thanks to a large increase in the TR photon yield per centimetre of detector (from 0.2 in the present HELIOS TRD to 0.4). This is accomplished by making the radiator sections thinner (most TR photons are absorbed by the radiator itself even in the best case) and using many thin PCs. Such a device would be quite compact, with 50 modules each of 20–40 foils of 15 μm CH_2 followed by a 2 mm thick PC and would have some interesting properties from the URN collision perspective. The very thin PCs would reduce the cluster counting to a 'yes-no' problem in each PC, eliminating the need for the rather complex cluster-counting electronics necessary in thicker PCs. The thin PCs are also very fast (40 ns as compared to the approximately 700 ns of the present HELIOS TRD) allowing high-rate operation. A calculation of the performance of such a TRD, based on Serpukhov prototype tests, indicates that clean electron identification and tracking is possible in very intense pion backgrounds. As an example, in Fig. 5 the predicted number of clusters detected in the 'ultra-sampling' TRD is given for electrons in a background of 1000 pions per m^2. Of course, such a TRD will require a very large number of electronics channels. In addition, the technical problems posed by the construction of a 0.5 to 1 m^2, 2 mm thick PC must not be underestimated. Nonetheless, a TRD such as described here, in conjunction with other tracking devices capable of high track density, could prove a very powerful tool in extracting the important electron signal in URN collisions.

7. CONCLUSION

The need for PID in URN physics experimentation is evident. The nature of URN interactions and the physics to be extracted places enormous demands on the flexibility and dynamic range of PID systems. We have seen that PID as complementary information that derives from specific detectors placed 'in series' with the detectors that provide tracking and calorimetery is barely adequate for light-ion beam fixed-target experiments. For heavier beams, and surely for collider experimentation, one must fully integrate PID into the detector system from the beginning. The design and construction of such detectors is one of the most interesting and challenging technical aspects of URN physics.

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