Detectors for Particle Identification

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1 Introduction

Recently, there has been considerable interest shown in the development of detectors for particle identification in the field of high energy physics because of the need to identify B meson decay secondaries in future experiments planned for the study of CP violation. Kaon identification is needed not only for reconstruction of some specific exclusive B decays modes known to be key to these measurements but also, for tagging the "other" B in an event through the decay chain $b \rightarrow c \rightarrow s$ so it known whether the reconstructed B was produced as a B^0 or $\overline{B}^0$. For the assymmetric B factories, the moemntum range over which this information is needed is rather broad when the full eta range to be covered is taken into account. Whle the momenta of tagging kaons (or muons or electrons) is rather low, $0.2-1.5\,GeV/c$, the momenta of exclusive B decay secondaries extend upwards from this to about $5\,GeV$. The most energetic nonleptonic decays products are the pion secondaries from the two body deacy, $B \rightarrow \pi\pi$, which must be separated from the background mode $B \rightarrow K\pi$. This background is difficult to remove using kinematics alone[1].

This discussion will be limited to specialized detectors designed for the purpose of particle identification. The detectors to be covered are all "non-destructive", which means that the particles they identify are simply absorved in the detector and survive to be detected in more downstream elements. Therefore, a necessary design goal is to optimize performance relative to the amount of material the particles traverse. In all cases it will be assumed that the momenta of the particles to be identified have been measured independently by use of a magnetic field combined with tracking detectors.

2 Time of Flight

For two particles with masses $m_1,\ m_2$, both having momentum p, the difference in their time of flight in traveling between two scintillation counters separated by distance L, is

$$\Delta t = t_1 - t_2 = \frac{L}{\beta_{1c}} - \frac{L}{\beta_{2c}} = \frac{L}{c}\left[\sqrt{1+\frac{m_1^2c^2}{p^2}} - \sqrt{1+\frac{m_2^2c^2}{p^2}}\right]$$

For $p^2 \gg m^2c^2$,

$$\Delta t \simeq \frac{(m_1^2 - m_2^2)l_c}{2p^2} \tag{1}$$

Figure 1 shows the difference in the time of flight, Δt, in nanoseconds, for $Kp,\ \pi - K$, and $e - \pi$ as a function of momentum over a flight path of one meter[2], an appropriate distance scale for a typical collider detector. As can be seen in the figure, because of the dependence on the inverse suqre of the momentum exhibited in equation 2.1, the time differences sre extremely small ($< 1\,ns$) except at very low momenta.

The identification power of a time-of-flight detector can be quantified in terms of the significance of the Δt measurement, which is defined in the following way. If σ_{t1} and σ_{t2} are the time resolutions of the two devices used to measure the time at the beginning and at the end of the particle trajectories, then the error in the time measurement Δt is

$$\sigma(\Delta t) = \sqrt{\sigma_{t1}^2 + \sigma_{t2}^2} = \sqrt{2\sigma_t^2} = \sqrt{2}\sigma_t,$$

for $\sigma_{t1} = \sigma_{t2} = \sigma_t$.

Then,

$$\frac{\Delta t}{\sigma(\Delta t)} = \frac{\Delta t}{\sqrt{2}\sigma_t} \tag{2}$$

is the significance of the Δt measurement in standard deviations.

The time diference corresponding to 4σ separation when scintillation counters used to measure the times is estimated at $\Delta t = 622$ picoseconds, assuming the 110 ps resolution reported in Reference 3. If parallel plate spark chambers, for which the time resolution is of order 50 ps, are used to measure the times instead, then the time difference at which 4σ separation is achieved is $\Delta t = 283\,ps$. These time differences are marked on the right hand axis of Figure 1 to demostrate that the time of flight techniques is only useful at very low momenta with currently available technologies.

By taking more measurements along the particle trajectory, the significance can be improved by $1/\sqrt{N}$, where N is the number of measurements, but at the expense of more material through which the particles must pass.

As an example of the use of time of flight in an experiment, the CLEO experiment at Cornell has been able to achieve 3π pion-kaon separation up to $\sim 0.9\,GeV/c$ by this technique[4].

3 Ionization Loss, or dE/dx

Tracking detectors designed to make position measurements along the trajectories of charged particles can simultaneously be used to identify particle species by measuring the mean ionization loss along the tracks. This applies to any detector in which particles lose energy to ionization, e.g., gas-filled wire chambers or silicon strip detectors. Since the pulse height on each wire or strip must be read out, this technique requires the use of analog readout electronics. Because the ionization energy loss is a statistical process with large fluctuations, many measurements are needed along eachtrack to get aprecise mean. for gas-filled detectors, the statistics are improved by operating at higher gas pressure, since this results in more primary ionizations along the particle path. The precision of the mean is improved by using the method of " truncated mean" whereby a certain fraction of the signals of largest size are removed in taking the average. This eliminates samples which come from points way out on the tail of the Landau distribution, named for the physicist who first calculated the shape of the typical energy loss distribution. The curve is significantly skewed toward higher energy losses because of the production of delta rays, ionizations where the electron is kicked out with high enough energy to itself form ionizations along its path.

The mean energy loss, dE/dx, of particles in matter is described by the Bethe-Bloch equation, which is a universal function of $\beta\gamma$ for all particle masses. The energy loss decreases with increasing momentum as $1/\beta^2$ at low momenta and reaches a minimum at $\beta\gamma \sim 4$. Above that point, the energy loss rises logarithmically, which is called the relativistic rise region, until it saturates at the "Fermi plateau"[5]. This characteristic shape is shown for various particle masses in Figure 2[6]. Figure 3, also from Reference 6, shows the realtive difference in ionization loss for $\pi's$ and K's as a function of momentum. The large dip in this distribution is the so-called "crossover region", momenta at which the ionization loss difference is very small because the relativistic rise portion of the π dE/dx curve crosses the K curve as it falls toward its minimum. Experiments which use the dE/dx technique for particle identification must use a second technique such as time of flight to identify thye particles in this region.

dE/dx has been used successfully for particle identification in the OPAL jet chamber at LEP[5,7]. The chamber has 24 sectors, each with 159 long anode wires aligned along the beam axis. Over 73% of the solid angle, tracks have hits on all 159 wires. Although 30% of the samples are removed in calculating the truncated mean, the sampling statistics are thus still large enough to allow a precise calculation of the mean ionization loss. The results are further improved by careful analysis, including quality cuts on the tracks and corrections for systematic shifts in the relevant parameters. The detector was run at a pressure of 4 bars, which was chosen to give optimum separation power. Lower pressure would give fewer primary ionizations per unit path lenght, but higher pressure would cause the curves to reach the Fermi plateau at lower momenta, and thus would degrade the particle separation that could be achieved in the realtivgistic rise region.

Figures 4 and 5, both from Reference 5, document the perfomance of the OPAL jet chamber. Figure 4a) shows the dE/dx distributions as a function of momentum for tracks seen in the chamber. The curves exhibit the features expected from the Bethe-Bloch formula and show clear separation of the particle species except in the crossover region. The intense distribution of points at high momentum in the figure are calibration data from exposure to a monoenergetic muon beam. Figure 4b) shows the same data in slices of momentum.Figure 5 is a plot of the significance of the separation for pairs of particle species in the detector. As shown in this figure, at least 2 standard deviation $\pi - K$ separation is achieved out to momenta as large as 20 GeV/c.

4 Čerenkov Counters

There are several types of detectors for particle identification that are designed to exploit the relativistic phenomenon first investigated in detail by the Russian physicist Čerenkov[8,9]. For particles traveling through a medium with velocity $v = \beta c$, when v exceeds the speed of light c/n in that medium, where n is the index of refraction, Čerenkov light is coherently emitted by the excited atoms along the particle path. The process can be visualized by picturing the appearance of the wake (small water waves that proceed out in the shape of the letter v) of a speedboat traveling through the water. The angle taht the light makes to the particle trajectory, is given by

$$cos\Theta_c = \frac{(c/n)t}{\beta ct} = \frac{1}{\beta n}. \tag{3}$$

Since $cos\Theta_c$ becomes unphysical for $\beta n < 1$, equation (4.1) holds only in case $\beta > \beta_t$, where $\beta_t = 1/n$ is the threshold velocity. For a medium with index of refraction n, the minimum Čerenkov angle is 0^o for a particle with velocity $\beta_t c$. The angle grows with increasing β above the threshold and reaches a maximum for $\beta = 1$, or $cos^{-1}\Theta_c = 1/n$.

Two types of Čerenkov Counter, threshold and differential, are shown schematically in Figure 6 a) and b). The threshold counter is the simplest such device. light emitted along the length of the counter, which near threshold is at low angle and therefore almost parallel to the axis of the counter, is reflected by a parabolic mirror surface into a photomultiplier tube placed at the focal point of the mirror. for a particle of mass m, the threshold momentum, p_t, in GeV/c, for a counter filled with material with index of refraction n, is

$$p_t = m\gamma_t\beta_t c = \frac{mc}{\sqrt{n^2 - 1}}. \tag{4}$$

Thus a threshold counter designed to "turn on" for pions at $6GeV/c$ will "turn on" for kaons at momentum

$$p_{t\ kaon} = \frac{m_{kaon}}{m_{pion}} \times 6GeV/c,$$

which is approximately $21GeV/c$. The number of photons emitted along the particle path grows as the square of the sine of the Čerenkov angle. Integrating over wavelenghts between 350 and 500 nanometers, the approximate range over which photomultiplier tubes, the most common means of detecting the produced Čerenkov light, operate, the number of the Čerenkov photons emitted per unit path length traversed by particle in the counter can be estimated using

$$\frac{dN}{dx} = 390 sin^2\Theta_c. \tag{5}$$

Other factors, e.g., the mirror reflectivity and the quantum efficiency of the photomultiplier tube used to detect the radiation, influence the response of the detector and the momentum at wich it becomes fully efficient for particles of a particular mass. Two typical efficiency curves for threshold Čerenkov counters filled with materials having different indices of refraction are shown in Figure 7. As the figure indicates, Čerenkov counters can be made to be very efficient, and while the response does rise rapidly with momentum, there is a range of momenta over which the detector is not fully efficient before reaching plateau.

The differential counter shown if Figure 6b) contains a spherical mirror and photomultiplier tubes placed in a ring of fixed radius looking at the mirror through a circular slit, or diaphragm, located at the focal plane of the mirror, indicated by the letter d on the figure. All light produced at the Čerenkov angle by a particle moving along the axis of the detector is focused into a circular ring of light of radius $R = f tan\Theta_c$ at the focal plane, f, of the mirror. (Recall that $f = 1/2R$ for a spherical mirror!) When the radius of the ring of light corresponds to the radius of the diaphragm, the Čerenkov light will be detected in the phototubes. The counter is filled with a gas, typically He. The index of refraction is controlled by varying the pressure. If the counter is placed in a hadron beam of fixed momentum p, then, starting at a pressure such than the index of refraction is below the threshold for pions, i.e., $\beta_{pion} < 1/n$, if the pressure is raised and thus n is increased, first the pion ring appears at 0^o and then moves to higher angle, then, as n becomes high enough for the kaon to be above threshold, the kaon ring appears at 0^o. As the pressure is increased further, the kaon ring moves to higher angle, and the proton ring apperas at 0^o. As the pressure is increased further, the kaon ring moves to higher angle, and the proton ring appears at 0^o, etc. Each particle ring is detected in turn as it passes through the angle which is focused onto the photomultiplier tubes. Figure 8 shows a typical such pressure curve for a differential Isochronous Self-focusing Čerenkov Counter (DISC)[10]. The yield of photons is plotted as a function of decreasing β, which, because of the relationship shown in Equation (4.1), corresponds to increasing n and therefore also increasing pressure.

For a differential Čerenkov counter,

$$\frac{\Delta\beta}{\beta} = tan\Theta\Delta\Theta. \tag{6}$$

Although this relation implies that the velocity resolution is best for small Θ and small $\Delta\Theta$, the number of photons grows with both the angle, Θ, and the slit width, $\Delta\Theta$. Since the efficiency depends on the number of photons collected, the angle and the slit size need to be carefull selected to optimize performance. note also that the beam must be cery tightly collimated in the order for this detector to give good separation. The resolution in β that can be achieved is ultimately limited by the dispersion of the produced Čerenkov light in the gas radiator, but, by using a non-dispersive gas like He, resolution in $\Delta\beta \sim 10^{-7}$ has been achieved in counters of this type.

In recent years a more sophisticated type of counter called a Ring Imaging Čerenkov Counter (RICH), first suggested by Ypsilantis and Seguinot[11], has been developed. The RICH as first envisioned was to have spherical geometry as shown in Figure 9 and was to becentered on the interaction point of a colliding beam experiment. Particles produced at the inetraction point travel outward along radii of the two concentric spheres that make up the counter, the mirror placed at radius R and the detector placed at the plane, $R/2$. As for the differential counter, photons emitted at the Čerenkov angle all along the path of the particle through the gaseous radiator material are focused into a ring of light at the focal plane. The detector is a multi-wire proportional chamber filled with gas doped with a photosensitive vapor like tetrakis (dimethylamine) ethylene (TMAE). When a Čerenkov photon is absorbed in the vapor, a photoelectron is emitted, which produces a samll cluster of ionization electrons. These drift toward the closest anode wire. Because of the avalanche produced as the cluster of electrons approaches the wire and the further amplification of the signal by the front end electronics, even a single photon can be detected with good efficiency. These are detected with the precision of the chamber wire spacing in the coordinate perpendicular to the wires.

To get the coordinate along the wires one can use pads etched on the back surface of a resistive cathode. Alternatively, the detector can be constructed as a time projection chamber (TPC) with anode wires at one end of the cell. The ring of ionization clusters is drifted toward the wires by an applied electric field. In this case, one coordinate is determined by which wire is hit and the second, by the time at which the hit is received as recorded in a time-to-digital converter. while this choice leads to an inherently slow RICH, the speed is adequate for use in e^+e^- colliders, where the time between event triggers is quite long.

The spherical geometry of the detector as originally proposed turned out to be rather impractical. But it was noticed, as demonstrated in Figure 10, that if the mirror/detector sphere is broken into small sections and these are moved radially outward from their original position keeping the distance between the two concentric surfaces the same, the condition of parallel rays close to the radius of curvature of the mirror still nearly holds for the Čerenkov light, which is emitted at low angle in a gaseous radiator, and thus it will still be focused into a ring of light at the detector, which remains at the focal plane. These small sectors can be moved out and rotated to point to the interaction point and thus can be made to conform to the overall detector shape. This is the principle used in building the RICH for the DELPHI detector at CERN[12].

A second version of the RICH uses a liquid radiator, which has a significantly higher index of refraction, and thus a significantly larger Čerenkov angle. As indicated in equation (4.3), this means that a much larger number of photons is produced per unit length of path and therefore the radiator can be made quite thin. Then, it is possible to use "proximity focusing" to project the ring of light onto the detector as shown in Figure 11. As seen in the figure, the radius, R, of the ring grows with increasing distance between the radiator and the detector while the width of the ring, ΔR, does not, because the Čerenkov light rays are all parallel even after refraction at the back surface of the radiator. Since the resolution in velocity depends on $\Delta R/R$, this can be improved by increasing the distance between the radiator and detector.

A new techniques using Čerenkov light has emerged recently that is of particular interest for the B factories because it provides better discrimination than RICH in the forward region, which is the most difficult to cover[1]. This called the DIRC for *Detection of Internally Reflected Čerenkov Light.* The detector as proposed is made from quartz bars 1.2cm thick, 4cm wide, and 260cm long. As shown in figure 12, for the simplest case of a particle incident perpendicular to the surface along the y axis, because the quartz has a high index of refraction, $n = 1.474$, not only will the Čerenkov angle be large but the light will also be totally internally reflected. It will undergo multiple reflections before emerging from the end of the bar. If the initial momentum vector is $\vec{p} = (p_x, p_y, p_z)$, then the final momentum vector will be $\vec{p} = (p'_x, p'_y, p'_z)$, where $p'_x = (-1)^n p_x$, for n reflections along the x direction, and $p'_y = (-1)^m p_y$, for m reflections along the y direction, and $p'_z = p_z$. With the flat mirror placed below the end of the bar as shown, p'_y will also equal p_y. Thus, the imege for this ideal case will be a conic section, or hyperbola, as shown in Figure 13. Figure 14 shows the image as it appers on an array of photomultipliers used to detect the light. The image becomes more complicated when the particle is incident at an oblique angle. As in proximity focusing for the liquid RICH, a separation distance, to be filled with liquid to match the quartz index of refraction, will be maintained between the bar and the detector to expand the size of the image.

5 Transition Radiation Detectors

Like Čerenkov Radiation, Transition Radiation (TR) is relativistic effect. The phenomenon was first predicted by two Russian physicist, Ginsberg and Frank, in the late 1940's, although more than 20 years went by before a Transition Radiation Detector (TRD) was used successfully in an accelerator-based high energy physics experiment[13].

TR is the radiation that must be emitted as a relativistic particle crosses the boundary between two media with different plasmaa frequencies (or, equivalently, different dielectric constants)[14]. An aproximate expression for the energy radiated per unit solid angle per unit frequency interval at a single such interface between medium 1 and medium 2 is

$$\frac{d^2W}{d\omega d\Omega} = \frac{\alpha}{\pi^2}\left|\frac{\Theta}{\gamma^{-2}+\Theta^2+\frac{\omega_{p1}^2}{\omega^2}} - \frac{\Theta}{\gamma^{-2}+\Theta^2+\frac{\omega_{p2}^2}{\omega^2}}\right|^2. \tag{7}$$

This approximation is valid for $\gamma \gg 1$, $\Theta \ll 1$, and $\omega^2 \gg \omega_{p1}^2, \omega_{p2}^2$, where γ is the Lorentz factor of the particle, Θ and ω are the angle and the frequency of the emitted radiation, and ω_{p1}, ω_{p2} are the plasma frequencies of the two media.

The effect is strongly peaked in the forward direction and it is symmetric, i.e., the radiation emitted is the same whether the particle enters medium 2 from medium 1 or enters medium 1 from medium 2.

Notice also that ω_{p1} should be very different from ω_{p2} for a large effect. This is true of the materials used in constructing the TRD's that have been used successfully in experiments to date. E.g., a typical foil material is polypropylene, CH_2, for which $\omega_{p1} = 21.8eV$, and a typical gap material is air, for which $\omega_{p2} = 0.7eV$.

TR is a small effect. This is because the total energy radiated at each interface depends linearly on the fine structure constant, $\alpha = 1/137$. But, by stacking many thin foils ($\sim$ 200, typically) of material 1, separated by gaps of material 2, and choosing the foil and gap thicknesses to get positive interface between the radiation emitted at the incident and exit surfaces, it is possible to enhance the effect enough to build a practical detector.

For a single foil in a gas, the amplitude of the radiation emerging from the second boundary is

$$\vec{E}(\omega,\vec{\Theta}) = \vec{e}_2(\omega,\vec{\Theta}) + \vec{e}_1(\omega,\vec{\Theta})e^{-\sigma_{foil}+i\phi_{foil}}, \tag{8}$$

where $\vec{e}_j(\omega,\vec{\Theta})$ is the amplitude of the radiation emitted at surface j, σ_{foil} is the attenuation of the radiation in the foil (Let's neglect that for now - in any case, it is small in a single foil!), and ϕ_{foil} is the phase lag due to the difference in the wave and particle velocities in the medium.

Now,

$$\vec{e}_1(\omega, \vec{\Omega}) \simeq \frac{\Theta}{\gamma^{-2} + \Theta^2 + \frac{\omega_{p1}^2}{\omega^2}} - \frac{\Theta}{\gamma^{-2} + \Theta^2 + \frac{\omega_{p2}^2}{\omega^2}} = -\vec{e}_2(\omega, \vec{\Theta}). \tag{9}$$

Substituting this expression into equation (5.2) and squaring to get the intensity of the radiation emerging from the foil, we see that

$$\left(\frac{d^2W}{d\omega d\Omega}\right)_{single\ foil} = \left(\frac{d^2W}{d\omega d\Omega}\right)_{single\ interface} \times 4sin^2\left(\frac{\phi_{foil}}{2}\right). \tag{10}$$

We therefore get positive interference for $\phi_{foil} = \pi,\ 3\pi$, etc.

It can be shown (Reference 14 - Equation 2.10) that

$$\phi_{foil} \simeq \frac{\left(\gamma^{-2} + \Theta^2 + \frac{\omega_{p,CH_2}^2}{\omega^2}\right)\omega l_{foil}}{2}, \tag{11}$$

where l_{foil} is the foil thickness. If we define

$$z_{foil} = \frac{2}{\left(\gamma^{-2} + \Theta^2 + \frac{\omega_{p,CH_2}^2}{\omega^2}\right)\omega}, \tag{12}$$

then

$$\phi_{foil} \simeq \frac{l_{foil}}{z_{foil}}. \tag{13}$$

z_{foil} is the well-known "formation zone". If l_{foil} is much smaller than this, we get no contribution from the foil because the interference terms is near zero. Thus, TR, like Čerenkov radiation, is a bulk property of matter. There is a minimum thickness of material that the particle must traverse below which radiation will not occur at the interfaces.

The procedure described above for calculation of the radiation emitted from a single foil can be generalized to an n-foil set by grouping the foil amplitudes two-by-two as above and adding the amplitudes from the n foils coherently. It is possible to make a series approximation to the expression that results to facilitate computer calculation. The computer program[15] used to simulate the performence of the E769[16] TRD to aid in the selection of design parameters used such an approximation. Integration over the angle of the radiation is detected in the same cell as the particle track itself in most cases. While the particle track could be bent away from the radiation by use of a magnetic field, this requires some distance for a stiff track, and the region must be evacuated to avoid absorption of the TR x-rays in material upstream of the detector.

Figure 15 shows the expected yield of TR per keV as a function of the energy of the radiation in keV for a foil set made from 200 CH_2 foils[17]. The foils are each $82\mu m$ thick, and they are separated by $1.4mm$ helium gaps. The particle gamma assumed in the calculations is $\gamma = 10^4$, which corresponds to a 5 GeV electron. Two curves are shown for the foil set, one including the effect of foil self-absorption and the other neglecting it to demonstrate the severe attenuation of the radiation in the foil stack itself at lower x-ray energies. These curves have been divided by 400 so that they can be compared directly with the single interface curve which is also shown on the plot. This provides grphic illustration of the modulation due to the inetrference term. Since the curves shown have been divided by 400, the total amount of radiation per unit energy emitted by the foil set is 400 times the number shown on the y axis.

The E769 TRD was designed to identify pions in an incident 250 GeV/c positive hadron beam, for which $\gamma \sim 1800$. This was the first time that a TRD was used for beam tagging in the hadron beam for a running particle physics experiment. The E769 detector is a good illustration of a typical, practical TRD. It was made from 24 identical modules, one of which is shown schematically in Figure 16. Each contains a radiator made from 200 $12.7\mu m$ polypropylene (CH_2) foils stacked alternately with nylon net sparcers, which are $180\mu m$ thick. The nylon net was cut away in the region of the beam since it was found to attenuate the TR x-rays by a factor of approximately 2. The radiator voulme was flushed with helium during the E769 run but was run with air during tests carried out with the TRD during Fermilab experiment E791, since, although the plasma frequency of helium is smaller than that of air, the difference in the TR output of the radiator stack is not significant. The radiator is followed by a two-plane proportional cahmaber with single cell depth 0.635cm, and active area 76 mm wide by 65 mm high. The sense wires (anodes) are spaced at 1 mm and all are oriented horizontally since the chambers were not used to measure position. The wires are $10.2\mu m$ gold-plated tungsten and the cathodes are $12.7\mu m$ mylar with $140\mathring{A}$ of aluminum sputtered onto both sides. The chamber gas used was xenon bubbled through methylal at 0C, which results in a mixture that is approximately 90% xenon. There is a 0.3175 cm buffer volume filled with nitrogen in front and in back of the two-plane chamber. The gas volume were maintained at equal pressure to keep the chamber gains uniform across the planes.

Because it is comprised of many layers, each with a relatively small number of foils in the radiator stack followed by two chamber planes that are shallow in depth, this detector is an example of a "fine-sampling" TRD[18,19]. This means that at most one x-ray is likely to be captured per plane per event. This is the reason that a simple digital readout by means of a latch on each detector plane, indicating one or more hits above the TR threshold, although not optimum, sufficed. Also, because of the short integration time of the electronics circuits used, which shaped the pulses from the very localized ionization of an Fe_{55} source to $26ns$ full width at half maximum, this TRD discriminates using the technique of "cluster counting"[19,20]. This has been shown to give better separation between species than the method of total charge collection.

The length of the detector as built was 2.79 m. The total amount of material in the detector was 8.7% of an interaction length and 16.9% of a radiation length including two 0.3175 cm scintillation counters used for gating. It would be difficult to reach the 90% efficiency for pions coupled with a factor of $30in$ background rejectiion (in this case protons, since the kaons were separately tagged by means of a Differential Isochronous Self-Focusing Čerenkov counter [DISC][10]) that was achieved with this detector with much less material than this. The method by which the pion sample was selected is illustrated in Figure 17, which shows the distribution of TRD planes hit per event for all events in which the beam particle was not tagged by the DISC as a kaon from a typical E769 data run. As shown by the curves in the figure, the proton and pion peaks were each fit with a double binomial on a run-by-run basis. A plane count cut was chosen such that 90% of the integrated pion distribution lay above it. Then, the background above this cut was calculated using the protons and pions separately during special runs in which the DISC pressure was set to tag them. Further details about the E769 detector are contained in Reference 16.

Figure 18 shows the expected average number of TR photons radiated and detected per module of the E769 TRD for electrons, pions, kaons, and protons incident as a function of particle energy. The numbers shown have been calculated using the simulation package developed for modeling this detector[1]5, which was found to reliably predict the actual detector performance. The measured efficiency for the x-ray capture signal to be above the $4keV$ threshold set on the electronic readout circuit, which was 83%, has been included in the numbers shown. Comparisons to the results of Reference 21 indicate that saturation is not modeled correctly in the simulations, so it has been put in by hand at the gamma value corresponding to that for pions at an energy of $500GeV$. This seems prudent, since no experimental data are avilable from the E769 detector at higher pion energies than this. Test run using the TRD during Fermilab E791 indicated that saturation does not occur below this value, although this is somewhat above the saturation energy for pions of $430GeV$ bpredicted usin the method discussed in Reference 14. Note the author's comments on the reliability of this estimate, however.)

Since, as shown in Figure 18, electrons radiate TR and hadrons do not over a two order of magnitude range in momentum, the momentum window over which it is possible to discriminate electrons hadrons is large. A TRD can be designed to saturate in the vicinity a few GeV for electrons, so that above that value, the efficiency for electrons is constant. In the same detector, since the effect goes as γ, pions do not radiate appreciable TR until they are at energies near that same value γ, in the range of hundreds of GeV. When used in combination with an electromagnetic calorimeter, the two can provide a background rejection of $\sim 10^{-4}$ with good selection efficiency for electrons. This is demonstrated in Figure 19, which shows the electron decay tracks for candidate hyperon beta decay events, $\Sigma^- \rightarrow ne^-\nu$, before and after requiring identification of the electron in the E715 TRD[21,22]. The branching fraction for the decay mode of interest is three orders of magnitude samller than that of the non-leptonic decay mode, $\Sigma^- \rightarrow n\pi^-$, which has a branching fraction close to 100%. Thus, in order for this experiment to obtain a beta decay sample with only a few percent hadron contamination it was necessary to achieve a better rejection of pions than could be accomplished by the use of calorimeter alone.

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