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CERENKOV COUNTERS AT ISABELLE

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INTRODUCTION

Particle mass identification capability will be very important for much of the physics at ISABELLE. It will be required for studying quantum number flow in quark-quark scattering (jet and high p_t physics), hadronic decays of W's and Z's, and "onium" states. It will be essential for detecting and studying "naked flavor" states and generally required or at least very useful for most hadronic physics at ISABELLE.

The large all-purpose detectors envisioned for ISABELLE require particle identification covering up to 4π solid angle with high multiplicity capability, high rate capability, insensitivity to high magnetic fields, and large dynamic range (1 to 400 GeV/c). In addition, it would be desirable to have this information for on-line event selection.

At present there are only four practical methods for doing charged hadron identification: time-of-flight, dE/dX (ionization sampling), transition radiation, and Cerenkov radiation. All these methods need independent momentum determination and are effective over only limited kinematic ranges.

Although the status and foreseeable development of these techniques are discussed at length elsewhere in these Proceedings, we briefly summarize their expected capabilities in order to compare them with Cerenkov techniques. For the sake of argument we assume a 4π steradian detector with an inner radius of 2 m.

TIME-OF-FLIGHT

The maximum momentum at which two particles of masses m_1 and m_2 can be separated by time-of-flight is

$$p_{\max} \text{ (GeV/c)} \approx 0.129 \sqrt{\frac{(m_1^2 - m_2^2)L}{\Delta t}} \approx 0.129 m_1 \sqrt{\frac{L}{\Delta t}}$$

where m_1 is the larger mass (GeV/c)², L is the distance (cm), and Δt is the separation in time (ns) necessary to achieve the desired separation (i.e., $\Delta t = 3\sigma_{\text{res}}$). Thus the maximum momentum for π/K separation, assuming $L = 2$ m and $\sigma_{\text{res}} = 0.2$ ns ($\Delta t = 0.6$ ns), is $p_{\max} = 1.2$ GeV/c. To extend this to 3 GeV/c, where there is good overlap with the separation achievable with dE/dX techniques, requires, for $L = 2$ m, $\sigma_{\text{res}} \approx 0.033$ ns. Whether this precision will be practical with microchannel plate PM tubes or avalanche photodiodes (or whatever) is not known, but it is certainly beyond present standard techniques (see Fig. 1).

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Ionization sampling in thin layers of gas in PWCs has been extensively investigated both theoretically and experimentally (e.g., see refs. 22-25). The technique requires of the order of 100 to 200 samples (in 1 to 2 cm of gas) from which the truncated mean is determined from the lowest 50 to 60%. Shown below are typical theoretical expectations²⁴ for π/K separation vs momentum for argon at 4 atm, 200 samples (1 cm), and $L = 2$ m.

p, GeV/c	2	4	8	16	32
Separation = $\Delta m/\text{FWHM}$	2.4	3.0	2.7	2.4	1.9

Experimental results appear to agree with these numbers.²³ To extend the separation to 50 to 60 GeV/c requires reducing the pressure to atmospheric (where the relativistic rise is greater) and increasing the length to about 5 m.

TRANSITION RADIATION

Transition radiation detectors are expected to be able to do useful $\pi/K/p$ separation down to about 100 GeV/c,^{26,27} and some

Fig. 1. Time, velocity, and angle separations of π , K, and p vs momentum (Δt in ns and L in meters). For π/K in He at NTP:

$$\Delta\theta \approx \frac{(m_1^2 - m_2^2)}{2p^2}; \quad \Delta t \approx 0.33L\Delta\theta; \quad \Delta e \approx \frac{(m_1^2 - m_2^2)}{2p^2/2\eta} \approx \Delta\theta/2\eta = \frac{1.5 \times 10^{-2}}{p^2}.$$

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people speculate that this limit can be pushed to as low as 50 GeV/c. At present, detectors give useful separation only above 200 GeV/c.

If all these developments are realized, then the combination of time-of-flight and dE/dX will give full particle identification from 0 to 30 GeV/c, and transition radiation detectors can pick up the high momentum end somewhere between 50 and 100 GeV/c or above. This leaves a hole between 30 and 50 to 100 GeV/c which appears to be difficult to fill with the given boundary conditions.

The number of wires, PM tubes, counters, etc., in such a system is staggering. The system also contains a lot of material (maybe about 0.1 radiation length) that may be unacceptable in the ISABELLE environment.

CERENKOV COUNTERS

In comparison, 2 m of Cerenkov radiator, made of conventional materials (including aerogel),¹⁶ can give particle separation between about 0.5 and 10 GeV/c using three threshold counters (e.g., see Appendix D-1). By using cryogenic liquids and vapors, the range conceivably could be pushed (neglecting problems of light collection) to 30 GeV/c or higher, as indicated in Table 1 (with some holes in K/p separation). The numbers in Table 1 do not leave any room for light collection, thermal insulation, windows, etc., and are based on relatively high collection and detection efficiencies ($N_0 \approx 100$ to 150). The realization of such a system of counters by conventional techniques is unrealistic for these reasons and for others to be discussed below.

However, a number of new ideas and technical developments in the past few years conceivably could result in significant improvements in Cerenkov counters. Greatly improved quantum efficiency, high segmentation, insensitivity to magnetic fields, high multiparticle capability, and extended momentum range are among the possible improvements. The devices and techniques discussed below are imaging counter techniques, photoionization PWCs, CCD arrays, microchannel plate tubes, wave-shifter collectors, and others. First we review conventional Cerenkov counter ideas, then we discuss imaging counters in general, and last we review the status and potential of each of the various schemes. Some specific examples of the application of these ideas to some ISABELLE experiments are given in Appendices D-I and D-II.

Table 1⁹
Cerenkov Counter Parameters

Radiator	n	N ₀	L(cm)	N _{pe}	Thresholds (GeV/c)			
					π	K	p	
N ₂ liq.	1.2	100	1.0	30	0.21(0.29)	0.75(1.02)	1.55(2.2)	
He liq.	1.02	100	5.0	19	0.69(0.95)	2.45(3.4)	4.9 (6.7)	
H ₂ vapor	1.002	100	20.0	8	2.2 (3.0)	7.9 (10.6)	14.8 (21.0)	
N ₂ + Ne mix	1.0002	150	174.0	10	7.0 (9.9)	25 (35)	53 (66)	

(L_{total} = 2 m)

The threshold values given in parenthesis are for one-half the maximum number of photons. Note that Spillantini⁹ gives the number of photons/cm emitted in the visible, not the number detected; he provides much useful data.

REVIEW OF CONVENTIONAL CERENKOV COUNTERS

Conventional Cerenkov counters have been described in many publications.^{2, 3, 28, 38} The number of photons emitted per cm is

$$N = \frac{2\pi\alpha}{c} \int \left(1 - \frac{1}{\beta^2 n(\nu)^2} \right) d\nu \quad (1)$$

where $n(\nu)$ is the index of refraction of the radiator medium, which is in general a function of the frequency, ν , of the photon. The dispersion of the index is a very important factor to consider when dealing with techniques that make use of the UV end of the spectrum. If we ignore the dispersion and integrate Eq. (1), then the number of photons/cm becomes

$$N \approx 370(E_2 - E_1)\sin^2\theta_c \quad \text{or} \quad N \approx 4.59 \times 10^6 \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right) \sin^2\theta_c,$$

where E is the energy in eV and λ is the wavelength in Å. Figure 2

illustrates this formula by showing the integral number of photons/cm for various higher energy cutoffs. The number of photons available in the visible (standard PM tube) region is given by the line in the lower right corner. The upper line is approximately the cutoff for He gas at NTP (600 Å).

Fig. 2. Number of photons emitted per cm as a function of energy for various energy cutoffs.

The number of photoelectrons detected per cm is the convolution of the number of photons/cm with the spectral response functions of all the components of the Cerenkov counter:

$$N_{p.e.}/cm = \int N_{\gamma}(\nu) \sin^2 \theta_c \Pi_i \epsilon_i(\nu) d\nu ,$$

where $\epsilon_i(\nu)$ are the reflectance of mirrors, the transmittance of windows, the quantum efficiency of the photocathode, etc. For a given configuration (ignoring dispersion)

$$N_{p.e.}/cm = N_0 \sin^2 \theta_c ,$$

Fig. 3. Spectral response of various materials in the far ultraviolet. Refractive indices: (1) LiF, (2) Ne (calculated, (3) He,²⁰ (4) Ar (which is very close to N₂). Percent reflection: (5) Al + MgF₂ (250 $\text{\AA}$),¹⁷ (6) Al + MgF₂ (480 $\text{\AA}$), (7) Al uncoated, after six months exposure to dry air, (18) Al + LiF.²¹ Percent absorption: (9) LiF (5 mm) (5) and (10) MgF₂ (5 mm).⁵ Also shown are (11) benzene photoionization probability, and cutoff wavelengths of various materials.

where N_0 can be taken as the figure of merit of that counter. For conventional counters using quartz-window PM tubes or wave-shifting phosphors on a glass window, $N_0 \approx 150$ to 170. More typically, a counter with conventional PM tubes (0.1),¹⁸ a mirror (~ 0.9), and a window (0.9) will have $N_0 \approx 40$ or less. To achieve values ≥ 150 requires all the components of the counter to be functional down to $\leq 2000 \text{ \AA}$. Figures 3 and 4 show the spectral response of some standard materials used in Cerenkov counters. All windows are very

Fig. 4. Refractive index vs energy for various window and lens materials. Also shown is the quantum efficiency of bialkali and trialkali photocathodes up to the LiF cutoff.¹⁸

dispersive below 3000 Å, and most materials are absorptive below 2000 Å except for the light noble gases, LiF, MgF₂, and a few other substances.

The conventional method of using Cerenkov counters for secondary particle identification over a large solid angle and large momentum spread is to use a number of multicelled threshold counters with an appropriate sequence of indices.

In principle, to get complete $\pi/k/p$ separation from the lowest momentum up to the highest momentum possible with atmospheric threshold counters requires a series of counters with indices decreasing as

$$\eta_{m+1} = \eta_m \frac{1}{\delta^2} \left(\frac{M_K}{M_p} \right)^2 \quad \text{for } \eta_m \ll 1 \quad (\eta = n - 1)$$

where δ is a fractional constant ($\delta \sim 0.9$) to ensure that the thresholds overlap. Starting with He results in the series of indices given in Table 2. The radiator materials listed are restricted to atmospheric pressure counters but include cryogenic vapors and liquids.⁹ Even with these materials, there is a hole in the K/p separation at $\gamma_t \approx 9$ ($p_K \approx 4.5$ GeV/c) which requires either a pressurized counter or discrimination by pulse height to fill.

Such a system is completely impractical for any solid angle larger than a fraction of a steradian for the following reasons.

1. The length of the overall system is too large. The counters in Table 2 contain about 8 m of radiator, exclusive of mirrors,

Table 2

Series of Threshold Cerenkov Counters for Total $\pi/K/p$ Separation Between 0.5 and 60 GeV/c at Atmospheric Pressure

$N_0 = 150/\text{cm}$ for 1 through 3 and 100/cm for the rest.

$(n - 1)$ $\times 10^{-4}$	N_e/m	γ_t	$L(>5 \text{ p.e.})$	(L/L_R) $\times 10^{-2}$	Possible radiator
0.35	1.1	120	5 m	0.1	He
1.00	3.0	71	1.7 m	0.02	Ne + N ₂ mix
2.80	8.4	42	0.6 m	0.02	He + N ₂ mix
8.10	16.2	25	0.31 m	1.0	Ne sat. vapor (27°K)
23.0	46.0	15	11 cm	0.9	H ₂ sat. vapor (20°K)
66.0	132	8.7	4 cm		(hole)
190.0	380	5.1	1.3 cm	0.17	He liq. (4.2°K)
540	1080	3.0	0.5 cm	0.3	Aerogel
			(10 cm)	(7.0)	
1530	3060	2.0	1.6 mm	1.1	Ar + Ne liq.
4350	8700	1.4	0.6 mm	0.4	LiF, CaF, MgF ₂

windows, thermal insulation, etc. In general, the length of a counter grows with the square of the threshold, i.e., for a gas counter with $\eta \ll 1$, the number of photoelectrons is

$$N_e = N_o L 2\eta ,$$

and the threshold is

$$\gamma_t \approx 1/\sqrt{2\eta} ,$$

so that

$$L = (N_e/N_o) \gamma_t^2 .$$

Also, since at pressure P

$$\eta(P) \approx P N_o ,$$

the pressure has to decrease with the square of the threshold,

$$P \propto 1/\gamma_t^2 ,$$

to get above 60 GeV/c.

2. The number of optically separate cells required for such a system will become very large at ISABELLE. For example, even in the most favorable location (90°), to get optimal information may require more than 800 cells per steradian per counter. A jet of 50 GeV/c total momentum will frequently have a leading particle of 25 GeV/c and next leading particle of 10 GeV/c. The angle between these particles, aside from any $p_\perp$ kick from the magnetic field, will be $\theta \approx 0.35/10 \approx 35$ mrad. Therefore, to have these particles separated in the Cerenkov counters requires the cells to be less than $\Omega \approx (0.035)^2$, which means more than 800 cells per steradian for each counter. A 4π detector with a complete system of Cerenkov counters would have 10^5 cells!

3. Such a system of counters will contain a large amount of material, due more to the windows, mirrors, etc., than to the radiators. The radiators in Table 2, which are for 5 photoelectrons, add up to 4% exclusive of the areogel, which realistically²⁸ will contribute about 7% itself. A real set of counters would have a large fraction of a radiation length of material. If the number of cells were anywhere near the number given above, this would not be too serious because the probability of confusion due to interactions would be low.

RATE CAPABILITY AND TRIGGERING

A system of multicelled threshold counters has an inherent high rate capability due to the speed and time resolution of PM

tubes and to the instantaneous nature of Cerenkov radiation. PM tubes can operate at $\geq 10^7$ /sec and give an event window of 1 to 2 ns. Microchannel plate tubes presumably can give a sharper time resolution but have reduced (unknown) rate ability. The time resolution may be limited by the light collection time, which in some cases can be as broad as tens of nanoseconds. Also, because of the lower momentum threshold, the rate that the counter sees is always less than the number of particles. The multiplicity capability is limited by the number of cells and the size of the Cerenkov angle. As previously discussed, this can be a serious problem in the ISABELLE environment because of high particle densities (jets) and high multiplicities.

The information from the threshold counters is of a "yes-no" nature and can therefore be processed in high speed logic and used for on-line event selection. Events with any particles above some threshold, or with a $K^\pm$ (or $p^\pm$) above some momentum, can be easily selected by correlating the cells in several counters. In principle, one can correlate the Cerenkov information with track chamber information (position and momentum) for second-level event selection. A RAM system such as that currently being used in the BNL MPS can make such correlations in about 300 ns.

RECENT DEVELOPMENTS AND NEW IDEAS FOR "CONVENTIONAL COUNTERS"

In the past few years a number of techniques have been developed which give improved quantum efficiency in conventional threshold Cerenkov counters. A number of groups have investigated the use of wavelength shifters on the photomultiplier tube windows.^{4,14} This technique extends the tube sensitivity into the ultraviolet by absorbing in the UV and reradiating in the visible. Since the light is reradiated isotropically, at best only 50% of the reradiated light can enter the PM tube. Even so, a gain in photoelectron emission of up to a factor of 3.4 over a standard glass PM tube can be achieved. Assuming that 50% of the reradiated light enters the PM tube, this result implies an effective cutoff of about 1100 Å. This means all components of the counter, i.e., radiator, mirrors, etc., have to be effective at 1100 Å to achieve this result. Quartz-faced PM tubes provide about a factor of three gain but extend to only about 2000 Å. The use of MgF_2 (or LiF) windows could give a factor of about 6.4 (7.0) with a cutoff of 1150 Å (1050 Å). See Fig. 2.

The use of a prism-face photomultiplier has been shown to yield quantum efficiencies as high as 40%¹⁹ by allowing the incident photons to reflect internally off the photocathode several times. Fig. 5 shows the quantum efficiency of an EMI 9558 Q/A photomultiplier with a MgF_2 window and S-20 photocathode with and without an enhancing prism. The cutoff of 2200 Å is due to the optical coupling of the prism to the tube face. Tubes can now be purchased with prism-enhanced windows.

A counter having MgF_2 -window PM tubes with prism enhancement, He, Ne, or N_2 gas (transparent at < 1200 Å), and one mirror with

Fig. 5. Quantum efficiency vs wavelength for EMI 9558 Q/A photomultiplier.¹⁹

80% reflectivity down to $\leq 1200^\circ$ could have $N_0 = 0.8$ (mirror) $\times 0.35$ (q.e.) $\times 3000$ (photon/cm) = 840.

Potentially N_0 could be improved by using photoionization proportional chambers^{1, 6, 7, 13} (discussed further below); $N_0 \approx 300$ is contemplated² and may be possible because of the large photoionization cross section of some gases. Additional benefits of this scheme are the relative ease in covering large areas and achieving large numbers of "cells" as well as being able to operate in high magnetic fields. The result is potentially a very compact counter covering a large solid angle in a magnetic field and capable of handling a high density of tracks. Such a system is being built for PEP.⁶

Another scheme for improving N_0 and achieving a high degree of segmentation for a threshold counter is to use panels made up of strips of plastic with wavelength shifter either coated on the surface or mixed into the plastic^{8, 10, 11, 29, 31} to collect the Cerenkov light. Figure 6 shows how this might be implemented. Such a counter would not need a mirror, thus the full spectrum of the radiator would be available. In the case of helium the absorptive cutoff is about 600 Å so that about 7000 photons/cm are emitted. If 30% are captured in the strips, the attenuation is 25%, and the quantum efficiency is 35%, then $N_0 \approx 550$. In addition, one could imagine a second layer with slightly shifted absorption and emission spectra (Fig. 6D) that would absorb the light lost out the back of the first layer. If this layer can capture 30% of this light, it has $N_0 \approx 165$. Figure 6E shows the imagined signal from a $\beta = 1$ particle. The spikes are due to the particle passing through the strips.

With N_2 for a radiator, $\lambda_c \approx 1100 \text{ \AA}$, so that a mirror could be used. $N_v \approx 3500/\text{cm}$, $e(\text{mirror}) \approx 0.8e(\text{q.e.}) \approx 0.35$, $e(\text{capture and transmit}) \approx 0.25$; thus $N_0 \approx 245$, yielding $N_{p.e.} = 7.4$ photoelectrons/meter in the first layer.

Fig. 6. Wavelength-shifter strip Cerenkov counter. (A) He counter with back plane of crossed wavelength-shifter strips. (B) and (C) Details of proposed scheme. (D) Absorption and emission spectra of vertical and horizontal strips. (E) Hypothetical signal from $\beta = 1$ particle.

IMAGING COUNTERS

Since Cerenkov radiation is emitted with a fixed angle, θ_c , with respect to the particle trajectory and a uniform azimuthal distribution, it appears to a focusing element as a ring source at infinity (see Fig. 7). The size of the ring at the focal plane is

$$R = f \tan \theta_c$$

where R is the radius of the ring, f is the focal length, and θ_c is the Cerenkov angle. Differential counters have for decades used this relation to determine particle velocities with very high accuracy $d\beta/\beta = 10^{-7}$, but only for particle beams with very small divergence. Recent developments in photon detection technology have made feasible virtually 4π steradian imaging counters that simultaneously measure the velocity of large numbers of particles over a wide momentum range.¹ A geometry for such a scheme is shown in Fig. 7. In this configuration a spherical mirror completely surrounds the interaction region (which is small compared with the radius of the mirror). A spherical photon detector sits at the focal "plane" of the mirror, $f = R/2$. All particles travel along

Fig. 7. Top: Focusing of Cerenkov radiation with a lens of focal length f . Bottom: Spherical imaging counter.

radii, and the Cerenkov radiation is focused onto the detector, which determines the x, y coordinates of each photon with high quantum efficiency. Differentiating the Cerenkov formula gives the obtainable precision of such a measurement:

$$d\beta/\beta = \tan\theta_c d\theta_c,$$

And, since

$$d\gamma/\gamma = \beta^2 \gamma^2 d\gamma/\gamma,$$

the energy (or mass or momentum) resolution is

$$d\gamma/\gamma = \beta^2 \gamma^2 \tan^2\theta_c d\theta_c.$$

For N detected photoelectrons, the error decreases by $1/N$, so that

$$\frac{d\gamma}{\gamma} = \frac{\gamma^2 \beta^2 n d\theta_c}{\sqrt{N} L} \approx \frac{\gamma^2 d\theta_c}{\sqrt{N} L} \quad (n \approx \beta \approx 1) \quad (2)$$

where we have used Eq. (1). The term $d\theta$ is the r.m.s. angular resolution due to all sources, including measurement error, chromatic dispersion, spherical aberration, multiple scattering, alignment errors, etc. For our purposes the measurement errors and the chromatic dispersion are the dominant effects. Measurement errors due to the detector resolution contribute

$$\Delta\theta_m \approx \Delta R/f \quad (n \approx \beta \approx 1)$$

and dispersion in the refractive index of the radiator contributes

$$\Delta\theta_D \approx \frac{1}{2} \theta_c \omega \quad (n \approx \beta \approx 1)$$

where

$$\omega = \frac{\eta(\lambda_1) - \eta(\lambda_2)}{\eta_{av}}.$$

Table 3² gives, for several gases of interest, values of ω and also the effective frequency cutoff.

Even though $\Delta\beta/\beta$ is more directly given by the Cerenkov formula and $\Delta\gamma/\gamma$ is very nonlinear, i.e., $\propto \gamma^2$, Eq. (2) is very useful because, if the momentum is known, then $\Delta\gamma/\gamma = \Delta m/m$. It is also interesting that for gases (where $n \approx 1$) Eq. (2) is (to within dispersive effects) independent of the refractive index.

Imagine such a counter with spatial resolution $\sigma_x = \sigma_y = 0.5$ cm, having N_2 at NTP as a radiator, and assuming $N_0 = 150$. Since $\eta(N_2) \approx 3 \times 10^{-4}$, there are 9 photoelectrons/m. Take $l = 2$ m, then $N_e = 18$.

Table 3		
Gas	$w(1900-5200 \text{ \AA}), \%$	$\lambda(50\%), \text{ \AA}$
He	4.5	600
Ne	4.8	~ 1200
N ₂	12.0	~ 1100
H ₂	16.5	~ 1700

$$\theta_c = \sqrt{2\eta} = 24.5 \text{ mrad} ,$$

$$\Delta\theta_m = \Delta R/f = 2.5 \text{ mrad} ,$$

$$\Delta\theta_w = \frac{1}{2}\theta_c w = 1.47 \text{ mrad} ,$$

$$R = 4.9 \text{ cm. for } \beta = 1 ,$$

$$\frac{\Delta y}{y} \approx \frac{y^2}{\sqrt{N_0} L} \frac{\Delta R}{f} = 1.68 \times 10^{-5} y^2 .$$

To have $\Delta m/m \geq 0.2$ gives $\gamma_{\max} = 108$; $\gamma_t \approx 1/\sqrt{2\eta} = 41$, so that $\pi/K, p$ separation is good from $p_{\min} \approx 55 \text{ GeV/c}$. Complete separation exists between 20 and 55 GeV/c, and $\pi, K/p$ separation extends to 102 GeV/c. If ΔR is reduced to the point where $\Delta\theta_m \ll \Delta\theta_w$ so that dispersion is the dominant effect ($\Delta R \leq 0.5 \text{ mm}$), then $\gamma_{\max} \approx 152$ and π/K separation extends to about 75 GeV/c. Figure 8 shows the radius of the ring for π, K , and p versus momentum with the resolution indicated by error bars. The left side of Fig. 9 shows how rings would appear on the detector with 0.5-cm resolution, and the right side shows the separation of the π and K hypotheses for $p = 50 \text{ GeV/c}$.

The center of each ring is known from external track chambers, as well as the momentum for each track. Thus the pattern recognition problem reduces to deciding which hit belongs to which track and then testing mass hypotheses. This conceivably could be done by a specialized processor, which would provide second-level event selections on-line. Such a detector is obviously very powerful, but many problems must be overcome before a practical system is made: How can we construct a cost-effective detector with high efficiency ($N_0 \geq 100$, preferably >200 or 300), good x, y spatial resolution (~ 0.1 to 1.0 cm) with $\sim 10^8$ elements/ m^2 of detector, good time resolution (to live in ISABELLE environment $\leq 100 \text{ ns}$), long life, etc.

Next we discuss several schemes that are being worked on in an effort to solve these problems.

Fig. 8. Radius of Cerenkov ring vs momentum using N_2 at NTP and assuming $N_0 = 150$. $\Delta R = 0.5$ cm, $L = 2.0$ m, $f = 2.0$ m, $\Delta\theta_w = 1.5$ mrad, $\Delta\gamma/\gamma(50\text{-GeV/c kaon}) = 17\%$, $n = 2.97 \times 10^{-4}$.

$$\Delta R = (\Delta\theta_m^2 + \Delta\theta_w^2)^{1/2} L / \sqrt{N}.$$

PHOTOIONIZATION

The possibility of making an imaging Cerenkov counter using large arrays of photoionization cells was suggested and analyzed a few years ago by Seguinot and Ypsitantis¹ in a paper giving many details of such a scheme, and recent work is reviewed in detail by Durkin et al.³⁷ (see also refs. 5, 13, 34). Therefore we give here only a summary of the basic ideas, virtues, and limitations of photoionization techniques insofar as they might apply to ISABELLE.

As mentioned earlier, there are a number of reasons why photoionization detectors may offer substantial improvements in Cerenkov counter techniques. First and foremost is the possibility of achieving the high two-dimensional spatial resolution necessary for an imaging device. Second, and perhaps independent of the first, is the hope of improving the number of detected photoelectrons per unit length, N_0 , both by using materials with very high quantum efficiency and by working (of necessity) at the UV end of the spectrum where Cerenkov radiation is more copious. Third, because wire proportional chambers, drift chambers, etc., are inherently "fine grained" compared with PM tube systems, the number of cells can be increased dramatically, and hence the counter can be used in a much higher density environment (ISABELLE). In addition, a number of potential improvements might be realized,

Fig. 9. Left: Pattern of hits for three overlapping particles in the counter described in text. Cell size is 0.5×0.5 cm; $N_{p.e.} \approx 18$. Right: Expanded view showing the difference between pion and kaon hypotheses.

such as insensitivity to high magnetic fields, more compact counters with improved light collection over large solid angles, reduced cost per steradian coverage, etc.

The basic idea is to use a gas or vapor that has a large photoionization cross section and a sufficiently low PI threshold as an admixture to the gas of a proportional (or Geiger) chamber. Cerenkov radiation entering the chamber creates photoelectrons in the gas which are then amplified and detected. The basic components of such a counter are shown in Fig. 10. Figure 2 shows the spectral response of various materials in the region of interest. Because the photoionizing agent must not poison the PWC, only a very limited number of potential materials can be used. So far the only gas that has been found to work is benzene (C_6H_6). Its photoionization threshold is about 9.2 eV (1350 Å), and hence all the components of the chamber counter have to work in the far UV. This severely restricts the possible radiator materials to the few solids (e.g., LiF, MgF_2), liquids, as gases (e.g., N_2 , He, H_2 , Ar, Ne) that are transparent below 1350 Å. If materials with PI thresholds down to

Fig. 10. Photoionization imaging Cerenkov counter.

6 eV ($\sim 200 \text{ \AA}$) can be made to work, then the heavier noble gases (and liquids) and a few other materials can be used. Almost all materials are very dispersive in this region, which will limit the spatial resolution and smear the threshold.

As can be seen in Fig. 3, for a combination of benzene and MgF_2 there is a useful window between 1150 and 1300 $\text{\AA}$. Within this window the number of photons emitted is about $460L\sin^2\theta_c$ (about equal to the number between 3500 to 5500). Folding together the various efficiency factors,

$$\begin{aligned} \epsilon_{\text{mirror}} &\approx 0.75, \\ \epsilon_{\text{window}} &\approx 0.45, \\ \epsilon_{\text{benzene}} &\approx 0.5, \\ \epsilon_{\text{cathode grid}} &\approx 0.9, \\ \text{Total efficiency } \epsilon &\approx 0.15, \end{aligned}$$

yields a value of $N_0 \approx 70$ photoelectrons per cm. Chapman et al.⁵ report, for this counter configuration, $N_0 \approx 50$. The difference is apparently due primarily to the benzene in their chamber causing "photon feedback," forcing them to run at about 150 V lower than without benzene and thus reducing the single-electron detection efficiency.

Although the value $N_0 \approx 50$ is considerably lower than what can be achieved with PM tubes with wave shifter ($N_0 \approx 150$ to 170), it is sufficiently high to make useful threshold counters having the virtues of high segmentation and insensitivity to magnetic fields. Improving the sensitivity of the electronics could give 25% gain. By using an LiF window and LiF-coated mirror, an He or Ne radiator could give an improvement of about a factor of 2 ($\lambda_{\text{cutoff}} \approx 1025 \text{ \AA}$). A big improvement requires pulsing the PI threshold to lower energies. The number of photons emitted is proportional to the width of the window (in energy units) so that

going from $\Delta E = 1.6$ eV to $\Delta E = 5$ (1130 to 1725 Å) obviously gives a factor of three. Thus, potentially $N_0 \approx 300$ can be achieved.

CCD READOUT

The development in recent years of charge-coupled device (CCD) arrays makes possible another method of constructing an imaging Cerenkov counter.²⁹ The CCD is an array of photosensitive elements that are capable of converting incident light to a proportional quantity of stored charge. This charge can be transferred from one element to the next or to special transfer registers and serially clocked to an output amplifier where it appears as an analog pulse proportional to the light that fell on a particular element during the time the photogate was open. CCD arrays of more than 40,000 elements (e.g., CCD211 has 46,360 sites) are on the market. The CCD elements (photosites) are typically about 2×10^{-8} cm² and are precisely located on the chip so that, if the Cerenkov ring can be focused on the array, precise spatial localization of each photon (with some quantum efficiency, to be discussed below) appears possible. Clock rates of up to 20 MHz are available. Because of their many applications, CCDs are being rapidly developed for improved speed, size, and sensitivity. In addition, CCDs can be purchased (e.g., from ITT) permanently coupled to image intensifiers which give as much as 10^3 gain in sensitivity.

The principle of operation of a CCD is briefly described below. Many such devices are available from a number of manufacturers, each with its own specialized characteristics, but the discussion here is restricted to a particular one, the Fairchild CCD211, having characteristics appropriate to our application.³⁶

The CCD211 is an array of 244 horizontal lines by 190 vertical columns. The 46,360 image-sensing elements are 14 μ m horizontally by 18 μ m vertically and are located on 30- μ m horizontal centers and 18- μ m vertical centers. The image sensing-area is 4.4x5.7 mm. Parallel to each vertical column is an analog transport register, and these 190 vertical registers join one horizontal analog transport register. Figure 11 shows a block diagram of the layout and details of an individual photosite. Each photosite has an area of about 2.5×10^{-8} cm², and about an equal area taken by the transport registers, so that about half of the image area is active.

In the standard mode of operation, incident light impinging on a photosite while the photogate is open creates electron-hole pairs. The resulting photoelectrons are collected in the photosite, and the total accumulated charge is a linear function of the incident luminous flux. Figure 12 shows the spectral response of this device. At the end of the integration period, alternate lines of charge packets (i.e., odd-numbered photosites in each column) are transferred to the vertical transport registers. Then each line is transferred to the horizontal transport register and serially transported to the output amplifier. This process takes 190 clock cycles for each of 122 lines, or 23,180 cycles; at 15 MHz this takes a minimum of 1.55 ms. At the end of this cycle, the

Fig. 11. Top: Block diagram of Fairchild CCD211.
Bottom: Photosite dimensions.

Fig. 12. (A) Spectral response of CCD211. (B) Curve of constant (relative) quantum efficiency. (C) Relative emission spectrum of BBQ phosphor.

even-numbered lines are transported to the output. The total readout time is about 3.1 ms, which limits the total number of events to about 300 per second. In this mode of operation the photogate is open during all but the time needed to transfer the charge from the photosites to the transport registers. Integration times of about 100 ns are perhaps feasible, as discussed further below. During this time all interacting particles above threshold in the counter will be recorded. Thus, the rate for events producing particles above threshold in the counter would have to be ≤ 10 MHz. There are many applications when this is the case such as in high p_1 events in the wide-angle hall, high X events in the small-angle hall, etc.

The sensitivity of the CCD211 is typically $0.2 \mu\text{J}$ per cm^2 for saturation, with an output signal of $1 \text{ V}/\mu\text{J}$ per cm^2 . Since an individual site has an area of about $5.4 \times 10^{-6} \text{ cm}^2$ (of which about half is live), the output is 0.185 V/pJ per site, which gives about 75 nV per incident photon at 5000 Å. The dark current is rated at 0.6 nV at 25°C running at 7.0 MHz, i.e., with an integration time of 3 ms. If the integration time is reduced to 100 ns, the dark signal will be reduced by a factor of 3000, which will leave it still almost 3 times the single-photon signal. Since the dark current is an exponential function of temperature, it can be reduced by a factor of 10 for each 25° to 30°C reduction of temperature. Thus, to get the dark signal down to the single-photon level requires reducing the temperature to 0°C and reducing the integration time to about 100 ns. An image intensifier such as the ITT F-4130 can give a factor of 1000 in gain with only a 25% reduction in resolution.³⁰ Whether the phosphor on the image intensifier can give such a high gain in 100 ns is not clear; if

it can, such a combination would give a single-photon signal of 75 μ V with a dark signal of 0.02 μ V.

The ITT image intensifiers can be supplied with quartz, MgF₂, or fiber optics* windows and UV-sensitive photocathodes such as CsTe and CsI as well as Be-alkali, S-20, S-11, etc.

MICROCHANNEL PLATE PHOTOMULTIPLIER TUBES

Microchannel plate PM tubes² (see Appendix D-II) with segmented anodes are ideally suited for imaging Cerenkov counters in the ISABELLE environment because of their excellent spacial and temporal resolution. The large number of individual channels presents a serious electronics challenge but allows a very high multitrack capability. Channel plate photon detectors with cross wire grid anodes have been built with single-photon spatial resolution of 10 μ m,^{6,32,33} and, as is true of channel plate image intensifiers, can be made with standard photocathodes, quartz or MgF₂ windows, etc. Problems of lifetime, quantum efficiency, and cost appear to be improving, which leaves the main problem of dealing with tens of thousands of individual anodes from which time and pulse height as well as "on-off" information may be necessary. Perhaps many channels can be connected to a delay line and serially read out. Or perhaps an LSI chip can be developed, somewhat like a CCD (without optical coupling), that can reduce the data to a more manageable form without sacrificing too much speed, etc. Whether the channel plates can be operated at high rates with sufficient gain to avoid additional amplification is also not clear.

Assuming the simplest mode of operation, in which each incident photon typically results in a pulse at only one anode, and only "on-off" information is required, one can imagine using a cluster of tubes, say 1x1 m (70 five-inch tubes or 220 three-inch tubes, etc.), with 1x1-mm anodes ($\sim 10^6$ channels) on which the images from many m² areas of mirrors are overlapped (Fig. 13). If each particle produces about 20 photoelectrons, then there could be 50 particles above threshold in this solid angle simultaneously, and the "hit" density will still be only $\sim 10^{-3}$.

OTHER (FAR-OUT) POSSIBILITIES

If avalanche photodiodes (APDs) become very inexpensive and can give reasonable quantum efficiency for a small number of photons, then one can imagine an image detector made up of a mosaic of small squares of wavelength-shifter doped plastic, each

Note that use of wavelength shifters on the intensifier window necessitates using a fiber plate window to retain the resolution. It is not clear under these conditions that there is an overall gain, since only a rather small fraction of the reradiated light will be transmitted.

Fig. 13. Optics for using channel plate PM tubes in an imaging counter.

with an APD. The detector would, as with microchannel plate tubes, sit at the focus of the mirrors and have overlapping images focused out of it. If the diodes need to operate at reduced temperature, the whole counter could be at liquid nitrogen temperature (77°K) and would have an index of $(n - 1)$ roughly 3.5 times that at room temperature: $\eta \approx 10^{-4}$. As previously discussed, the wavelength cutoff of helim is about 600 Å, so that, at the expense of resolution due to dispersion, a very high value of N_0 is conceivable. If $N_0 = 300$, we get 3 photoelectrons/m. Obviously many details have to be worked out, but such a system, if feasible, has many virtues.

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