Performance Characteristics of Large Aperture, Ten-Cell,
Atmospheric Pressure Isobutane γ Cerenkov Counters

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ABSTRACT

Two large aperture, 10 cell atmospheric-pressure isobutane γ Cerenkov counters were designed and constructed for a SLAC streamer chamber experiment. The rejection efficiencies for a 9 GeV/c π^- were measured to be $99.848 \pm .006\%$ and $99.717 \pm .008\%$ for the two counters. The design details and performance characteristics are discussed.

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I. Introduction

Due to the simplicity in concept and design, threshold Čerenkov counters have become an indispensable part of many large multiparticle detector systems. In this paper, the design and the characteristic performance of two identical large aperture, 10-cell isobutane Čerenkov counters are presented. The counters were designed for a streamer chamber experiment to study the production mechanism of ϕ -meson in π^+p interaction at 16 GeV/c. The reaction of interest is

with no trigger restriction intended for associated secondary particles produced with the ϕ -meson.

To suppress the secondary K^+ flux from associated strange particle production, the K^- particle was chosen as the trigger in the experiment. The experimental set-up is shown in Figure 1. The K^- produced in the 61 cm. long liquid hydrogen target in the Stanford Linear Accelerator Center 2-meter streamer chamber was momentum defined by four planes of picket fence counter arrays V_1 , V_2 , V_3 and V_4 . The counter arrays are deployed on the left side of the beam line between 2 and 6.25 m downstream from the center of the streamer chamber and the logic associated with the arrays selects negative particles with a minimum momentum of 2.50 GeV/c. The mass identification was achieved with the aid of one large aperture 10 cell isobutane Čerenkov counter placed between the V_3 and V_4 planes. Another identical Čerenkov counter, placed on the right side of the beam line served to tag the K^+ from the ϕ -decay. Since the background trigger rate due to π^- particles was estimated to be some 132 times that due to a legitimate K^- particle, a rejection efficiency of 99.9% against pions was considered the prime goal in the design of these counters. A

secondary, nonetheless crucial, consideration was cost. A limit was set at twenty-five thousand 1977 dollars for the two counters. Both efficiency and cost goals were met. In Section II, the mechanical design of the counter tank, the gas delivery, control and monitoring system is discussed. The light collection and the related optical system are presented in Section III. The mounting and shielding of the photomultiplier tubes are detailed in Section IV. The performance characteristics and the analysis of the test data comprise Section V.

II. Physical Configuration and Gas System

The physical configuration of the Čerenkov Counter is shown in Figure 2. The counter is 2.25 m long and has an entrance aperture of 1 m high and an exit aperture of 1.5 m high by 1.75 m wide. The windows are made with two layers of a 3 mil thick aluminized mylar and two layers of a 4 mil thick polyethelene film. Since the counters were designed to operate with an isobutane gas, it was vitally important that the tank be capable of sustaining overpressure in order to prevent accidental backfilling which could lead to an explosive mixing with air. The high tensile strength of mylar plus the opaqueness of black polyethelene film provides of an excellent combination for a light-weight window material. The tank, with the exception of two 1/4" aluminum plates supporting the ten phototube-Winston collector-cone assemblies, was constructed with 1/8" aluminum sheets and extruded aluminum channels. Each of the ten phototubes, with its associated cone was responsible for monitoring the Čerenkov light produced by charge particles entering the entrance window and collected by one of the ten mirrors.

The counter has an interior volume of some 5.7 m³. A gas manifold and a gas sampling port are provided on the top as well as on the bottom of the tank. Since the isobutane is denser than the air, the gas was introduced via the bottom and exhausted via the top manifold systems. A small quantity of the gas was drawn continuously from the sampling port at the top of the tank and processed through a laser interferometer of the Rayleigh type. The interferometer was composed of two gas cells of 6.35 cm in length. One of the cells was evacuated. The sample cell could be switched manually between vacuum and the isobutane gas from the counter. The number of interference fringes generated using a Ne-He laser ($\lambda = 6328 \text{ \AA}$) is equal to $(n - 1) \times 10^5$, where n is the index of refraction of the gas. The fringe count was registered by a locally designed up-down counter and CAMAC logic unit and was recorded for every

streamer chamber trigger. An index of refraction measurement during one of the isobutane filling operation's is shown in Figure 3 as solid dots. The isobutane gas was introduced from the bottom of the tank and the interferometer samples gas from the top of the tank, the curve indicates that a typical fill time is about four hours. The bulk of the isobutane is normally in a liquid state. The depletion rate of the supply is measured by weighing the isobutane bottle. The weight measurement is also shown in Figure 2 as open circles. About 45 lbs. of isobutane was used for each filling.

III. Light Collection and Optical System

The Čerenkov radiation produced by the charge particles entering the upstream window was viewed by a system of ten 73.8 cm high acrylic mirrors. The widths of the mirrors, four each of 37.80 cm and 30.71 cm and two each of 27.59 cm, were tailored specifically to the geometry of the experiment. The light focussed by each mirror was further concentrated into a 12.5 cm spot using a 2.5X Winston cone¹. The mirrors as well as the cones were manufactured by the Plastic Shop at Argonne National Laboratory.

The mirrors are pressure formed with 1/4" acrylic sheets in a heat chamber to a nominal radius of 2 m. The blanks were then coated with a thin aluminum film by means of evaporation in a vacuum chamber. The bank of ten mirrors was deployed in the form of a 2 x 5 matrix 2 m downstream from the entrance window. The mirrors were responsible for focussing Čerenkov light into one of the ten Winston cones. The cones have an opening diameter of 25 cm at the entrance and 11.5 cm at the exit and are made by successive build-up of epoxy resin layers on a spinning aluminum mold. When the thickness reached 1/8 inch, the cone was heat-released and coated with a layer of lacquer and then aluminized in a vacuum chamber. A UVT-lucite plano-concave lens was afixed to the exit end of the cone. The flat side of the window is coated with a wavelength shifter, paraterphenol which served to convert the primarily ultraviolet Čerenkov radiation into a visible light², thus improving matching with the frequency response characteristics of phototubes having glass windows. The concave side of the lens had a radius of curvature of 12.95 cm matching that of the front window on a RCA 4522 phototube. The lens was held between two aluminum rings. The ring closer to the phototube was electrically connected to the photocathode potential and mechanically fastened using 1/4-mch G-10 threaded rods to the other ring which, in turn, was glued to the Winston cone and was electrically grounded. The space between the two rings, (5/8" thick) was filled with a black

silicone rubber material which, in addition to being a light shield also served to remove the surface potential gradient from the photocathode of the phototube.

IV. Magnet Shielding Design Considerations

While magnetic shielding of the 5-inch phototubes is, in general desirable and necessary to ensure optimum efficiency of collection of the relatively few photoelectrons in the presence of the earth's magnetic field, it was essential in this experiment. It is known that the SLAC streamer chamber magnet had an expected stray ambient field of about 50 gauss, and the field was known to lie skew to the phototube axes and thus to require compensation of both parallel and transverse components. The compact and lightweight construction of the Čerenkov counter tank, with the phototubes externally mounted on relatively brittle epoxy Winston cones, effectively precluded conventional solutions in the form of massive solid-iron shielding of either the individual tubes or the entire detector. These would have been expensive in any case. In addition, the mounting of these massive iron shields would have interfered with adjacent counter elements. Consequently a relatively light and inexpensive multi-layer shield was developed to cover the individual phototubes and the associated Winston cones.

The primary shield element was cylindrical with an outside diameter 30.5 cm and length 76.2 cm. The inside diameter is 17.8 cm and was tapered down gradually from one end to an inside length of 43.2 cm to accommodate the Winston cone while providing maximal shielding coverage of the area of the photocathode. The other end was flat. The structure was composed of eleven thin concentric cylinders of successive radii differing by 0.63 cm. The individual cylinders were formed from sheets of transformer iron (an un-oriented electrical steel) of thickness 0.58 mm which were cut to size while flat, rolled to an approximate diameter, and then riveted to more exact diameter while mounted on a simple jig, with about 1.9 cm overlap. The final structure was then assembled using at each end four radial strips of aluminum in which appropriate saw cuts had been made to receive the edges of the respective cylinders. These maintained the appro-

priate spacings in an overall conformation of the assembly. Longitudinal seams were at the same azimuth to permit alignment parallel to the field. These spacers were then glued with epoxy resin. The final unit weighed about 24 kg. This weight, and the simple cylindrical outer shape, made it possible to mount and dismount the shield manually and individually from the concentric phototube and inner shield assembly by simply resting the former on parallel rails made of an aluminum channel and sliding it off longitudinally whenever interior access was required.

The transformer iron used was a mixture of ARMC0 - M-19 and M-36 steels, expected to have a permeability of the order of 500 at field of a few tens of gauss, a coercive force of less than 1 Oersted, and to saturate at about 20 kgauss. In the present shield design it is thus a very convenient compromise between cold-rolled steel, with a permeability of about 180, and mu-metal and similar expensive alloys which have much higher permeability but saturate at about 1/4 the field. Indeed, saturation will in any case limit the utility of thin high-permeability shields in ambient fields above a few gauss. While some improvement might have been obtained using a grain-oriented steel instead of the un-oriented transformer iron, the additional expense and complex annealing required to realize the 2-3-fold higher permeabilities after fabrication were not deemed to be necessary for the present system. An exact calculation based upon 11 infinitely long concentric cylinders of the sizes used and a constant permeability of 500 indicated that a 50-gauss transverse field would be reduced to 0.8 gauss inside, with a maximum induction of 5460 gauss in the sides of the outer cylinder. Thus, the design appeared to be conservative magnetically, as well as in cost and weight.

The phototube itself was mounted inside a separate mu-metal shield of diameter 14 cm which extended backwards 30.5 cm from the region of the photocathode, with an additional 14 cm at a reduced diameter. This shield also

formed the mechanical and optical enclosure of the phototube, and contained within the base and resistor string as well as the phototube itself. With an outside diameter of 16 cm, this assembly permitted removal of the 17.8 cm inside-diameter outer shield unit, described above. The exact calculation for the magnetic shielding by an idealized outer assembly indicated that the addition of this inner mu-metal shield, with presumed permeability of 20,000, would further reduce a 50-gauss external transverse field to about 12 milligauss, with at most 237 gauss induction in the mu-metal. Although these calculations did not reflect in detail either the complex dependencies of permeability upon the field, or the end-effects of the geometry used, they did provide grounds for confidence that the overall structure would give a satisfactory reduction of the transverse component of the external field.

The longitudinal field component, whose approximate effect was expected to be the longitudinal polarization of the inner mu-metal shield surrounding the phototube, was compensated by winding a coaxial bucking coil of 120 turns of an insulated wire (AWG #18 & #20) on the outside of this inner shield to achieve a bucking field of about 0.09 gauss/ampere-turn inside the phototube. The actual bucking current for each tube was established empirically by maximizing the pulse height with the external magnetic field present. The currents required ranged between 0.3 and 1.8 amperes for the 20 phototubes used on the two identical Cerenkov counters in this experiment.

V. Performance Characteristics and Analyses of Test Data

During the testing run period, a 9 GeV/c π^- beam is used to measure the efficiency of each of the twenty cells with an atmospheric pressure isobutane filling. At each of the four crossing points on an imaginary 3 x 3 grid that divided the useful area of a mirror surface into nine equal sectors, the probability that a Čerenkov signal from a beam particle traversing the Čerenkov counter is measured using the logic

$$\pi^- \cdot \check{C} \cdot S_6 / \pi^- \cdot S_6 \quad (2)$$

where π^- is a logic signal for a 9 GeV/c π^- entering the streamer chamber. The counter S_6 is an 1" x 1" square scintillation counter of 1/4" thickness and is placed downstream of the Čerenkov counter. The logic $\pi^- \cdot S_6$, therefore defines a π^- particle traversing the Čerenkov counter. The efficiency data ranges from 98.8% to 100.0% for the eighty points measured. These results are combined for each mirror and are tabulated in Table I. Averaging over the ten cells in each of the Čerenkov counters, the overall efficiencies are $99.848 \pm .006\%$ and $99.717 \pm .008\%$ for the K^- and K^+ Čerenkov counters respectively.

Since no wide variations in efficiencies are observed among the cells, one was chosen at random for the study of the photoelectron statistics. Figure 4 shows a sample pulse height spectrum from one of the cells in the K^- Čerenkov counter for a 9 GeV/c π^- beam.

The spectrum exhibits a sharp rise from zero to a maximum near channel number 500. From there, the spectrum declines sharply and is followed by what resembles a shoulder in the region of channel number 800. Due to the long decay time of the RCA 4522 phototube pulses, a 300 nanosecond gate was used in the pulse height analyzer. The shoulder in Figure 4 is believed to be due to a second pulse occurring within the gatetime of the previous pulse. For the purpose of this analysis, cuts are made on the data. Only events between channels 110

and 630 are used. The channel number has been corrected for the internal pedestal of the pulse height analyzer. Fitting to the Poisson distribution, a mean value of 17.2 ± 0.1 is obtained. The predicted distribution is shown as the solid curve in Figure 4. Since the statistical fluctuations due to the dynode multiplication add to that due to the photoelectric effect at the cathode, the mean value obtained using a simple Poisson distribution should be viewed as a lower limit of the photoelectron statistics.

The analytic form of an experimentally observed pulse height spectrum and its implication on the photoelectron statistics have been studied by a number of authors³. It is generally believed that a simple Poisson distribution cannot adequately account for the observed spectra. In particular, the single photoelectron spectrum does not always exhibit a clear peak as is expected from Poisson statistics for a mean value of one. In a number of cases, the spectra resembles that of an exponential function. The actual explanation for such behavior may be complex, however, it is not difficult to comprehend some of the dynamic factors involved in the collection and multiplications of the few photoelectrons produced by the photocathode. For example, the collection efficiency of the primary photoelectrons by the first dynode depends on the local electric field shape, thus the probability of secondary electron emission may vary across the surface of a dynode. Similar dependence may also be expected in electron multiplications in latter dynodes. To account for these non-Poissonian effects, it was suggested that instead of a conventional fit to the Poisson distribution, one may adopt the use of the Polya distribution:

$$P(\mu, n) = \frac{\mu^n}{n!} (1 + b\mu)^{-n-1/b} \prod_{i=1}^{n-1} (1 + ib) \quad (3)$$

where the quantities n and μ are the expected and the mean number of secondary electrons emitted due to a single electron hitting the dynode. The parameter b is to be determined using experimental data. The Polya distribution approaches

Poissonian as b tends towards zero and becomes a monotonically declining function of n as b approaches unity. The experimentally observed pulse height spectrum from a photomultiplier tube of k -stages may be compared with a k -fold convolution of equation (3). In this work, RCA 4522 phototubes were used. The tube has 14 stages with an expected overall current amplification factor of 3×10^7 , corresponding to an average per-stage gain of 3.42. Due to the stochastic nature of electron multiplication, to fit the observed spectrum using the conventional least squares method requires an enormous amount of computer time. However, it is apparent that with the exception of the two tail regions, the pulse height spectrum shown in Figure 4 can be well approximated by the Poisson distribution as is evidenced by the fitted curve discussed earlier. Therefore, the shape of the spectra can be well represented by a single parameter, $\sqrt{\sigma}/\bar{N}$ where the quantities $\bar{N}$ and σ are the mean and the variance of the spectra. In the case of a pure Poissonian distribution, the ratio $\sqrt{\sigma}/\bar{N}$ can be approximated by $(\bar{N})^{-1/2}$. It should be noted, however, the quantity $\bar{N}$ is not the same as the averaged number of photoelectrons emitted by the photocathode. The fact that the average per-stage gain is only 3.42 suggests that the statistical fluctuation observed at the fourteenth dynode is the end product of the photocathode statistics broadened at each succeeding dynode stage due to the stochastic nature of secondary electron emission. The ratio is expected to approach a constant value with later stages of the dynode. Using the Monte Carlo technique, it was determined that for the mean number of photoelectrons between 20 and 65, the ratio $\sqrt{\sigma}/\bar{N}$ reaches within 0.1% of its asymptotic value before the sixth dynode. For the remainder of the paper, a seven fold convolution of the Polya distribution is adopted as a standard practice. Figure 5 shows the expected ratio $\sqrt{\sigma}/\bar{N}$ as a function of the parameter b for averaged numbers of photoelectrons between 25 and 65. As may be expected, a larger value of b effectively broadens the pulse height spectrum in a manner similar to that caused by low photoelectron statistics.

Applying the same cuts to the data, the ratio $\sqrt{\sigma}/\bar{N}$ for the observed spectrum is found to be 0.245. Since the value of b is between 0 and 1, this indicates that the true average number of photoelectrons from the photocathode is between 25 and 45. The higher values of $\bar{N}$, corresponding to a large value of b , are expected to be accompanied by an exponential pulse height spectrum, which is inconsistent with the observed spectrum. For lower values of b , the Monte Carlo results suggest an $\bar{N}$ value between 25 and 35. In order to determine the value of b independent of $\bar{N}$, it is necessary to deal with data of known $\bar{N}$ value, for example, the single photoelectron data, which is not available here. For the remainder of the analysis, it is assumed that $b = 0$, or, the Poisson statistics dominates the photoelectron production at the photocathode as well as the electron multiplication by the dynodes. Figure 6 shows the expected ratio of $\sqrt{\sigma}/\bar{N}$ as a function of $\bar{N}$. The observed value of 0.245 corresponds to an $\bar{N}$ of 21. Using the standard formula of

$$\bar{N} = A \lambda \sin^2 \theta \quad (4)$$

the data suggests a value of 44 for the parameter A . The result compares well with that obtained by other large aperture Čerenkov counters⁴⁻⁸.

Several known factors contributed to the rather low value of A as compared with what can ultimately be achieved theoretically, i.e., $A = 226$. These factors are listed below: (a) The residual magnetic field at the phototube may have contributed to some loss of electrons. Since the μ -metal shields were not specifically designed for the set-up, the upstream ends of the shields were about even with the photocathode, leaving the task of reducing the rather high stray field of the streamer chamber magnet to the multi-layer laminated iron shields. (b) The optical quality of the mirrors is not the best possible. The rather thin layer of the evaporated aluminum film on each mirror contributed to a loss of Čerenkov light. However, it must be pointed out that the counter performance satisfies the original stated goal. The cost for the

construction of these two counters amounts to twenty-one thousand 1977 dollars, and the rejection efficiency against a fast pion is consistent with a goal of 99.9%.

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TABLE I.

Pion Rejection Efficiency

<u>Cell No.</u>	<u>K⁻ γ Cerenkov Counter</u>	<u>K⁺ γ Cerenkov Counter</u>
Upper 1	99.78 $\pm$.02%	99.57 $\pm$.03%
2	99.82 $\pm$.02	99.62 $\pm$.03
3	99.89 $\pm$.02	99.75 $\pm$.03
4	99.84 $\pm$.02	99.42 $\pm$.04
5	99.84 $\pm$.02	99.83 $\pm$.02
Lower 1	99.85 $\pm$.02	99.74 $\pm$.02
2	99.80 $\pm$.02	99.78 $\pm$.02
3	99.88 $\pm$.01	99.87 $\pm$.02
4	99.88 $\pm$.02	99.89 $\pm$.01
5	99.88 $\pm$.02	99.78 $\pm$.02
Average	99.848 $\pm$.006%	99.717 $\pm$.008%

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FIGURE CAPTIONS

Figure 1. Experimental set-up at the SLAC streamer chamber facility.

Figure 2. An artist's conception of the Čerenkov counter.

Figure 3. A typical curve of index of refraction measured during one of the gas filling operations. The open circles show the weight of the isobutane bottle during the filling operation.

Figure 4. A sample pulse height spectrum from a 9 GeV/c π^- beam.

Figure 5. The expected ratio of standard deviation to mean of the pulse height spectrum as a function of the parameter b for various mean numbers of photoelectrons.

Figure 6. The expected ratio of standard deviation to mean of the pulse height spectrum as a function of the mean number of photoelectrons for $b=0$.