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1 Introduction

Threshold Cherenkov counters are widely used in experiments of Nuclear and High Energy physics for particle identification. Conventional Cherenkov counters has limited spectral sensitivity, usually due to the ultraviolet (UV) transmission cut-off of the window material, which separates the region where Cherenkov light is generated by particles from the region where photo-detectors are situated. This limitation often leads to a poor detectable Cherenkov light yield and imposes an increase of the radiator length, e.g. Cherenkov He radiators of about 10 m length have already been used. The hadron rejection efficiency of conventional Cherenkov counters are usually limited by the emission of delta-rays.

We have been developing a novel threshold Cherenkov detector, consisting of a gas radiator followed by a UV photosensitive wire chamber using CsI photocathodes. The photo-detector lies directly in the particle path and is thus required to have single photo-electron sensitivity and yet to be insensitive to the passage of a charged particle. In addition, the detector should be made of low mass material to minimize the effect of multiple scatterings.

CsI photocathode has high quantum efficiency (Q.E.) in the UV region (35–40% at 170 nm and even higher at shorter wavelengths). Large number of CsI detectors can be mass produced in the form of either one dimensional strips or two dimensional pads to allow the measurement of electron trajectories.

The proposed threshold Cherenkov counters are called Hadron Blind Detectors (HBDs) because they are blind to low energy hadrons which have lower speed β for given momentum p than that of electrons. HBDs can be used in colliders, especially heavy ion hadron colliders (RHIC, LHC), which have huge # of hadrons produced per event, to select electrons by being blind to low-momentum hadrons. Layers of photo-detectors, such as 4 mm wide CsI photo-cathode pads, inside the HBD could then detect Cherenkov light emitted by relativistic particles to identify electrons and to measure their trajectories. Since delta-rays emitted at random angles is unlikely to be on the trajectory of the original particle, the hadron rejection efficiency of several HBDs is almost as good as the product of the hadron rejection efficiency of individual HBDs and becomes very powerful. This is not the case for conventional Cherenkov counters. We proposed to use HBD for experiment in Heavy Ion Colliders to reject Dalitz pairs in order to cleanly identify direct electrons from vector meson decays to study quark-gluon plasma physics [1].

We have studied two different methods to build HBDs described as follows:

1. **windowless configuration:** in this case we use the same gas as the radiator and for the electron multiplication in the well-known high-gain proportional operation mode of gaseous detectors. The windowless design allows the detection of photons down to the lowest wavelength transmittable by the radiator gas. This requires a gas which simultaneously provides the proper index of refraction to distinguish electrons from pions, is transparent at extremely low wavelengths,

and has stable high gain in the avalanche wire chamber.

2. **thin window configuration:** we use a thin window (for example 0.5 mm LiF) to separate the radiator from the avalanche gas volumes. This provides more flexibility in the choice of gases. The detector structure however becomes more complex.

We describe herewith our recent experimental results on HBD research obtained with CsI photo-cathodes and HBD prototype beam testing in 1995.

2 Development in (1993-1994)

Here we briefly describe HBD development in 1993-1994. One can find more details elsewhere (see [2, 3]).

The quality of a Cherenkov counter can be expressed in terms of a quality factor (N_0) defined in the following formula:

$$N = N_0 \times L \times \sin^2 \theta_C \quad (1)$$

where

N is the number of detected Cherenkov electrons;

L is the length of radiator and

θ_C is the Cherenkov emission angle.

The results of our particle beam test of a HBD prototype, which has been published in [3], are encouraging: a large quality factor (N_0) of 500 was obtained, far exceeding what have been achieved with conventional Cherenkov detectors (typically from 40 to 100). It confirms the first goal of the HBD concept: the absence of a window separating the Cherenkov radiator and the photon detector can significantly improve the detected Cherenkov photon yield.

The second goal of the HBD concept was also demonstrated: the quite low efficiency of the Parallel Plate Avalanche Chamber (PPAC) for the primary ions created in the gas by particles with speed below threshold. Depending on the gas admixture used and the gain of the PPAC, this inefficiency was of the order of 10-30 %. Full efficiency was measured for high energy incident electrons.

3 Results on HBD research in 1995

In 1995 we continued research on CsI photo-cathode and PPAC properties using new CsI photocathode made in State University of New York (SUNY) at Stony Brook and a new built-in calibration system made at MIT.

We also participated in the beam test of HBD using two separate volumes for Cherenkov radiator and for gas amplification with a thin LiF window between the two volumes.

3.1 CsI photocathode preparation

Evaporation of CsI was done in SUNY. The evaporator had one shutter and a quartz crystal resonator to measure the CsI thickness. CsI evaporations took about 2 minutes. To achieve vacuum better than 10^{-7} torr it takes between 1 to 12 hours of pumping depending on the cleanness of the material used in the detector placed inside the evaporator. Temperature of the cathode was kept at about 50 degree C during the processes of pumping and evaporation.

The evaporation process included the following steps:

- pumping down until vacuum is below 7×10^{-8} torr.
- keeping the temperature of the cathode plate at about 50 C.
- with shutter closed, heating the molybdenum plate with CsI on it.
- when CsI became melted, open shutter and watch frequency of crystal oscillator which was installed near aluminum plate.
- when desirable thickness was obtained, closed the shutter and stop heating.
- fed clean nitrogen into the evaporator and open the door.
- remove the CsI cathode, mount the anode and put it inside a small vacuum tight clean chamber.
- connect this chamber to vacuum system and start pumping.

During the whole process, CsI was in contact with air for a total of about 3 minutes. The CsI cathode was kept warm (about 50 C) all the time to prevent water condensation.

3.2 CsI photocathode Q.E. measurement

To determine the Q.E. of the SUNY CsI photocathode, we measured the relative response of the CsI PPAC with respect to a reference Photomultiplier Tube (PMT) with known Q.E. under low intensity light. The light from a Xe flush lamp was attenuated to the point of having fewer than 0.1 photo-electrons per flush (flush frequency was about 100/sec). The light from the lamp passed through a band filter and then through a grating monochromator (Model 77250 from Oriel Corp. [6]), which selected UV with wavelength 187 ± 1 nm. A quartz fiber of about 1.5 meter long was used to guide and deliver light to the PMT and separately to the CsI PPAC chamber. Data were taken at the same wavelength for the PMT and for the CsI chamber. The ratio of the count rates in the two devices yields the ratio of their quantum efficiencies.

Typically we collected 5000 events in one data run to fill histograms for the CsI PPAC or for the PMT. In one typical measurement, we observed 4682 pedestals events for the CsI PPAC and 4021 events for the PMT. These gave us the mean number of photoelectrons per flush: $N = -\ln(n_{ped}/n_{tot})$ equal 0.066 and 0.22 for CsI PPAC and PMT respectively. Taking into account the sapphire window transparency 73% at 187 nm, the PMT Q.E. 40%, the mesh transparency 81%, and the collection efficiency of PMT 80%, the CsI quantum efficiency was estimated as follows:

$$QE_{CsI} = 40\% \times \frac{0.066}{0.22} \times \frac{0.8}{0.81} \times \frac{1}{0.73} = 17\% \quad \text{at 187 nm} \quad (2)$$

We assign 25% for the relative error of this measurement due to the uncertainty in the PMT photocathode quantum efficiency (20%), the statistical errors (6%), and the uncertainty in light positioning (15%).

3.3 HBD with build-in calibration system

In 1995 we designed and built a calibration system integrated in the HBD. Using this system one can measure Q.E. of CsI photocathodes and investigate various avalanche gas properties without opening the HBD vessel and hence the contact of CsI with air can be avoided. This allows us the possibility to measure the CsI Q.E. during future beam tests.

The experimental setup used for investigating the gas mixture properties and CsI photocathodes in 1995 is shown in Fig. 1. UV light was produced by a home made H_2 lamp working in the self triggering mode. An UV sensitive PMT was used to check the stability of the UV light as well as for triggering. The UV light from the lamp passed a 1 mm thick sapphire window and then through an UV filter with the center wavelength at 175 nm and a bandwidth of 19 nm. The filter installed in attenuation volume was used to reduce the intensity of light. After this volume, light went through 10 mm thick quartz window and entered the HBD radiator volume. An UV mirror, installed on the combination of rotary/motion feedthrough, was used to direct light to the reference PMT or the CsI photocathode. We used Hamamatsu R1657P PMT (see [8]) with known quantum efficiency. This tube has a reflective cathode (this cathode have less variability in Q.E. than the transmission type). PMT worked in photon counting mode and PMT anode was AC coupled to LeCroy Charge-to-Digital Converter (QDC) 2249W.

We used 3 mm gap PPAC (see Fig. 2) with Stainless Steel (SS) anode mesh (50 μ m wire and 500 μ distance between wires with transparency 81%). The CsI layer in the photocathode has 0.5 μ m thickness and was vacuum evaporated on SS plate. A heater from Minco Products, Inc. (see [7]) was attached to the back side of SS plate. Temperature of the cathode was measured by the thermocouple attached to the SS plate near the heater and usually kept at about 50° C.

The signal from the CsI PPAC (See Fig. 3) was amplified by a home made charge sensitive preamplifier (based on LeCroy HQV810 [9]) and then by a shaping amplifier

with adjustable shaping time based on LeCroy chip TRA1000 (see [10]). In the following table we summarize the noise measurement of this pre-amplifier (using 3 mV signals from a pulse generator with 20 nsec rise time and 1000 μ sec fall time, fed into the pre-amplifier input through a 1 pF capacitor so the total charge injected to amplifier to be $3 \text{ mV} \times 1 \text{ pF} = 3 \times 10^{-15} \text{ C} = 18,750 \text{ electrons}$):

Shaping time, nsec	QDC gate, μ sec	Noise (FWHM), electrons	Preamplifier input connected (+) or disconnected (-) from CsI
120	1	2,000	-
120	1	3,400	+
150	1	1,750	-
150	1	3,200	+
170	1	1,550	-
170	1	2,700	+
170	2	3,000	+
170	2.5	3,200	+

The output of the shaper was connected to a LeCroy 2249W QDC. An IBM PC computer was used to collect and histogram experimental data.

The collimator system produced a light spot bigger than the PMT photocathode but less than the CsI photocathode. This allowed us to estimate the Q.E. of CsI photocathode using following formula:

$$QE_{CsI} = QE_{PMT} \times \frac{S_{PMT}}{S_{CsI}} \times \frac{\epsilon_{coll}}{\epsilon_{mesh}} \times \frac{N_{CsI}}{N_{PMT}} \quad (3)$$

where

QE_{CsI} - quantum efficiency of CsI photocathode,

QE_{PMT} - quantum efficiency of reference PMT,

S_{PMT} - area of reference PMT photocathode (95 mm²),

S_{CsI} - area of light spot on CsI photocathode (660 mm², defined by collimation system. We used spot size instead of CsI size because light spot is less than CsI photocathode),

ϵ_{coll} - collection efficiency of first dynode in reference PMT (80%),

ϵ_{mesh} - transparency of mesh used in CsI PPAC (81%),

N_{PMT} - experimentally measured mean number of photoelectrons in reference PMT,

N_{CsI} - experimentally measured mean number of photoelectrons from CsI photocathode.

The mean number of photoelectrons can be calculated using the Poisson distribution formula. Since the single photoelectron spectra from both the PMT and the CsI PPAC were registered, we do not need to know the PMT amplification factor or the gas amplification in the PPAC.

Typical spectra from reference PMT and CsI PPAC are shown in Fig. 4 and Fig. 5. In one measurement, the mean number of photoelectrons from the PMT was 0.06 and that for the CsI cathode was 0.45. This yields:

$$QE_{CsI} = 35\% \times \frac{95}{660} \times \frac{0.8}{0.81} \times \frac{0.45}{0.06} = 28\% \quad \text{at } 175 \text{ nm} \quad (4)$$

We assign 35% for relative error for this measurement, taking into account the uncertainty in PMT Q.E. (20%), the nonuniformity of light distribution (20%), the bandwidth uncertainty of UV filter (20%), and the statistical errors (15%). The measurement was made using 0.4 atm of CH_4 and CsI PPAC with 4 mm gap operated at $HV=4250$ V. This result is in good agreement with the published values of other groups (see Fig. 6).

3.4 Beam test of HBD at BNL

Windowless HBD requires the use of the same gas for the Cherenkov radiator and for the amplification of CsI PPAC and thereby is capable to detect photons at the lowest wavelength transmittable by the radiator gas. This requires a gas which simultaneously provides the proper index of refraction, transparency at extremely low wavelengths, and the ability to be operated at high gain in the CsI PPAC. The research of windowless HBD are still on-going.

In the mean time, a different type of HBD using a thin (0.5 mm, $X_0 = 0.3\%$) LiF window has been built and tested in SUNY at Stony Brook (see Fig. 7). The thin window allows one to separate the radiator and the avalanche volumes, giving greater flexibility in the gas choices. The disadvantages of this approach are relatively more complicated internal structure of detector; and more complicated gas supply system because one has to maintain the same pressure on both side of the LiF window to prevent it from breaking. Care also should be taken in the choice of window: it has to be VUV transparent and has sufficiently large index of refraction. If the index of refraction is not high enough, the Cherenkov light produced in the window by passing charge particles (i.e. pions) will give false signal on the CsI, i.e. detector will no longer be 'hadron blind'. The LiF window has such large index of refraction that the Cherenkov light produced in it is totally internally reflected in the window and hence gives no signal on the CsI. The CsI cathode consists of 41 pads with individual signal readout from each pad. Details of the design can be found in [11].

The detector was beam tested at the AGS accelerator of BNL, operated with C_2F_6 as the radiator with an effective radiation lengths of 120, 80, and 40 cm respectively. The avalanche gas used was 95% He + 5% CH_4 at atmospheric pressure.

The 29 GeV/c primary proton beam was incident upon a thick production target. The B2 test beam line views that target with double focusing analysing spectrometer. A Pb sheet was placed at the entrance of B2 to induce photon conversions and to increase the fraction of electrons present in the beam.

Just prior to the the second analysing magnet, the beam passed through a scintillator paddle (S2) and a Cherenkov detector (C1). After the magnet, the beam passed through a second Cherenkov detector (C2) and another scintillator paddle (S3). The beam passed directly through HBD and was finally incident upon a $6 \times 6 \times 18$ inch Pb-glass PBGL. A small scintillator (1×1 cm, S4) was placed before the PBGL counter and ensured that the incident beam particle landed near the center of the PBGL. We use the the following trigger: $BEAM = S2 \times S3 \times S4$. Information from all Cherenkov, scintillation and Pb-glass counters were digitized and used off-line for clean electron and pion identification.

The number of hit pads with signals greater than 3.5 sigma above pedestal, for electrons and for pions, and the total charge from the anode mesh are shown in Fig. 8. As seen, at 95% electron efficiency, the pion efficiency was 1/300, 1/200, and 1/100 corresponding to an radiation length of 120, 80, and 40 cm respectively.

Since the number of hit pads for electrons is much greater than that for pions, we can identify electrons from pions by demanding the number of hit pads to be greater than a certain cut-off. If in addition of this cut-off we can further improve e/pi rejection factor. In Figure 9 we present the pion efficiency vs the electron efficiency of the 1.2 meter long HBD obtained by applying various cuts on the anode signal amplitude and the number of hit cathode pads. In Figure 10 we present the same plot for the HBD with 0.4 m long radiator volume. It is obvious that huge e/pi rejection factors can be achieved using several short (e.g. 40cm) HBDs in series.

3.5 Main results

- A windowless HBD with a build-in calibration system was designed, built and tested, ready for future beam tests.
- New low noise charge sensitive fast pre-amplifiers with shaper was designed, built and tested, with a noise = 2,700 electrons (FWHM) for 170 nsec shaping time. Using this pre-amplifier, we are able to detect single photoelectron spectrum from CsI PPAC.
- We studied the response of the CsI photo-cathode with PPAC using low intensity light from a UV lamp. We used a calibrated PMT to determine the absolute photon flux which allows us to compute the expected CsI PPAC response to Cherenkov light.
- We measured Q.E. of photocathode to be about 30% at 175 nm.
- We participated in a beam test of HBD with LiF window at BNL. Using C_2F_6 as the radiator gas in a 40 cm long HBD, and 95% He + 5%CH₄ as the avalanche gas at atmospheric pressure, we obtained a pion rejection efficiency of 1/100 and an electron detection efficiency of 95%. This result shows large pion rejection can be achieved with high electron detection efficiency in a compact, thin

package. Huge e/π rejection factors can be achieved using several short (e.g. 40cm) HBDs in series.

4 Conclusion on HBD

The concept of using Cherenkov light to measure the trajectories of electrons among hadrons are proven: a large quality factor (N_0) of 500 was obtained, far exceeding what have been achieved with conventional detectors (typically from 40 to 100). It confirms the fundamental HBD concept: the detection of the UV spectrum of the Cherenkov light generated by the electron can greatly improve the detected Cherenkov photon yield and be used to efficiently identify electrons.

The second goal of the HBD concept was also demonstrated: the quite low efficiency of in the PPAC on the primary ions created in the gas by minimum ionizing particles, i.e. hadrons. Depending on the gas admixture used and the gain of the PPAC, this inefficiency was of the order of a few percent. Full efficiency was measured for high energy incident electrons. Using several HBDs, one can thus achieve very high hadron rejection power.

Two approaches, one with and one without a UV window, to separate the Cherenkov radiator and the photon detector were demonstrated. How to design a practical system to separate the Cherenkov radiator and the photon detector for a large device, however is a technology which needs to be further investigated.

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Figure 1: Experimental HBD setup with build-in calibration system used for Q.E. measurement and to be used for future beam tests. The reference PMT section (on the top of UV mirror) is out of the plane and thus not shown.

Figure 2: Enlarged schematic drawing of the CsI PPAC section of HBD of Fig. 1. Cherenkov light produced by the beam particles comes from the right, passes through an anode mesh, and produces photoelectrons on the CsI cathode, which amplified while drifting toward the anode.

Figure 3: Schematics of electronics used for CsI cathode Q.E. measurements.

Figure 4: Experimental single photoelectron spectrum from the reference PMT (Hamamatsu R1657P) with HV=970 V. Pedestal width is very narrow due to small dark count of PMT (0.2 counts per second).

Figure 5: Experimental single photoelectron spectrum from the CsI PPAC used in this experiment with the anode-cathode distance = 4 mm, HV=4250 V, and 0.4 atm of CH_4 . The mean number of photoelectrons is 0.36.

Figure 6: Q.E. of CsI cathodes as function of wavelength from various groups. Our measurements are shown in the center of the plot. The Q.E. of Hamamatsu PMT R1657P used by us as reference is also shown.

Figure 7: Schematic drawing of an HBD with a LiF window to separate the radiator and the amplification volumes. The front and back blankoffs were used only during pumping to prevent the thin capton windows from breaking.

Figure 8: Distribution of number of hit cathode pads (upper plot) and total charge from anode mesh (lower plot) for electrons (dashed histogram) and pions (solid histogram) for the BNL beam test of HBD with a LiF window.

Figure 9: The pion efficiency vs the electron efficiency of the 1.2 meter long HBD obtained by applying various cuts on the anode signal amplitude and the number of hit cathode pads.

Figure 10: The pion efficiency vs the electron efficiency of the 0.4 meter long HBD obtained by applying various cuts on the anode signal amplitude and the number of hit cathode pads.