A Measurement of the Scintillation Light Yield in CF_4 Using a Photosensitive GEM Detector

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***Abstract*—The absolute photon yield of scintillation light produced by highly ionizing particles in pure CF_4 has been measured using a photosensitive Gas Electron Multiplier (GEM) detector. The detector consists of two standard GEMs and a CsI coated GEM which acts as a photocathode that is sensitive to the 160 nm scintillation light produced in CF_4. The light yield was determined in terms of the number of scintillation photons emitted into a 4π solid angle produced per MeV of energy deposited in the gas by a 5.5 MeV alpha particle and found to be 314 ± 15 photons per MeV. The quantum yield was determined using a fitting method to determine the number of photoelectrons from the measured pulse height distribution, and by an independent method using the measured gain of the GEM detector. The effect of scintillation light in CF_4 on the performance of Cherenkov detectors, such as the PHENIX Hadron Blind Detector (HBD) at RHIC, is also discussed.**

***Index Terms*—CF4, Cherenkov detectors, CsI photocathodes, GEM detectors, HBD, micropattern gas detectors, PHENIX, scintillation light.**

I. Introduction

THE production of scintillation light in highly UV transparent gases such as CF_4 can have an important effect on their use in Cherenkov counters. If the light yield is high, it can produce a significant background that can interfere with the detection of the relatively weak Cherenkov signal. The PHENIX Hadron Blind Detector (HBD) is a windowless Cherenkov counter that uses pure CF_4 as the radiator gas, and also as the operating gas for a set of photosensitive Gas Electron Multiplier (GEM) detectors that are used to detect the Cherenkov light from electrons produced in relativistic heavy ion collisions and polarized proton interactions at RHIC [1]–[5]. CF_4 has a scintillation emission that peaks at 160 nm [6] which is in a region where the CsI photocathode GEMs used in the HBD are highly sensitive. It is therefore important to know the level of scintillation light produced by charged particles in CF_4 in order to understand its effect on the performance of the HBD at RHIC. The absolute scintillation light yield in CF_4 was therefore measured using a CsI GEM detector that is very similar to the ones used in the HBD.

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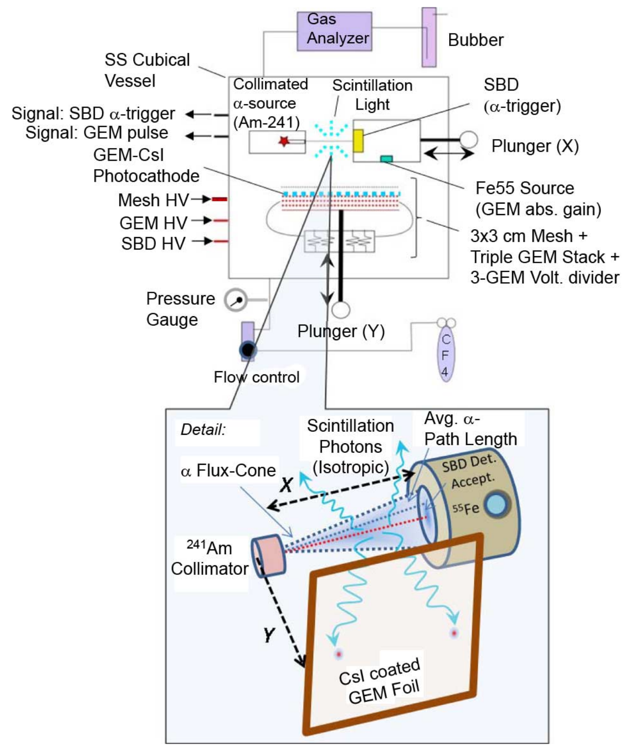

Fig. 1. Setup used to measure the scintillation light produced in CF_4 using a photosensitive GEM detector.

II. Method

A small GEM detector, similar to the ones used in the PHENIX HBD, was constructed that consisted of a stack of three $3 \times 3\ cm^2$ GEMs, with standard GEMs on the bottom and in the middle, and a gold plated GEM coated with ~ 350 nm of CsI that served as a photocathode on the top. Photoelectrons produced on the photocathode were extracted by the electric field produced between a mesh and the top GEM and amplified by the GEM stack. Fig. 1 shows the setup used for this measurement.

As depicted in the figure, scintillation light is produced by alpha particles emanating from an ^{241}Am source, which traverse a known distance in CF_4. After depositing energy in the gas, the residual energy of the alpha was measured using a silicon surface barrier detector (SBD). The total energy deposited in the gas was computed as the difference between the residual

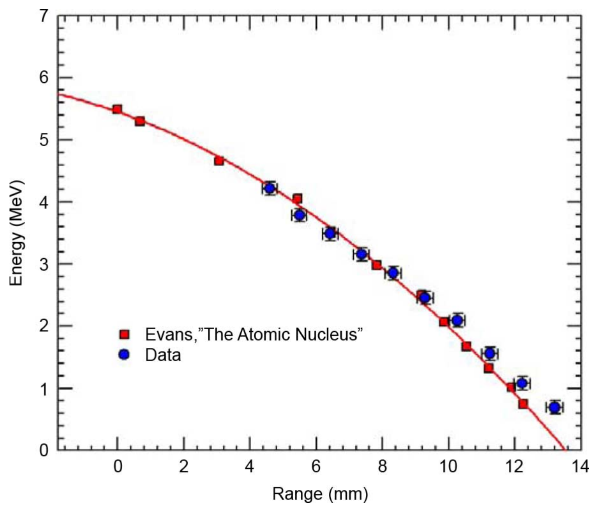

Fig. 2. Measured range-energy curve for 5.48 MeV alpha particles in CF_4. Also shown is the range-energy curve derived from [7].

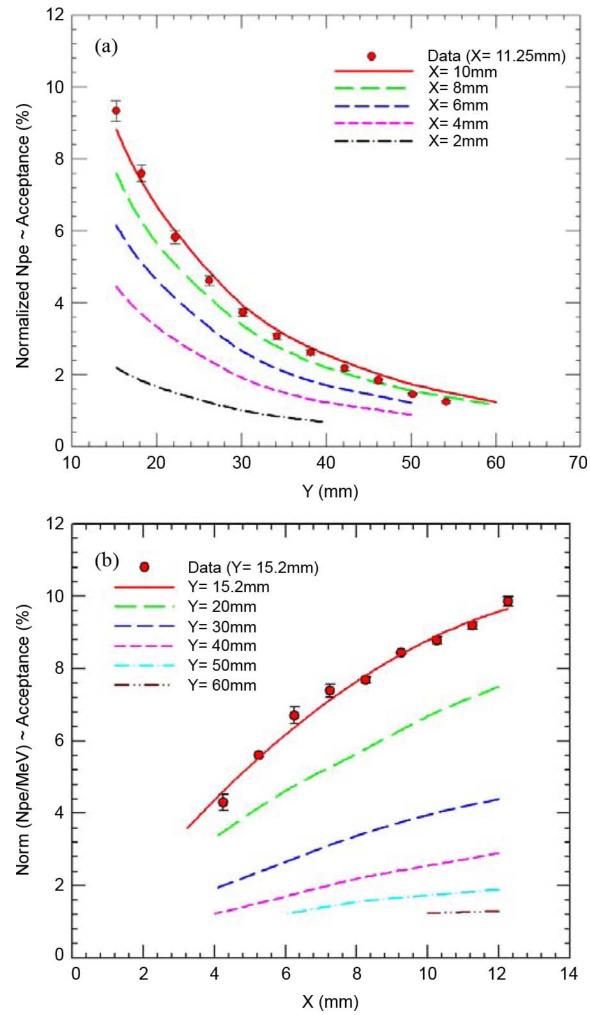

Fig. 3. Monte Carlo calculation of the geometrical acceptance of the GEM photocathode detector compared to measured data: a) as a function of Y for various X values, b) as a function of X for various Y values. The measured data have been normalized to the simulated results.

energy and the initial energy of the alpha (5.48 MeV). The absolute energy scale was calibrated using the signal from the SBD produced in vacuum, which corresponded to the full energy of the incident alpha.

The SBD was mounted on a moveable plunger so that the path length (X) of the alpha through the gas could be varied. The SBD also acted as a trigger for reading out the GEM detector, thus allowing a simultaneous measurement of the photon yield. By differentially comparing the energy loss to the photon yield, dN_γ/dE may be determined.

Fig. 2 shows the range-energy curve for 5.48 MeV $^{241}\mathrm{Am}$ alpha particles in CF_4 measured in our setup. Alpha particles emanating from the source form a flux cone that reach and trigger the SBD. The range is defined as the average alpha particle trajectory through the gas from the source to a point on the face of the SBD. Fig. 2 also shows a curve for CF_4 that was derived from the well known range-energy curves for alpha particles in air [7], and is in good agreement with our measured data.

The GEM detector was mounted on a second plunger which allowed the distance (Y) between the detector and the alpha particle trajectory to be varied. This allowed the photon yield to be measured for different values of the detector acceptance, thus providing a systematic check of the measurement.

The acceptance was calculated using a Monte Carlo simulation as a function of Y for various X values, and the results are shown in Fig. 3(a). The Monte Carlo calculation was performed with sufficient statistics that the errors on the computed curves are negligible. The relative acceptance was also determined using the measured scintillation light signal at a single value of $X = 11.25$ mm. This is also shown in Fig. 3(a), normalized to the calculated curve at $X = 10$ mm along with the experimental measurement errors. The agreement in the shape of the two curves is quite good, which serves to validate the calculated acceptances at different X values.

Fig. 3(b) compares the simulation of the acceptance as a function of X at various Y values, along with measured data normalized to the simulated curve at $Y = 15.2$ mm. In this case, as the path length of the alpha's trajectory through the gas is varied, the amount of light produced also varies, but the ratio of the number of photons produced to the amount of energy deposited in the gas remains constant. Therefore, any change in the ratio of the signal measured from the GEM to the amount of energy deposited in the gas is due to the change in the acceptance alone. The shape of the measured points agrees well with the simulation, which again adds validity to the acceptance calculation.

Fig. 4 shows the quantum efficiency, measured in vacuum, of a typical CsI photocathode used in our setup. The photocathode was produced using the same facility that is used to produce the photocathodes for the PHENIX HBD detector [5]. All of the photocathodes typically had a quantum efficiency of around 27–30% at 160 nm

As shown in Fig. 1, an $^{55}\mathrm{Fe}$ source was mounted to the back side of the plunger holding the SBD and was used to calibrate the gain of the GEM detector. Fig. 5 shows a typical pulse height spectrum of the $^{55}\mathrm{Fe}$ signal. The peak corresponds to 109 primary electrons produced by the 5.9 keV X-ray in pure CF_4. The gas gain was computed using the primary charge and the calibration of the preamp and readout electronics obtained using a

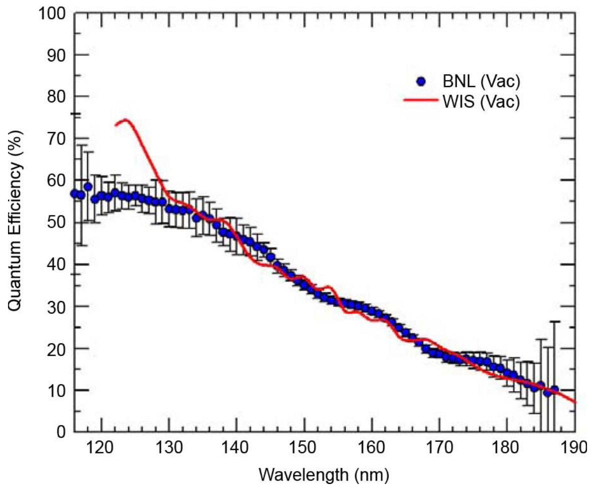

Fig. 4. Quantum efficiency measured in vacuum of a typical CsI photocathode used in this experiment. Measurements were made at the Weizmann Inst. of Science (WIS) [4] and Brookhaven National Lab (BNL). Errors on the WIS measurement are similar to those at BNL.

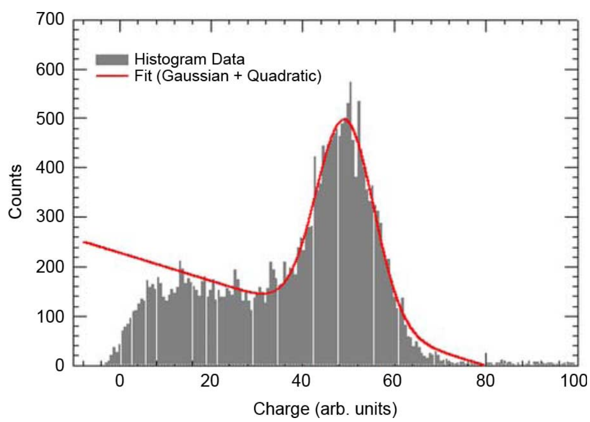

Fig. 5. Pulse height spectrum of the $^{55}\mathrm{Fe}$ source used to calibrate the gain of the GEM. The peak corresponds to 109 primary electrons produced in CF_4.

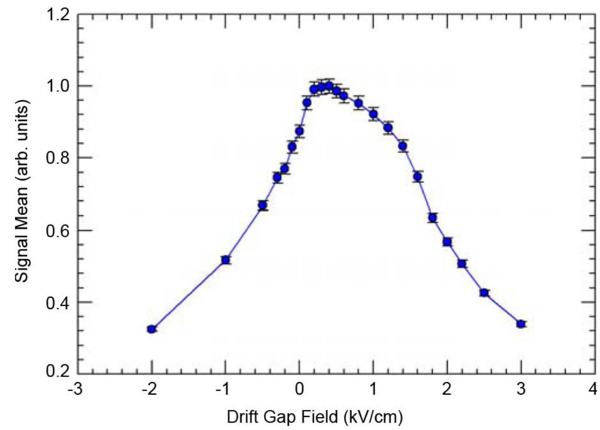

Fig. 6. Mean signal versus drift gap field. The field was optimized in the range of 0.1–0.4 kV/cm for each set of measurements.

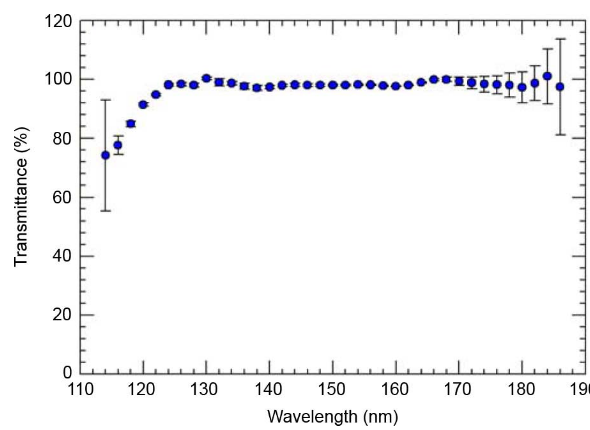

Fig. 7. Transmittance of CF_4 as a function of wavelength.

pulser and a known charge injection capacitor. The GEM was operated at a gas gain in the range 8,000 –12,000 with a voltage of $\sim$ 480 volts across each GEM. It was monitored periodically throughout the course of each of the measurements and was found to vary by a maximum of about $\pm 5\%$.

At a given X,Y position and GEM voltage, the amplitude of the measured signal is proportional to the photoelectron collection efficiency, which depends on the extraction field in the drift gap above the top GEM. Fig. 6 shows the dependence of the mean signal on the field in the drift gap. The optimum drift field was found to vary from ~ 0.1 kV/cm to 0.4 kV/cm between different sets of measurements, but remained constant to within 2-3% for the same set of measurements. The drift field was also studied for different X positions and showed that the optimum value did not depend on the position of the SBD over the range that we measured. The absolute photoelectron collection efficiency, defined here as the efficiency with which photoelectrons, once produced, are extracted from the photocathode surface and transported to the GEM holes for amplification, was studied in detail in [8], and was determined to be $66 \pm 6\%$ for 160 nm photons.

The entire detector assembly was housed inside a stainless steel box that provided a sealed gas volume. As gas flowed through the detector, water and oxygen levels were continuously monitored and were typically below 10 ppm each. The operating pressure was one atmosphere and the temperature was typically $\sim 20^\circ\mathrm{C}$. The temperature and pressure were monitored in order to correct for any P/T variations in the gas gain. The gas transmittance was also measured and is depicted in Fig. 7. It was found to be 100% transparent in the region of the peak of the CF_4 scintillation emission at 160 nm, indicating that there were no losses incurred from photon absorption in the gas.

Finally, in order to verify that the measured GEM signal is indeed derived from scintillation light, a null test was performed with P-10 (argon-methane 90:10), which is a gas that is known not to scintillate. No measurable photon signal was observed, as expected

III. Results

A typical raw GEM preamplifier pulse height distribution is depicted in Fig. 8. The spectrum was fit to a Poisson distribution for the number of photoelectrons produced, and is convoluted with a Polya gain distribution from the GEM detector and a Gaussian distribution due to the pedestal noise. The fit was performed by generating a series of Monte Carlo simulated data

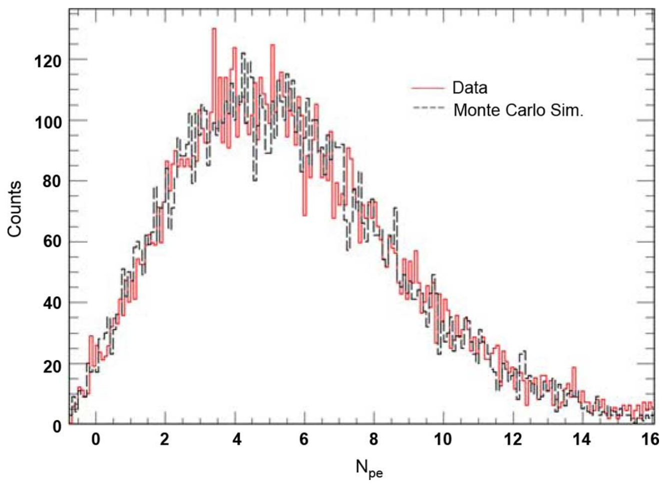

Fig. 8. Solid-red curve is the measured GEM pulse height distribution. Dashed-black curve is the simulated parent Poisson distribution giving the best fit for the number of primary photoelectrons, convoluted with a Polya distribution for the GEM gain variation and a Gaussian pedestal distribution.

in which the number of primary photoelectrons of the Poisson was allowed to vary, and also included the broadening effects of the gain variation and pedestal noise. The form of the Polya distribution used is described in [9] and the value of the Polya parameter θ was 0.38. The best fit between the simulated results and the raw data was determined using a chi square analysis. An example of the results is shown in Fig. 8. The mean number of incident photons was derived from the mean number of photoelectrons by dividing by the photocathode quantum efficiency and other efficiencies.

In addition to the quantum efficiency (QE), the photoelectron collection efficiency (CE), and the geometric acceptance (A), the mesh transparency $(\mathrm{T_{mesh}})$ and GEM transparency $(\mathrm{T_{GEM}})$ must also be corrected for in order to determine the mean number of photons emanating into a 4π solid angle. The absolute number of photons is then given by:

$$\mathrm{N}_\gamma = \frac{\mathrm{N_{pe}}}{(\mathrm{QE}^*\mathrm{CE}^*\mathrm{A}^*\mathrm{T_{mesh}}^*\mathrm{T_{GEM}})}.$$

We used our own measured values of $\mathrm{QE} = 27\%$, $\mathrm{CE} = 66\%$, $\mathrm{T_{mesh}} = 80\%$, and $\mathrm{T_{GEM}} = 83\%$, along with our previously discussed values for the geometrical acceptance, to determine N_γ.

Fig. 9 shows the mean of the preamplifier pulse height distribution measured as a function of the energy deposited in the gas before any acceptance corrections. As described above, the energy deposited in the gas was defined as the difference between the known initial energy of the alpha and the energy deposited in the SBD. As seen in the figure, there is an offset of ~ 1.4 MeV for which no scintillation light is observed. This offset is due to a ~ 3 mm path length of the alpha that is obstructed from the view of the photocathode by the source holder and mounting fixture for the SBD, and the light produced in this region does not contribute to the observed signal. After applying the acceptance correction, this offset is partially removed (~ 0.5 MeV) and the curve becomes linear as a function of energy, but there is a remaining offset ($\sim$ 0.9 MeV) that is not fully accounted

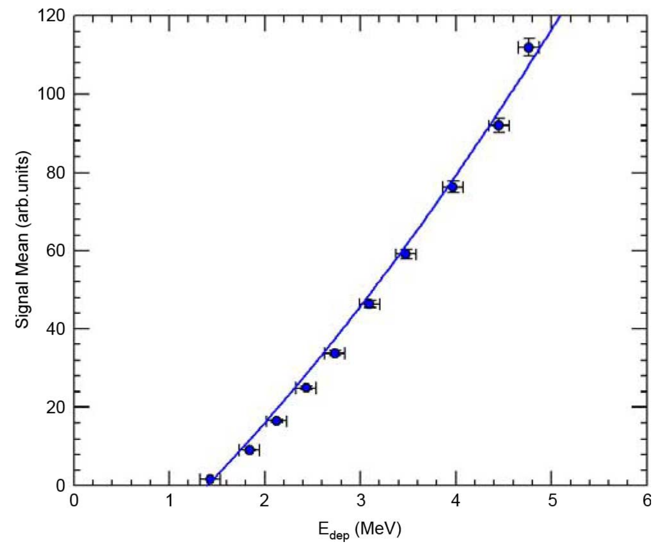

Fig. 9. Mean preamplifier pulse height signal as a function of the amount of energy deposited in the gas with no acceptance corrections applied. The 1.4 MeV offset is due to a small ($\sim$ 3 mm) path length of the alpha in the gas that is obstructed from the view of the photocathode and therefore produces no observed scintillation signal.

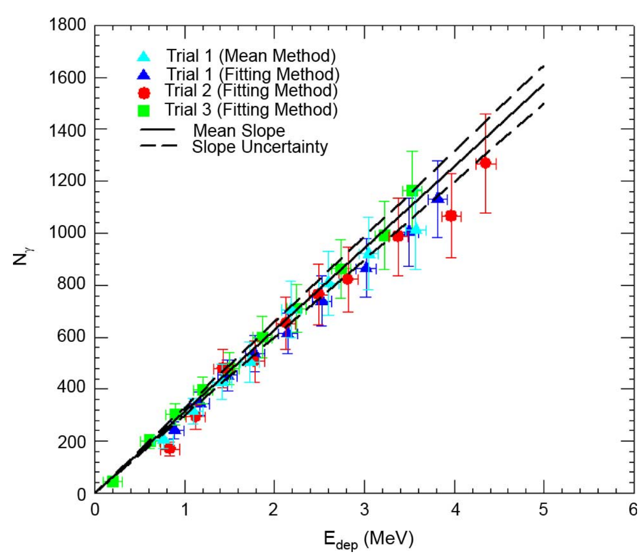

Fig. 10. Scintillation photon yield normalized to 4π solid angle measured as a function of the energy loss of alpha particles in pure CF_4. A fit to the four independent data sets gives an average value of 314 ± 15 photons/MeV, including the effect of systematic errors.

for by our Monte Carlo. We believe this is due to the details of the small and rapidly changing acceptance near the source holder and SBD. However, since the absolute photon yield is determined by measuring the slope of the curve of photon yield versus energy (dN_γ/dE), it is not affected by this constant energy offset.

Fig. 10 gives the absolute scintillation photon yield measured as a function of the energy deposited by alpha particles in CF_4. The yield has been normalized to 4π and has been corrected for all efficiencies and the geometrical acceptance, and the 1.4 MeV energy offset has been subtracted off. The plot shows three data sets taken at different times where the mean number of photoelectrons was determined by the fitting method described above.

It also shows another data set where the mean number of photoelectrons was determined using the measured gain of the detector. In this case, the signal from the GEM is calibrated in terms of electrons using a pulser and divided by the gas gain as determined by the $^{55}\mathrm{Fe}$ source to give the number of primary photoelectrons. This is then divided by the quantum efficiency and corrected for all other efficiencies and the geometrical acceptance to give the total number of scintillation photons. All four data sets agree quite well, and the difference gives an indication of the size the systematic error due to the different trials and methods.

The final photon yield was determined by performing a linear fit to each of the four data sets separately and computing a weighted average for the slope. This gave a value of 314 ± 15 photons per MeV for the absolute photon yield. Inclusion of a quadratic term due to uncertainties in the acceptance correction did not significantly improve the fit, and the effect of this acceptance uncertainty is included in the error of the slope of the linear fit. The final measurement, including all systematic errors, constitutes a significant improvement over our previously reported preliminary results [10]. Our new result also agrees with the value of 242 ± 60 photons per MeV measured at 0.75 atmospheres of $\mathrm{CF_4}$ using a different method that utilized a CsI photocathode gaseous photomultiplier to determine the scintillation yield [11]. However, the value obtained here is considerably more precise, and was obtained using a method that is directly applicable to the detection of scintillation light in $\mathrm{CF_4}$ in the PHENIX HBD detector.

IV. The Effect of Scintillation Light on the HBD

Scintillation light from $\mathrm{CF_4}$ can affect the performance of the PHENIX HBD or other types of Cherenkov detectors in several ways. The first is that scintillation light is produced by all charged particles passing through the detector and not just electrons. This generates a flux of scintillation photons that hit the photocathode and produces a broad background underneath the Cherenkov signal from electrons. Using our measured scintillation photon yield, we may estimate this background in the HBD due to the scintillation produced by charged particles in heavy ion collisions.

A Monte Carlo calculation was used to estimate the flux of photons on the readout plane of the HBD produced by charged tracks passing through the detector [1]. The value obtained, scaled by our new measured number for the photon yield, is 0.01 scintillation $\mathrm{photons/cm^2/track}$. For central gold-gold collisions at RHIC, the average number of tracks in each arm of the HBD is ~ 200, and the area of a single readout pad is $6.2\ \mathrm{cm}^2$, which gives ~ 12.4 scintillation photons incident on each pad. Multiplying this by the transmission of the mesh, the transmission of the GEM, the CsI quantum efficiency, and the photoelectron collection efficiency, gives 1.5 photoelectrons per pad due to the scintillation. This number needs to be compared with the signal from the Cherenkov light produced by electrons, which is ~ 20 photoelectrons. However, the Cherenkov photons are typically spread out over 3 or so pads, so the added background signal due to the scintillation is $\sim 4-5$ photoelectrons. This is a fairly substantial background that must be subtracted off in the analysis of the HBD data in central gold-gold collisions. However, this background becomes negligible in lighter ion, deuteron-gold or proton-proton collisions.

While the scintillation light produces a background for measuring Cherenkov light, it also provides a convenient means for calibrating the gas gain of the detector. Since the flux of scintillation light produces essentially single photoelectron hits on each pad, the pulse height spectrum may be fit to an exponential distribution to determine the gas gain of the GEMs (in principle, the distribution is in fact a Polya distribution, but it is very nearly purely exponential). This feature was used to measure the gas gain of each pad in the HBD, which provided a means to not only measure the gain variation across the entire detector, but also to monitor the gain throughout all of Run 9 at RHIC.

Finally, the HBD is a windowless Cherenkov detector which has a very open geometry, with the radiator and GEM photocathodes sitting inside the same gas volume. There is therefore a possibility for scintillation light produced by avalanches in the GEMs to cause photon feedback to neighboring GEMs inside the detector, which could potentially cause problems with sparks or discharges. However, GEM detectors tend to limit this photon feedback by virtue of their internal geometrical structure, and aside from some early difficulties with sparking and discharges with the HBD due to unrelated high voltage problems, we have not seen any problems related to photon feedback from normal avalanches in the gas.

V. Conclusions

The absolute scintillation light yield of $\mathrm{CF_4}$ has been measured with a photosensitive GEM detector using two different and independent methods. The first method used a fitting procedure to determine the number of photoelectrons from the shape of the pulse height distribution produced by triggering on alpha particles in $\mathrm{CF_4}$, and the second used the knowledge of the gas gain of the detector as determined by $^{55}\mathrm{Fe}$. Both methods agreed quite well, and the resulting light yield was derived from the slope of the curve of the photon yield versus energy (dN_γ/dE) and found to be 314 ± 15 photons per MeV into a 4π solid angle. The value for the yield agrees with previous measurements obtained using a CsI photocathode gaseous photomultiplier, but the precision of this measurement is considerably improved.

Scintillation light is a potential problem for Cherenkov counters using highly UV transparent gases such as $\mathrm{CF_4}$, which is the case with the PHENIX HBD. However, due to the high granularity of the HBD readout, the scintillation background is not a serious problem in terms of measuring the signal for Cherenkov light from electrons, even in central gold-gold collisions at RHIC. In addition, the intrinsically limiting geometry of GEM detectors prevents photon feedback, which has resulted in no problems with operating the HBD at RHIC. Finally, scintillation light from charged particles produced in the collisions can be used to measure the gas gain of the GEMs, which provides a means to study the gain variations across the detector and monitor its stability during normal operation.

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