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IMAGING CERENKOV DETECTOR:
PHOTO-IONIZATION OF TRI-ETHYL-AMINE

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ABSTRACT

We show that an argon plus tri-ethyl-amine filled photo-ionization detector consisting of a parallel plate conversion gap, amplification gap, transfer gap and a multi wire proportional chamber is capable of efficiently counting single photoelectrons. The maximum tri-ethyl-amine quantum efficiency has been measured to be $34 \pm 4\%$ at 8.44 eV photon energy. It is shown that such a detector with an improved mirror will allow observation of Cerenkov ring images with 6.4 points per image for a 1 m long atmospheric pressure argon gas radiator.

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1. INTRODUCTION

Since the proposal [1] by two of the present authors to use a photo-ionizing gas in a Multi Wire Proportional Chamber (MWPC) to efficiently convert, amplify and count individual ultra-violet (UV) photons, considerable progress has been made towards achieving this goal. The first experiments [2,3,4] used an Argon-CO₂ filled MWPC with a small admixture (~ 1%) of the photo-sensitive vapour of benzene. This concentration is sufficient to totally absorb all photons of energy $E > 6.2$ eV within the MWPC gap, typically ± 5 mm. The photo-ionization threshold in benzene is 9.24 eV with an average quantum efficiency Q of about 50% for energies above 9.5 eV [1]. The photon source was the Cerenkov radiation spectrum produced by a high energy particle passing through a transparent optical medium of refractive index n . The number of photons converted (to photoelectrons) in the detector is [1]

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

where

$$\sin^2 \theta = \frac{(\gamma/\gamma_t)^2 - 1}{\gamma^2 - 1}, \quad \gamma = W/m, \quad \gamma_t = n/\sqrt{n^2 - 1} \quad (2)$$

with L the length of the optical medium, W the total energy and m the mass of the charged particle and γ_t the threshold γ for Cerenkov radiation. The constant N_0 , which characterizes the detector, is [1]

$$N_0 = \frac{\alpha}{\hbar c} \int \epsilon \, dE = (370/\text{eV} \cdot \text{cm}) \bar{\epsilon} \Delta E, \quad (3)$$

where $\epsilon = QRT$ with R the mirror reflectivity and $T = T_g T_w T_m$ the system transmissivity (radiator gas, detector window, cathode mesh). The average is taken between the photon energy cut offs E_1 and E_2 with $\Delta E = E_2 - E_1$.

In an argon-CO₂-benzene filled counter the photon acceptance is effectively from 9.5 eV to 10.75 eV (the CO₂ absorption cut off [1]) hence $\Delta E = 1.25$ eV. Over this interval $Q = .5$ and assuming $R = .7$, $T_w = .5$, $T_m = .8$ and $T_g \geq .99$ then $\bar{\epsilon} = .14$ and $N_0 = 64.8 \text{ cm}^{-1}$. This value

of N_0 would correspond to 6.6 photoelectrons on the ring image produced by a $\beta = 1$ ($\gamma = \infty$) charged particle traversing 1 m of argon gas (20° C, 760 Torr) having index $n(10 \text{ eV}) = 1.000509$ [5] hence $\gamma_t = 31.4$. The condition $T_g \geq .99$ requires O_2 or H_2O impurities less than 3 PPM. In the case of a 1 m long N_2 gas radiator (20° C, 760 Torr) the index is $n(10 \text{ eV}) = 1.000528$ [5] and $\gamma_t = 30.8$. Taking all efficiency factors as above except $T_g = .7$, which is due to intrinsic N_2 molecular absorption bands in this energy region^(*) [6], $N_0 = 45.3/\text{cm}$ which corresponds to 4.8 photoelectrons on the ring image ($\beta = 1$). The parameters given here are representative of the values attained in this energy region, however they must be evaluated individually for each experiment. These are summarized in table 1. As can be seen from this table, the experiment of Chapman, Meyers and Thun [3] achieves 76% of the expected value of N_0 whereas the experiments of Gilmore et al., [2] and Durkin, Homma and Leith [4] obtain only 12%. We assume that this ratio characterizes the single photoelectron counting efficiency ϵ_c of the detector. In the first case the detector was a group of individual square proportional counters (12.7 mm on a side) whereas in the second case the detectors were standard MWPC arrays (20 μ wires, 2 mm wire spacing). It is expected that a proportional counter should have better single photoelectron counting efficiency than MWPC arrays because the wires are separated by the solid metallic cathodes (thus removing the electrostatic forces and photon cross talk between wires) which allows operation at higher voltage or gain. Even so, Chapman et al. [2] estimate that they were only able to achieve 75% single photoelectron counting efficiency (which agrees with the estimate of table 1) when the detector had a benzene vapour filling whereas without benzene the counter could support 150 V higher voltage and achieve a good plateau for single photoelectrons produced on the cathode walls.

The data in table 1 shows that MWPC arrays are considerably less efficient for single photoelectron counting than are proportional counters. This is in agreement with experimental and theoretical studies [7] of the avalanche process around a proportional wire which

(*) Measured by T. Ypsilantis using a UV monochromator at Saclay.

show the pulse height distribution $P(x)$ to be of the form

$$P(x) = \frac{m^m}{\Gamma(m)} x^{m-1} e^{-mx}, \quad (4)$$

where m is determined by the maximum electric field around the wire. For low fields $m \approx 1$ and the distribution is exponential with a relative variance $\sigma_x/\bar{x} = 1$ whereas for the highest fields attainable in proportional counters $m \approx 3/2$ hence the distribution is peaked with a relative variance $\sigma_x/\bar{x} = \sqrt{2/3}$. Recently a new method of efficient single photoelectron counting has been demonstrated by Charpak and Sauli [8] and Breskin et al. [9]. It entails an additional stage of amplification of the primary electron in a constant electric field parallel-plate gap inserted before the MWPC array as shown in fig. 1. The gas filling is mainly a noble gas with a small admixture (1 to 5%) of a gas whose ionization potential (photo-ionization threshold) is lower than the metastable state(s) of the noble gas. For example, argon has metastable states of 11.63 and 11.83 eV hence molecules such as benzene (ionization potential 9.24 eV), acetone (9.68 eV), ethanol (10.49 eV) and tri-ethyl amine (7.52 eV) are all suitable. Note that these molecules may serve a double function, first as a photo-ionizing gas and secondly as the medium in which pre-amplification occurs.

The various gaps shown in fig. 1 are separated by woven metallic meshes having 81% optical transparency and are maintained at the indicated potentials V_1, V_2, V_3 and V_4 . The UV photon incident from above passes through the UV transmitting window and the mesh V_1 and is absorbed in the conversion gap C by the photo-ionizing gas molecule (M) to produce an electron. This electron drifts in a low field $E_C \approx 1$ kV/cm toward the pre-amplification gap PA and is transferred through the mesh V_2 with essentially unit probability if $E_{PA} \gg E_C$ or probability E_{PA}/E_C if $E_{PA} \ll E_C$. In actual operation $E_{PA} \approx 7$ kV/cm hence the transfer from C to PA is highly efficient. In the large uniform field E_{PA} the electron drifts toward V_3 but sometimes it gains sufficient energy between collisions to: (a) excite a metastable state of argon (A^{*m}) which is subsequently collisionally de-excited by (M) to produce ionization via the process $A^{*m} + M \rightarrow A + M^+ + e^-$ (Penning effect); (b) excite a non-metastable

state of argon (A^*) which quickly radiates and if its energy is sufficient produces ionization via the two step process $A^* \rightarrow A + h\nu$, $h\nu + M \rightarrow M^+ + e^-$ and (c) produce an electron by direct impact ionization of the molecule $e^- + M \rightarrow 2e^- + M^+$. All of these processes probably contribute to the avalanche produced in the PA gap. Gain or amplification of between 10^3 to 10^4 have been measured for a single 3.2 mm gap^(*). More important than the magnitude of the gain is the fact that the fluctuation in the gain is much smaller than in proportional counters. The pulse-height distributions, produced by a single photoelectron in gap C and measured on mesh V_3 , are shown in figs 2(a), (b) and (c) for electric fields of 6.77 kV/cm, 6.88 kV/cm and 6.98 kV/cm. It is evident that the variance of the distribution (fig. 2(c)) is considerably better than that for a proportional counter eq. (4). This effect has been predicted by Alkhazov [7] based on a model calculation in which every excited atom of the noble gas ionizes a molecule (M) of the admixture gas at the point where the atom was excited. The calculation showed a "considerable reduction" of the relative variance for a parallel plate configuration (uniform electric field) whereas for a cylindrical configuration (non-uniform electric field) the reduction of the relative variance was small (5 to 10%). After the avalanche reaches mesh V_3 it is transferred into a transfer gap T having an electric field $E_T \approx 1$ kV/cm hence with a transfer efficiency $E_T/E_{PA} \approx 1/7$. The measured gain includes this transfer efficiency, so the actual avalanche gain is about seven times the measured gain. Finally the electron drifts across the gap T and reaches the mesh V_4 where it is transferred into the MWPC array with good efficiency since $E_{PC} \geq 2$ kV/cm. An earlier experiment of Charpak et al. [10], used a similar parallel-plate configuration with the MWPC array replaced by a spark chamber so as to observe individual photons of the Cerenkov ring image by end-on photography of the sparks. This had the advantage of two-dimensional imaging of each converted photon but introduced an additional unknown factor, namely the spark chamber efficiency especially in the case of multiple sparks. We will discuss this experiment in sect. 3.4 in conjunction with the results

(*) This amplification has been attained for argon with an admixture of the following molecules: benzene, acetone, ethanol, cyclopropane, ethane and with lesser amplification: propane and CO_2 . Henogal (70% neon and 30% helium) with acetone or cyclopropane also gave high gain.

of the present experiment since they both use Tri-Ethyl-Amine (TEA) as the low ionization potential gas for photon conversion and for pre-amplification.

The advantages of TEA over benzene as the photo-ionizing gas are related to its low ionization potential 7.52 eV ($1650 \text{ \AA}$) compared to 9.24 eV ($1340 \text{ \AA}$) for benzene. The chromatic aberrations of the ring image, due to dispersion $n(E)$ in the radiator gas, are always less at lower photon energy. The transmission of crystal windows and the reflectivity of mirrors are higher and more easily controlled at lower photon energies. A disadvantage is that the O_2 absorption cross section is $\sim 12 \text{ Mb}$ at 8.40 eV (the peak response of TEA) whereas it is $\sim 1/2 \text{ Mb}$ at 10.2 eV (the region of benzene response) so for the same radiator gas transmission the O_2 impurity must be 24 times less at 8.40 eV than at 10.2 eV. The quantum efficiency of benzene is well known [1] and is $\sim 50\%$ for photon energies above 9.5 eV whereas only one measurement [11] of 46% for the TEA quantum efficiency at 8.44 eV is available. The energy dependence of Q for TEA has been measured by avalanche multiplication of the produced photoelectrons on a needle point detector [12] and the results are presented and discussed in sect. 2.1.

2. SINGLE PHOTOELECTRON COUNTING

As has been discussed in the previous section the critical problem for ring imaging applications is efficient single photoelectron counting. To this end, as well as to obtain quantitative quantum efficiency measurements, we set up a laboratory facility to test the detector before going to a high energy particle beam.

2.1 Ultra-violet source spectrum and flux calibration

Since we did not yet have an UV monochromator in our laboratory we constructed the UV generator cell shown at the bottom of fig. 3(a). The UV radiation originates from scintillation in a rare gas when an alpha particle, from an Am^{241} radioactive source ($5.5 \text{ MeV}/\alpha$, $2.5 \times 10^4 \alpha/s$), loses energy and stops in the rare gas medium. The cell, which has a

MgF₂ window 2.5 mm thick and 15 mm in diameter, was filled with 99.997% pure krypton gas at an absolute pressure of 4 bar (the alpha particle range is ~ 5 mm). The initial UV photon relative energy distribution $P_0(E)$ at 3 bar krypton pressure has been measured by Ophir et al., [13] and is shown in fig. 4 (curve a) along with the relative TEA quantum efficiency $Q(E)/Q_{\max}$ (curve b) where $Q_{\max}$ is the maximum TEA quantum efficiency. Also shown in fig. 4 (curve c) is the energy distribution $P(E)$ of the krypton UV source after transmission through the 2,54 mm thick LiF window [14] of the detector. From this distribution we calculate the average quantum response $\bar{Q}$ of the TEA filled photo-ionization detector for this photon source as

$$\bar{Q} = \frac{\int Q(E)P(E)dE}{\int P(E)dE} = .68 Q_{\max} \quad (5)$$

hence a measure of $\bar{Q}$ will determine $Q_{\max}$.

To measure the photon flux I after transmission through the LiF window we replaced the photo-ionization detector by a two-inch diameter RCA 8850 "quantacon" photomultiplier (PM) tube as shown in fig. 3(b). This PM has a high gain (≈ 25) first dynode allowing high efficiency counting of single photoelectrons ($\geq 95\%$). The PM window was coated, by vacuum evaporation, with $10^4 \text{ \AA}$ of p-terphenyl wave length shifter. A PM so treated has a constant quantum efficiency Q_{PM} for photons above 3.5 eV [15]. The counting rate of photons which passed through the 1 cm diameter solid angle defining aperture (fractional solid angle $(\Delta\Omega/4\pi)_{\text{PM}}$) was measured with pure argon gas flowing on both sides of the LiF window and then with O₂ (air) on the PM side of the LiF window. The difference between these count rates, C_{PM} , represents the photons from the krypton UV part of the spectrum (since O₂ is opaque for $E > 6.9$ eV) and is given by the relation

$$C_{\text{PM}} = I \left(\frac{\Delta\Omega}{4\pi} \right)_{\text{PM}} Q_{\text{PM}} T_g, \quad (6)$$

where T_g is the transmission of the argon gas. When the photo-ionization detector is in place, subtending a fractional solid angle

$(\Delta\Omega/4\pi)_{PC}$, we measured the counting rate C_{PC} caused by the photon flux I transmitted through the argon gas, the first mesh of the detector and which produced photoelectrons in the gap C with average quantum efficiency $\bar{Q}$. Hence

$$C_{PC} = I \left(\frac{\Delta\Omega}{4\pi} \right)_{PC} \bar{Q} T_g T_m \quad (7)$$

Combining eqs (6) and (7) we obtain

$$\bar{Q} = Q_{PM} \frac{\left(\frac{\Delta\Omega}{4\pi} \right)_{PM}}{\left(\frac{\Delta\Omega}{4\pi} \right)_{PC}} \frac{C_{PC}}{C_{PM}} \frac{1}{T_m} \quad (8)$$

and from eqs (5) and (8) the value of Q_{max} is obtained. It is this quantity we wish to determine and compare with the only (to our knowledge) direct determination of the TEA quantum efficiency by Salomon and Scala [11] of 46% at $E = 8.44$ eV. As can be seen from fig. 4 (curve b) the relative quantum efficiency has its maximum very near $E = 8.44$ eV so the value given of $Q = .46$ is in fact Q_{max} . This determination is chemically based and entails calibration of the photon flux at $1470 \text{ \AA}$ (8.44 eV) by measurement of the CO gas evolved when hexafluoro-acetone is irradiated for a known time by the photon flux. A photolysis reaction proceeds exclusively to produce one molecule of CO and one molecule of hexafluoro-ethane for each incident photon. Assuming that the photon flux is correctly calibrated, there exists a possible difference between the usual definition of photo-ionization efficiency and one applicable in high energy physics. The usual method is to measure the total current produced during the irradiation of the gas with a calibrated mono-energetic photon flux. This allows reactions $h\nu + M \rightarrow M^+ + e^-$ and $h\nu + M \rightarrow M_1^+ + M_2^-$ to both contribute to the measured photo-ionization efficiency whereas only the first reaction is useful for fast pulse counting. In the case of iodine (I_2) both types of reactions have been observed, as a function of photon energy, by measuring the mass of the positive ion in a mass spectrometer [16]. The predominant process seems to be the first reaction which produces electrons rather than negative ions.

2.2 Detector

The detector is shown schematically in fig. 1 (along with the distances between gaps) as well as at the top of fig. 3(a). The LiF crystal was 76 mm in diameter and 2.54 mm thick but the useful open area was only 65 mm in diameter. The various meshes which define the conversion gap C, the pre-amplification gap PA, the transfer gap T and the cathodes of the proportional chamber PC were all 110 mm in diameter and made of interwoven stainless steel wires 50 μ m in diameter with 500 μ m pitch ($T_m = .81$). The proportional chamber had 20 μ m diameter gold-plated tungsten wires with 2 mm spacing. A total of 64 wires, each of length 130 mm, defined the MWPC sensitive area of 130 mm $\times$ 130 mm; however, the sensitive area of the full detector for photons was limited to the 65 mm open diameter of the LiF window. It was possible to irradiate the detector with an X-ray source via a hole (covered by 50 μ m mylar) in the armor top plate of the detector (fig. 3(a)). The detector was operated in a gas mixture of argon-TEA with the TEA concentration thermostatically regulated and variable between 1.3% and 5.6%. The flow rate of gas through the detector (volume $\approx$ 0.5 l) was between 6 and 9 l/hour. Each of the 64 wires of the MWPC was connected to a pre-amplifier, amplifier and discriminator circuit having a bandwidth of 20 MHz and a detection threshold adjustable between 30 μ V and 200 μ V for an entry impedance of 2.5 k Ω . The pre-amplifier circuit, which has a gain of 40, was mounted directly on the detector and connected to the amplifier and discriminator via a twisted pair of 120 Ω impedance and 25 m in length.

2.3 Transfer and pre-amplification

Since the TEA absorption cross section at 8.4 eV is $\sim$ 15 Mb, the absorption mean free path at 20 Torr TEA partial pressure (2.6%) is 1 mm; hence the 3.2 mm conversion gap C absorbs 96% of the incident photons

($A_C = .96$). An electron produced in gap C will drift towards the mesh V_2 without avalanche multiplication since E_C is kept lower than the threshold for this process. In the next gap PA the field is high ($E_{PA} \approx 7$ kV/cm) so that efficient transfer $C \rightarrow PA$ is followed by avalanche multiplication in this gap. This transfer efficiency is shown in fig. 5(a) versus $(V_2 - V_1)$ with E_{PA} , E_T and E_{PC} fixed at the values indicated. In the figure the ratio E_{PA}/E_C is always greater than 1.65 so the transfer efficiency $C \rightarrow PA$ should be good as is confirmed by the measurements. Any loss in the transfer of the single electron from $C \rightarrow PA$ will immediately show up as a counting rate loss on the MWPC.

Transfer loss going from gap PA to T will not necessarily cause a counting loss at the MWPC because the number of electrons being transferred from PA is large ($\approx 10^3 - 10^4$) i.e. the gain of the PA gap. As an example, suppose the MWPC voltage V_4 is set to be 0.4 kV higher than the knee of the plateau and also suppose that the MWPC gain doubles for a voltage increase of 0.1 kV, then a transfer loss of 16 could be tolerated before counting loss occurs. In fig. 5(b) is shown the counting rate of the MWPC versus E_T/E_{PA} when ≈ 213 electrons were deposited in the PA gap by absorption of the 5.9 keV X-ray of a Fe^{55} radioactive source. As indicated, E_T and E_{PC} are constant so the MWPC gain and transfer $T \rightarrow PC$ are also constant. We note that for large E_T/E_{PA} the counting rate is constant and corresponds to a regime of efficient transfer $PA \rightarrow T$ without preamplification. As E_T/E_{PA} approaches 1 the counting rate drops indicating an important loss of transfer efficiency. At $E_T/E_{PA} = .4$ (i.e. $E_{PA} \approx 4$ kV/cm) avalanche multiplication in PA begins and eventually compensates for the transfer loss $PA \rightarrow T$ causing the MWPC counting rate to rise to its previous level.

Transfer efficiency from T to PC is shown in fig. 5(c) for $\sim 10^3$ electrons in T which originated as a single electron in C. The ratio E_{PC}/E_T is large, so efficient transfer is expected and observed.

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A measurement of the MWPC gain G_{PC} and energy resolution $\Delta E/E$ and the gain G_{PA} of the pre-amplification gap is obtained by irradiating the detector with 5.9 keV X-rays from Fe^{55} through the top slot (fig. 3(a)). X-rays which convert in the MWPC gap (called direct) produce a characteristic pulse height response due to avalanche multiplication on a wire. X-rays which convert in other gaps are excluded by biasing V_1 , V_2 and V_3 more positive than V_4 . The pulse height (channel number) of the 5.9 keV X-ray peak, measured with a pulse height analyzer (Lecroy 3001), is shown in fig. 6(a) as a function of voltage V_4 for different concentrations of TEA (in %). These data are well fitted by straight lines which, when extrapolated to low voltages, intersect at a voltage $V_{4t} = .81$ kV and at channel number 1/3. This is approximately the voltage at which avalanche multiplication begins (hence $G_{PC} = 1$ at channel number 1/3) and calibrates the channel number to be $G_{PC}/3$. We note that the A + TEA filled MWPC has a maximum gain of $\sim 6 \times 10^3$. The energy resolution of the MWPC was measured at three different gains ($G_{PC} = 1500, 1200$ and 600) as a function of TEA concentration and the results are shown in fig. 6(b). Here we note that to obtain the usual MWPC energy resolution of 10% requires 4% or more of TEA. To obtain the gain of the pre-amplification gap, the voltages V_1 , V_2 , V_3 are biased normally (so that transfer and pre-amplification occur) and the direct pulses in the MWPC are compared to the largest of the pre-amplified and transferred pulses. These are due to X-rays which have converted in the C gap and have been fully pre-amplified. The ratio of these two pulse-heights gives directly the pre-amplification gain G_{PA} which is shown in fig. 7 as a function of the potential difference $(V_3 - V_2)$ across the PA gap for different concentrations of TEA. We note that the maximum gain G_{PA} is $\sim 6 \times 10^3$ which is also the MWPC limit. This shows that we could replace the MWPC with a parallel plate gap, having the same gain, but whose final electrode V_5 is not a mesh but a gridiron of non transparent pads ($2 \text{ mm} \times 2 \text{ mm}$) etched on a printed circuit board. This would have the advantage of collecting all the pre-amplified charge (hence increasing the useable gain by a factor ≈ 5) as well as giving the two-dimensional position of each photon for ring imaging applications.

2.4 Tri-ethyl-amine quantum efficiency

With the detector placed as shown in fig. 3(a) and irradiated by photons from the krypton UV source, the counting rate (fast OR of all the MWPC wires) of the detector was measured versus discriminator level for two different values of the pre-amplification electric field ($E_{PA} = 6.73$ and 7.03 kV/cm) and the results are shown in fig. 8. The discriminator curves are reasonably flat and indicate that a good counting efficiency has been attained with extrapolated (to zero discriminator level) counting rates of 9.2 and 10.7×10^4 c/s. These rates, C_{PC} , after correction for counting dead time, due to the decay lifetime of the krypton UV light emission, become 10.1 and 12.0×10^4 c/s respectively. The ratio $\bar{Q}/Q_{PM}$ is obtained from eq. (8) which requires $(\Delta\Omega/4\pi)_{PM}$, $(\Delta\Omega/4\pi)_{PC}$, C_{PM} , T_M as well as C_{PC} . The MWPC distance from the krypton source was 34.4 cm with a 4 cm diameter defining aperture whereas the PM distance (fig. 3(b)) was 42.4 cm with a 1 cm diameter aperture; hence the solid angle ratio in eq. (8) is 4.11×10^{-2} . The counting rate measured by the PM was $C_{PM} = 2.8 \times 10^3$ c/s and since $T_M = .81$ we obtain for $\bar{Q}/Q_{PM}$ the values of 1.83 and 2.18 at the fields $E_{PA} = 6.73$ and 7.03 kV/cm respectively. Taking the average of these two measurements we obtain $\bar{Q} = (2.0 \pm .15) Q_{PM}$. From Baillon et al. [15], the uncoated PM quantum efficiency was measured to be 13% . The coated PM quantum efficiency Q_{PM} should be at least equal to this value according to the theory there developed. Taking $Q_{PM} = .13 \pm .03$ we thus obtain the estimate $\bar{Q} = .26 \pm .06$ and from eq. (5) the value of $Q_{MAX} = .38 \pm .09$. This is to be compared with the value of $Q_{MAX} = .46 \pm .03$ obtained by Salomon and Scala [11] by chemical analysis of the reaction products. The present measurement is sensitive only to the produced photoelectrons and not to photo-ionization where negative ions are produced.

The individual wires of the MWPC were also counted and cross talk between neighbouring wires was observed. The probability of a coincident count was found to be $\sim 36\%$ which indicates the spatial diameter of the electron avalanche is ~ 1 mm in agreement with Breskin et al. [9].

3. CERENKOV RING IMAGE

When a high energy charged particle (velocity βc) traverses a medium of refractive index n , then Cerenkov radiation is emitted whenever $\beta n > 1$. This radiation is produced uniformly along the particle trajectory at an angle $\theta = \cos^{-1}(1/\beta n)$ with respect to the particle direction. It may be focused by a reflecting spherical mirror (radius R , focal length $f = R/2$) to a ring image of radius $f\theta$ on the spherical focal surface. If this surface is approximated by a plane then the ring image has radius $r = f \tan\theta$. For full detection of the ring image, as in the experiment of Charpak et al. [10], the two-dimensional position (x, y) of each photoelectron on the focal plane was measured. In this experiment only a one-dimensional projection of the ring image is observed since the detector has a series of MWPC wires (in the y direction) which give only the x coordinate of each photoelectron. Taking $x = x_c + r \cos\phi$ and $y = y_c + r \sin\phi$ where (x_c, y_c) is the coordinate of the centre of the ring image and (r, ϕ) are the polar coordinates of a photoelectron. We note that photoelectrons are equally probable along the circles circumference, hence the normalized ϕ probability distribution is $1/2\pi$ from which we obtain the normalized x probability distribution

$$\frac{dP}{dx} = \frac{1}{\pi} \frac{1}{\sqrt{r^2 - (x - x_c)^2}} \quad (9)$$

The experimental distribution P_i is obtained by integrating over the x_i values $(x_i - s/2 < x < x_i + s/2)$ corresponding to the i 'th wire whose coordinate is x_i and where s is the wire spacing. This gives

$$P_i = \frac{1}{\pi} \left[\sin^{-1} \left(\frac{x_i - x_c + s/2}{r} \right) - \sin^{-1} \left(\frac{x_i - x_c - s/2}{r} \right) \right] \quad (10)$$

which is the probability that the i 'th bin has detected a photoelectron. If the total number of photoelectrons N is large then P_i is well enough determined and can be used to extract r and x_c for each incident particle. If however N is small, as is the case here, then we must integrate over many incident particles to obtain sufficient photoelectrons to define P_i .

Since the ring image centre is determined only by the particle direction and not its position, eq. (10) applies if all the beam particles have the same direction i.e. no divergence. Suppose that a particle along the beam axis z produces a ring image with centre $x_c = x_0$, then a particle having polar angle θ_p and azimuthal angle ϕ_p has a projected angle $\alpha = \tan^{-1}(\tan\theta_p \cos\phi_p)$ in the xz plane and will produce a ring image whose centre $x_c = x_0 + a$ where $a = f\alpha$. If the distribution of angles α (or a) is known then eq. (10) can be averaged over this distribution to obtain $\bar{P}_i$ which is to be compared with experiment. As an example, for a constant distribution between $-a/2$ to $a/2$ we obtain

$$\bar{P}_i = \frac{r}{\pi a} \left\{ \left[u \sin^{-1} u + \sqrt{1-u^2} \right]_{v_i+\lambda}^{v_i+\mu} - \left[u \sin^{-1} u + \sqrt{1-u^2} \right]_{v_i-\mu}^{v_i-\lambda} \right\}, \quad (11)$$

where $v_i = (x_i - x_0)/r$, $\mu = (s + a)/2r$ and $\lambda = (s-a)/2r$ with the proviso $\sin^{-1} u \equiv \pi/2$ and $\sqrt{1-u^2} \equiv 0$ if $u > 1$.

3.1 Experimental set-up

The experiment was performed on the P17 beam in the East Hall of the CERN Proton Synchrotron. The beam consisted of $\approx 3 \times 10^6$ negatively charged particles (mostly pions) of momentum $p = 12.7$ GeV/c per beam pulse of 300 ms repeated every 2.8 s. The momentum spread $\Delta P/P = \pm 2\%$ and the angular divergence was ± 7 mr horizontal and ± 20 mr vertical with a focal point located ~ 11 m upstream from the detector of this experiment. The high flux and geometry of the beam was dictated by the primary approved experiment whereas this experiment was run parasitically. To reduce the flux of particles irradiating the detector and Cerenkov gas radiator a brass collimator, 1.5 m in length with a square 20 mm $\times$ 20 mm opening, was placed in the beam ~ 6 m upstream from the experimental set-up which is shown in fig. 9. As is seen from this figure the beam was electronically defined by four scintillation counters S_1 , S_2 , S_3 and S_4 in coincidence. The dimensions of S_2 and S_3 were 5 mm in diameter while S_1 (50 mm ϕ) and S_4 (30 mm ϕ) were much larger. The distance between S_2 and S_3 was 3 m and defined a gaussian

distribution of divergence angles with $\sigma = .68$ mr or approximately a flat distribution of angles between $-\sigma\sqrt{3}$ to $\sigma\sqrt{3}$. Expressed in terms of the displacement of the centre of the ring image between $x_c = x_0 \pm a/2$ with $a/2 = f\sigma\sqrt{3}$ and since $f = 937.5$ mm then $a = 2.2$ mm. The counting rates were $S_1S_2S_3S_4 \approx 3500/\text{pulse}$, $S_1S_4 \approx 5 \times 10^4/\text{pulse}$ with the latter value indicating the total flux of particles irradiating the detector and gas radiator.

As is seen from fig. 9 the gas radiator is a cylinder of aluminium 1100 mm in length and 300 mm in diameter closed on the entrance end by a flange on which is mounted the photo-ionization detector and on the exit end by a stainless steel cupola. A spherical mirror 200 mm in diameter and focal length $f = 937.5$ mm was mounted, as shown, at the distance f from the detector mesh V_1 . The cylinder has four ports: a gas entrance port, a pump port, a gas exit port and a Penning vacuum gauge port. In fig. 10 can be seen the connections to the various ports. Initially the entrance and exit port valves are closed and the system pumped by the rotary vacuum pump, via a liquid N_2 trap, to a pressure of $\sim 10^{-2}$ Torr. The pre-heated diffusion pump system (Edwards "Diffstak") is switched into the pumping line and the pressure is reduced to $\sim 10^{-4}$ Torr. The pump port valve is then closed and the gas entrance port valve opened so that argon gas (99.9997% purity) fills the cylinder via a stainless steel step-down valve located at the pressurized (200 bar) argon gas bottle. This process is repeated twice and on the third time the exit port valve is opened when the cylinder pressure passes 1 bar. The radiator gas cylinder pressure (1 to 1.65 bar) is adjusted by the step-down valve gauge (not very accurate) and the flow adjusted to $\approx 10\ell/\text{hour}$ by the needle valve on the exit port line. A rare gas purification system (British Oxygen Corp.) could be switched into or out of the gas entrance line.

3.2 Mirror reflectivity, window and gas transmission

The mirror ($f = 937.5$ mm) used in this experiment was purchased from Cerco (Paris) and was thought to be a high quality UV mirror

produced by vacuum evaporation of aluminium on a glass substrate and overcoated with a protective MgF_2 layer. Its reflectivity was not measured until after the experiment was terminated and the results are shown in fig. 11 by the curve labelled R. The measurements were made on a UV monochromator at Saclay. The monochromator D_2 discharge lamp (MgF_2 window), its diffraction grating and its entrance and exit slits were isolated from the measurement compartment by a MgF_2 window placed immediately following the exit slit. The monochromator volume was pumped ($\approx 10^{-2}$ Torr) and then filled with high purity argon (N55) at a flow rate of 20-30 l/hour. Under these conditions the light flux, at any given wave length, was constant. The direct (0°) photon flux was calibrated by mounting a p-terphenyl coated RCA 8850 "quantacon" PM tube on the 0° port of the Argon filled measurement compartment and recording the PM current versus photon wave length. The compartment was opened and the mirror mounted so its normal was 15° to the photon beam and the same PM was moved to a symmetric 150° port of the compartment so as to intercept the reflected photon flux. With the compartment again filled with argon the reflected flux was measured versus photon wavelength and the ratio of these measurements gave the curve R shown in fig. 11. The reflectivity is not higher than 50% and cuts off at ~ 9 eV, thus considerably reducing the N_0 of this system. We have since produced and measured mirrors having a flat 80% reflectivity to 10 eV so while the low reflectivity of the present mirror is unfortunate, it is not a fundamental limitation.

The 2.54 mm thick LiF window transmission was measured using the krypton UV source and gave an average transmission of 78%. The curve T_w shown in fig. 11 is taken from Heath and Sacher [14] but normalized to give the observed 78% transmission for the krypton source spectrum (fig. 4 curve a).

The transmission of the argon gas T_g in this energy region is completely determined by its impurities. Assuming 3×10^{-6} parts of O_2 for an average Cerenkov photon path length of 1.5 f and the known O_2 absorption cross section [17] we obtain the curve labelled T_g in fig. 11 for an argon pressure of 1.52 bar.

The product of the four quantities $Q/Q_{\max}$, T_g , T_w and R shown in fig. 11 is the curve labelled "total". If the integral of this curve is $A(\text{eV})$ then from eq. (3) $N_0 (\text{cm}^{-1}) = 370 A T_m A_c Q_{\max}$ where T_m is the first mesh transmission and A_c the absorption probability in the gap C (i.e. factors independent of photon energy). The ring image runs were carried out at pressures $P = 1.058 \text{ bar}$ and $P = 1.465 \text{ bar}$ for which $A = .236 \text{ eV}$ and $A = .220 \text{ eV}$ respectively. With $T_m = .81$ and $A_c = .96$ we find $N_0 (\text{cm}^{-1}) = 68 Q_{\max}$ and $N_0 (\text{cm}^{-1}) = 63.3 Q_{\max}$ respectively.

3.3 Observation of projected ring-images

The coincidence $S_1 S_2 S_3 S_4$ signalling the passage of a charged particle through the gas radiator was used to produce a delayed writing gate. The delay of $\sim 325 \text{ ns}$ was adjusted to correspond to the drift time of electrons from the middle of gap C to the plane of the MWPC wires. The width chosen was 150 ns , about double the 80 ns drift time across gap C, so as to be sure of collecting all photoelectrons. This gate was used to start the read cycle of the MWPC hit wires via a CAMAC interface for transfer to a HP 2100 computer and eventual storage on a magnetic tape. A histogram of x coordinates, accumulated for 2000 incident pions, is shown in fig. 12(a) with the conditions of the detector and radiator gas pressure indicated in the figure. A coordinate is defined such that two contiguous hit wires (x_i, x_{i+1}) are interpreted as a single electron at x_i or x_{i+1} with equal probability. Three contiguous hit wires (x_{i-1}, x_i, x_{i+1}) are interpreted as a single electron at x_i . Four and five contiguous hit wires are also interpreted as a single electron in a similar manner. This definition is conservative in that the events with four or five contiguous hit wires are more likely to be caused by two nearby electrons.

From fig. 12(a) we note the characteristic shape of a projected ring image with a peak at each edge corresponding to the tangents of the circle and a central peak produced by the passage of the charged particle across the detector. This peak is observed with low efficiency ($\approx 25\%$) because

the electrons arising from particle energy loss (dE/dx) in gap C arrive (at the same point of the wire) ~ 325 ns after the electrons which were produced by particle energy loss directly in the MWPC gap. The late arriving electrons (coincident with the writing gate) encounter a reduced electric field around the wire due to the positive ion debris left after avalanche multiplication of the earlier group of electrons. When the writing gate is advanced, so that read out occurs for the early group of electrons we find good detection efficiency ($\geq 98\%$) for beam tracks. In confirmation of this saturation effect caused by the early group of electrons we found increasingly good efficiency for the late electrons as the MWPC gain was decreased. The solid line histogram plotted in fig. 12(a) is the result of a calculation based on eq. (11) with MWPC spacing $s = 2$ mm and the beam divergence parameter $a = 2$ mm for a radius $r = 29$ mm. The ordinate of the histogram is $N_{\pi} \bar{N}_i$, where N_{π} is the number of incident pions and N the number of detected coordinates and $\bar{P}_i$ defined by eq. (11). The value of N is obtained from an event-by-event histogram of the number of detected coordinates. It may be seen that the histogram fits the data points reasonably well at least on the right side of the detector. The left side has a lesser efficiency which may be due to a non-uniformity in the mirror reflectivity. In fig. 12(b) is shown a histogram with all conditions, the same as fig. 12(a) except that the electric field E_C has been reversed in sign so that no electrons are collected from the C gap. The only signal that remains is background plus inefficient detection of beam tracks. It may be noted that the electric field $E_{PA} = 6.25$ kV/cm is lower than the 7 kV/cm used during the laboratory tests at the same TEA concentration. To check this effect we varied the potential difference ($V_3 - V_2$) for fixed values of E_C , E_T and E_{PC} as shown in fig. 13(a). The ordinate is the number of detected coordinates per incident pion, measured as described above, and we note N is on plateau from $E_{PA} = 6.1$ kV/cm and above. The plateau of the MWPC was also checked, as shown in fig. 13(b) which indicates good efficiency above $E_{PC} = 3.0$ kV/cm. The difference in electric fields E_{PA} between the laboratory tests of sect. 2 and the beam tests is ascribed to two possible sources: (a) thermostatic control of TEA temperature not yet installed during the laboratory tests and (b) different gas flow-metres were used: in either case the TEA concentrations are not exactly comparable.

Data were taken at argon gas pressures of $1.15 \pm .05$ and $1.65 \pm .05$ bar (as read on the step-down gauge) and the histograms collected are shown in fig. 14(a) and fig. 15(a) respectively. The conditions of the detector and radiator are indicated on each figure. The measured radii are $r = 23.5$ mm and $r = 28.6$ mm with $\bar{N} = 1.3$ and 1.6 respectively as is seen from figs 14(b) and 15(b). The data points are from the event-by-event analysis of number of coordinates per event corrected for background and beam tracks. These solid line histograms are Poisson distributions with the indicated values $\bar{N}$. The indicated pressures of 1.058 and 1.465 bar were obtained in the following manner. From eq. (2) and the relation $r = f \tan\theta$ we calculate n . From the Lorentz-Lorenz relation

$$\frac{n^2-1}{n^2+2} = \frac{4\pi}{3} N_A r_B \frac{\rho}{M} f(E) = 4.5 \times 10^{-3} \frac{P}{T} f(E) \quad , \quad (12)$$

where N_A is Avogadro's number, r_B the Bohr radius, ρ the gas density, M the gas molecular weight, P the gas pressure (bar) and T the gas temperature ($^{\circ}\text{K}$). The function $f(E)$ is a Sellmeier fit to the nearest photon absorption resonances of the gas molecule i.e.

$$f(E) = \frac{F_A^2}{E_A^2 - E^2} + \frac{F_B^2}{E_B^2 - E^2} \quad , \quad (13)$$

where the constants have been evaluated for all the rare gases as well as H_2 , N_2 and O_2 by Langhoff and Karplus [5]. They give for argon $E_A = 13.08$ eV, $E_B = 24.22$ eV, $F_A = 28.14$ eV and $F_B = 61.60$ eV. From eqs (12) and (13) with $E = 8.5$ eV, $T = 293$ $^{\circ}\text{K}$ and with the calculated values of n gives $P = 1.058$ and 1.465 bar as the calculated argon gas pressure during the data runs. These should be compared to the step-down gauge readings of $1.15 \pm .05$ and $1.65 \pm .05$ from which should be subtracted the pressure drop in the feed line. No provision had been made for direct measurement of the pressure in the radiator.

3.4 Interpretation and discussion

From the data runs of the previous section ($r = 23.5$ mm, $N = 1.3$) and ($r = 28.6$ mm, $N = 1.6$) and the relation $N_0 = N (f^2 + r^2)/fr^2$, which follows from $r = f \tan\theta$ and eq. (1) with $L = f$, we calculate $N_0 = 22.1$ cm⁻¹ and 18.4 cm⁻¹. From the calculations of sect. 3.2 the expected values of N_0 (cm⁻¹) for the conditions of these runs are $68 Q_{\max}$ and $63.3 Q_{\max}$ respectively. Combining these equations we find $Q_{\max} = 32.5\%$ and $Q_{\max} = 29.1\%$ or an average value of 30.8% which may be compared to the value measured in sect. 2 of $38 \pm 9\%$.

We now may calculate $Q_{\max}$ for the experiment of Charpak et al. [10] who used the same mirror as the present experiment (however its reflectance had not yet been measured). The photo-ionizing gas used was also TEA but the window was 3 mm thick CaF₂ with a measured transmittance at 8.44 eV of 71%. The radiator gas was argon at 1.027 bar pressure. With these conditions the expected value of N_0 (cm⁻¹) = $61.9 Q_{\max}$. They observed a true two-dimensional ring image of radius $r = 24.41$ mm with $N = 1.7$ electrons/event hence $N_0 = 26.7$ cm⁻¹ and $Q_{\max} = 43.1\%$.

In the present experiment the single photoelectron counting efficiency has been verified to be high since, for example, N shows a plateau versus E_{PA} and E_{PC} (fig. 13) so we must attribute any differences between this experiment and Charpak et al. [10] to photon loss before reaching the detector. Both experiments used the same gas and gas radiator and in each experiment the window transmission was measured on termination of the experiment. The same mirror was used in both experiments, Charpak et al. in December 1978 and this experiment in August 1979 with the reflectivity measurement in October 1979. It seems probable, due to its anomalously low reflectivity, that the mirror has been deteriorating with time and any difference between these experiments may be ascribed to this source.

An experiment has been carried out by Comby et al. [12] using a 20 mm thick CaF₂ lens as a Cerenkov radiator, proximity focusing (i.e. no mirror), a needle array with cathodic focusing as the detector

and TEA as the photo-ionizing gas. They obtain ring "images" with 5 to 8 points per event which corresponds to an uncorrected value of N_0 of only 8.1 cm^{-1} . The corrections for photon absorption in the CaF_2 radiator are large and not directly measured. Other corrections due to defocusing effects of the lens must also be applied. They quote values of the TEA quantum efficiency similar to ours after applying the above large corrections. Perhaps more important is the result that the needle point array is efficient for single photoelectron counting.

We then have three experimental measurements of Q_{max} of 30.8%, 38% and 43.1% which are perhaps compatible and give an average of 37.3%. With this value of Q_{max} and an 80% mirror, a 78% CaF_2 window, a 90% wire mesh and argon impurities less than 10^{-6} then $N_0 = 88 \text{ cm}^{-1}$. Since all of these components have been produced and tested at the stated values, it seems that such a value of N_0 is attainable. This would produce 6.4 photoelectrons on ring image for one metre of argon gas at atmospheric pressure ($\gamma_t = 37.2$). An attempt to obtain such performance along with pad read-out of the two-dimensional ring image is now in preparation.

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REFERENCES

- [1] J. Seguinot and T. Ypsilantis, Nucl. Instr. and Meth. 142 (1977) 377.
- [2] R.S. Gilmore, J. Malos, D.J. Bardsley, F.A. Lovett, J.P. Melot, R.J. Tapper, D.I. Giddings, L. Lintern, J.A.G. Morris, P.H. Sharp and P.D. Wroath, Nucl. Instr. and Meth. 157 (1978) 507.
- [3] J. Chapman, D. Meyer and R. Thun, Nucl. Instr. and Meth. 158 (1979) 387.
- [4] S. Durkin, A. Homna and E.W.G.S. Leith, Isabelle; Proceedings of the 1978 Summer Workshop BNL 50885, Brookhaven National Laboratory, Upton, New York 11973. Also SLAC-PUB 2186, August 1978.
- [5] P.W. Langhoff and M. Karplus, Journ. Opt. Soc. Am. 59 (1969) 863.
- [6] Y. Tomkiewicz and E.L. Garwin, Nucl. Instr. Meth. 114 (1974) 413.
- [7] G.D. Alkhazov, Nucl. Instr. and Meth. 89 (1970) 155.
- [8] G. Charpak and F. Sauli, Phys. Lett. 78B (1978) 523.
- [9] A. Breskin, G. Charpak, S. Majewski, G. Melchart, G. Petersen and F. Sauli. Nucl. Instr. and Meth. 161 (1979) 19, see also Yellow Report CERN 78-5.
- [10] G. Charpak, S. Majewski, G. Melchart, F. Sauli and T. Ypsilantis, Nucl. Instr. and Meth. 164 (1979) 419.
- [11] D. Salomon and A.A. Scala, Journal Chem. Phys. 62 (1975) 1469.
- [12] G. Comby, P. Mangeot, J.L. Augueres, S. Claudet, J.F. Chalot, J. Tichit, H. de Lignières and A. Zadra, Saclay Report 79/06/08/227.
- [13] Z. Ophir, V. Even, B. Raz and J. Jortner, Journ. Opt. Soc. Am. 64 (1964) 1175.
- [14] D. Heath and P.A. Sacher, Applied Optics 5 (1966) 937.
- [15] P. Baillon, Y. Déclais, M. Ferro-Luzzi, B. French, P. Jenni, J.M. Perreau, J. Séguinot and T. Ypsilantis, Nucl. Instr. and Meth. 126 (1975) 13.
- [16] J.D. Morrison, H. Hurgeler, M.G. Inghram and H.E. Sranton, Journ. Chem. Phys. 33 (1960) 821.
- [17] R. Goldstein and F.N. Mastrup, Journ. Opt. Soc. Am. 56 (1966) 765.

Table 1
Summary of experiments using A-CO₂-benzene filled chambers

Experiment	Radiator gas	R	T _g (1 bar)	T _w	T _m	Expected N ₀ (cm ⁻¹)	Measured N ₀ (cm ⁻¹)	Counting efficiency ε _c
Gilmore et al. [2]	A	.71	≥.99	.2	.9	29.6	4.6 ^(a)	.16
Chapman, Meyers and Thun [3]	N ₂	.65	.73	.4	.9	39.5	30.2 ^(b)	.76
Durkin, Homna and Leith [4]	N ₂	.49 ^(c)	.71	.5 ^(c)	.77	31.0	3.3 ^(a)	.11
	A	.49 ^(c)	≥.99	.5 ^(c)	.77	43.6	4.0 ^(a)	.09
	He ^(d)	.49 ^(c)	≥.99	.5 ^(c)	.77	43.6	5.1 ^(a)	.12

- (a) Obtained from the relation $N_0 = NY_t^2/L$ which holds for $\beta = 1$.
- (b) Obtained from the Cerenkov efficiency curve ν versus pion momentum (fig. 6 of ref. [3]) via the equation $N_0 = -2n(1-\nu)/L \sin^2\theta$. Data at all pressures are consistent with the single value of N_0 (in the table) when corrected for additional absorption at pressures above atmospheric.
- (c) Not a measured value but rather the minimum value given by the manufacturer. The mirror reflectance is $R = .7$ whereas the value in the table is R^2 due to the double reflection geometry of this experiment.
- (d) From ref. [5] the helium index $n(10 \text{ eV}) = 1.000041$, hence $\gamma_t = 110.4$.

FIGURE CAPTIONS

- Fig. 1 Schematic view of the photoionization detector.
- Fig. 2 Pulse height distributions in a henogal (70% neon + 30% helium) plus acetone (3%) filled detector due to a single photoelectron produced in gap C, pre-amplified in gap PA and measured on mesh V_3 versus electric field E_{PA} : (a) $E_{PA} = 6.77$ kV/cm, (b) $E_{PA} = 6.88$ kV/cm and (c) $E_{PA} = 6.98$ kV/cm,
- Fig. 3 (a) Krypton UV generator cell on bottom with the photoionization detector mounted on top. The in-between region is filled with pure flowing argon so as to transmit the UV radiation to the detector.
- (b) krypton UV generator cell on bottom with a photomultiplier tube mounted above. The same LiF crystal as in (a) separates the argon filled region into two sections each with independent gas flow.
- Fig. 4 (Curve a) the 3 bar krypton UV spectral distribution $P_0(E)$; (curve b) the relative TEA quantum efficiency $Q(E)/Q_{max}$; (curve c) the 3 bar krypton UV spectral distribution $P(E)$ after transmission through 2.54 mm of LiF.
- Fig. 5 (a) Transfer efficiency of a single photoelectron from gap C to gap PA versus $(V_2 - V_1)$ for fixed E_{PA} , E_T and E_{PC} .
- (b) Transfer efficiency of ≈ 213 photoelectrons from gap PA to gap T versus E_T/E_{PA} for fixed E_T and E_{PC} .
- (c) Transfer efficiency of ≈ 1000 photoelectrons from gap T to gap PC versus $(V_4 - V_3)$ for fixed E_{PC} .
- Fig. 6 (a) MWPC gain G_{PC} versus voltage V_4 for various TEA concentrations.
- (b) The pulse height (energy) resolution $(\Delta E/E)_{HWHM}$ of the 5.9 keV Fe^{55} X-ray peak versus TEA concentration for three different MWPC gains G_{PC} .

FIGURE CAPTIONS (Cont'd)

- Fig. 7 Preamplification gain G_{PA} versus $(V_3 - V_2)$ for various TEA concentrations.
- Fig. 8 Counting of the krypton UV source by an argon + TEA (2.6%) filled photoionization detector versus discriminator threshold for two values of E_{PA} .
- Fig. 9 Ring image experimental set-up showing gas radiator cylinder, mirror, detector, scintillators and collimator.
- Fig. 10 Connections to gas radiator: pumping system, gas feed system, gas outflow system and Penning vacuum gauge.
- Fig. 11 Cerenkov ring image system efficiencies versus photon energy E . Radiator gas transmission T_g , LiF window transmission T_w , relative TEA quantum efficiency $Q(E)/Q_{max}$, mirror reflectivity R and their product "total".
- Fig. 12 (a) Histogram of data points from 2000 incident pions. Solid line histogram is calculated using eq. (11) with $s = a = 2$ mm.
(b) Same as above, except E_C reversed so that no photoelectrons are collected from the G gap.
- Fig. 13 (a) Number of photoelectrons N per incident pion versus $(V_3 - V_2)$ for fixed E_C , E_T and E_{PC} .
(b) Number of photoelectrons N per incident pion versus V_4 for fixed E_C , E_{PA} and E_T .
- Fig. 14 (a) Histogram of data points for 2000 incident pions. Observed number of counts N_i at coordinate x_i versus x the projected ring image radius ($x = r \cos\phi$).
(b) Observed probability (data points) of N coordinates per incident pion versus N . The solid line histogram is a Poisson distribution for $\bar{N} = 1.3$.

FIGURE CAPTIONS (Cont'd)

- Fig. 15 (a) Histogram of data points for 8949 incident pions. Observed number of counts N_i at coordinate x_i versus x , the projected ring image radius ($x = r \cos\phi$).
- (b) Observed probability (data points) of N coordinates per incident pion versus N . The solid line histogram is a Poisson distribution for $\bar{N} = 1.6$.

Fig. 1

(a)

(b)

(c)

Fig. 2

0 5cm
Scale

Fig. 3(a)

Fig. 3(b)

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Discriminator threshold (arbit. units)

Fig. 8

Fig. 9

Fig.10

Fig. 11

Fig.12

Fig.13

Fig.14

Fig. 15