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Afterpulses in a Photomultiplier Tube Poisoned With Helium

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ABSTRACT

A five-inch photomultiplier tube (RCA #4522) was run continuously for eight weeks surrounded by a pure helium atmosphere. Although some evidence of afterpulsing was seen as early as the end of the first week, the fraction of pulses having afterpulses did not reach 15% until after four weeks. The gain of the tube was unaffected by the helium until about the sixth week when suddenly the gain dropped by a factor of 10. The temporal distribution of the afterpulses (600 - 1200 ns) is readily explained by the voltage distribution betweeen the cathode and the first dynode.

INTRODUCTION

When a photoelectron strikes a residual gas molecule near the cathode of a photomultiplier tube, there is a good chance that the ionized molecule will be accelerated back to the cathode. Here the ion is stopped. Several electrons are emitted. These are accelerated and multiplied by the dynode chain, thus forming an unwanted afterpulse. This phenomena was studied systematically by Morton, Smith, and Wasserman who directly introduced trace amounts of various gasses into photomultiplier tubes (PMT's)[1]. Subsequently, Coats[2,3] and Paske[4] identified helium as the contaminant which causes afterpulses in PMT's which are a few years old. Although helium is only a weak constituent of air, the atom is very small and can permeate readily through the glass envelope of the PMT. Additionally, PMT's are often used in laboratories where the ambient concentration of helium is artificially elevated by the emissions of dewars or gas Cherenkov counters.

The latter circumstance is particularly important for us. Our experiment to photoproduce charmed particles at Fermilab required using many expensive 5-in. PMT's to look for Cherenkov light inside a large, helium filled box[5]. Unavoidably there are small leaks from the box to the cylindrical shields which surround each PMT. Dry nitrogen flows through these shields, thus purging them of accumulated helium. To know how much nitrogen to use it is necessary to know what concentration of helium near a PMT is tolerable.

DESTRUCTIVE TEST OF PMT

In an attempt to find a tolerable concentration, we ran an RCA-4522 photomultiplier tube[6] in a pure helium atmosphere. This atmosphere was contained in a cylindrical magnetic shield which surrounded the tube entirely exept for the pins. Helium flowed continously into the shield at a rate of about 1 cm^3 per second; the purity of the exaust gas from the shild was monitored by a gas chromatograph.

A $\frac{1}{2}$-inch thick plastic scintillator was placed immediately in front of the PMT. A collimated ^{106}Ru source directed beta rays of 3.5 MeV maximum energy towards the scintillator irradiating it in a 1-cm diamter spot. The spot was generally located on the axis of the tube. Scintillation light from the stopping betas was seen by the cathode which emitted about 100 photoelectrons for a typical beta.

The fast anode pulse (3ns rise; 10ns fall) was amplified by a factor of 6. At the usual operating voltage of 3000 V, a single photoelectron gave an amplified anode pulse of about 75mV. The discriminator threshold was set at a slightly lower level so that a single photoelectron would be detected about 70% of the time; two photoelectrons, nearly 100%.

A logic pulse from the discriminator triggered both the start and stop circuits of a qVt time digitizer[7]. A cable delay was introduced before the start channel to prevent the same pulse from both starting and stopping the digitizer.

This unit scanned the time interval from 200 to 1200 ns after the receipt of a trigger pulse looking for an afterpulse. This pulse was generally 3 - 4 photoelectrons high.

OBSERVATIONS

The most careful study of the tube was done after four weeks of continuous exposure to helium. During this period the high voltage had been applied all the time and the ruthenium source had been present one quarter of the time. The gain of the tube as measured by the source pulse heights had changed by less than 3%.

After four weeks, the temporal distribution of the after pulses observed with the source present showed a main peak at 1000 ns and a secondary peak at 700 ns. (See fig. 1a). The total number of after pulses shown on the plot is 70,000. In this one minute exposure there were 450,000 triggers, so the probability of generation of an afterpulse was 16%.

Even when the radioactive source was removed after pulses were still generated. This background distribution (fig. 1b) is similar to the source distribution except that the secondary peak has disappeared. The total number of pulses in this plot is 40,000. In the 8 minute exposure there were 350,000 triggers, so the probablility of generating an afterpulse was 11%.

That the tube was still alive at all was surprising. Informal reports had indicated that similar tubes had suffered severe poisoning after shorter exposures to presumably smaller helium concentrations.[8] As is common in gas Cherenkov detectors, the

face of these poisoned tubes had been coated with a wavelength shifter Perhaps the wavelength shifter was much more effective than the normal glass surface in adsorbing helium, leading to an increased rate of permeation of helium into the PMT. To test this possibility, the tube was coated with a shifter of a customary kind; 0.2 mg/cm^2 peterphenyl topped by 270 Å of magnesium floride.[9]

The coating did affect the gain of the tube somewhat. But a comparison of the afterpulse distribution immediately after coating with one four days later showed no signifigant difference. Evidently the wavelength shifter did not grossly affect the adsorption of helium. The coated tube was left in its helium environment with the voltage on for an additional three weeks. Sometime during this period the tube died. Its gain decreased by a factor of ten.

These observations raise questions: Why was the early peak missing in the source absent data? Can the absolute rate of afterpulses reasonably be ascribed to helium permeation? Why did the tube die abruptly?

INTERPRETATION

At first glance, the appearance of peaks at all is a little surprising. Since the transit time of the photoelectron is only 40 ns, the peaks reflect bunching in the transit times of the helium ions. This bunching could arise because of a peak in the cross section for the ionization of helium by electrons. Yet this cross section is very broad; its width (at half maximum) spans the interval between 40 and 600 eV. At 150 eV, the cross section reaches a peak of 0.4 x πa_o^2, where a_o is the Bohr radius.[10]

Consider first only the region between the cathode and the first dynode at a potential difference of 1000 volts. If this potential were uniformly distributed, the ions would be accelerated at a constant rate and a distribution of after pulses dn/dt varying approximately as t would result. Alternatively, if the potential varied quadratically with distance from the cathode, $V = kz^2$, the ions would accelerate harmonically with a quarter period $t = (\pi/2)(ek/m(He^+))^{\frac{1}{2}}$ independent of production point.

To account for the distribution of after pulses we clearly need to use the actual axial potential distribution V(z). Since energy W is conserved, we readily obtain a first integral of the motion $W = eV(z_o) = eV(z) + \frac{1}{2}m(dz/dt)^2$. Thus the transit time t for helium ion produced a distance z_o away from the cathode is given by[11]

$$t = (2e/m(He^+))^{\frac{1}{2}} \int_{z_o}^{o} dz/(V(z_o) - V(z))^{\frac{1}{2}}. \qquad (1)$$

V(z) is plotted in fig. 2a[12]. The results of a numerical integration of Eq. (1) for various z_o are given in fig. 2b. Inspection of this figure shows that peaks in the time distribution occur at just those times for which t is stationary with respect to variations in z. Surprisingly, for this tube, distances and times are anti-correlated; the early peak at 700 ns

is associated with ions that are produced far from the cathode.[13]

This interpretation is corroborated by the absence of the early peak when the radioactive source is removed. In this case only one or two photoelectrons strike the first dynode. If one of these photoelectrons ionizes a helium atom close to the dynode, both secondary electrons are likely to be scattered at such an angle that they cannot be collected efficiently by the small dynode. Thus the first peak is absent because the probability of obtaining a trigger is reduced.

It seems evident that the structure of the afterpulses shows that they are produced by photoelectrons striking helium atoms between the cathode and first dynode (and not further down the multiplier chain as found in some tubes)[3]. To confirm this we consider the absolute rate of helium permeation through the envelope of the phototube.

In principle, helium can enter the tube through any of three surfaces: the spherical photocathode (Corning glass No. 9741), the cylindrical steel can which surrounds the cathode to first dynode region, or the tail section (glass No. 7052) which surrounds the dynodes. In practice, permeation through the steel can is so small that it can be neglected. The permeation of helium through the glass surfaces[14] is given by

$$dq/dt = K A \Delta p/d, \qquad (2)$$

Here dq/dt is the permeation rate, A is the area of the surface, and d is its thickness, Δp is the pressure difference and K is a constant which for either glass at room

temperature[14,15] is $10^{-11.8}$ cm^3 of He at STP - mm thickness/(sec-cm^2 area - cm Hg pressure). For the window of the RCA-4522, A = 130 cm^2, d = 2.5 mm; for the tail section, A = 240 cm^2, d = 2mm. The pressure ∆p is 76 cm Hg; thus dq/dt is 18 x 10^{-9} cm^3/sec. Since the tube's volume is 2500 cm^2, the pressure of helium inside the tube was 18 x 10^{-6} atmospheres after an exposure of 4 weeks.

To see whether this concentration is significant, it is convenient to calculate the electron's mean free path. In the region between the cathode and first dynode the average cross section for ionization is $0.25\pi a_o^2$. (See fig. 2c). Thus the mean free path for ionization of helium after four weeks is $1/n\sigma = 1/((2.5 \times 10^{19} cm^{-3} atomos.^{-1}) \times (18 \times 10^{-6} atomos) \times (0.20 \times 10^{-16} cm^2) = 110$ cm. Since the distance between the cathode and first dynode is 13 cm, there is a 12% probability that a photoelectron will ionize a helium atom.

This calculation is consistent with the background observation. There only one or two photoelectrons were emitted per pulse and the probability of afterpulsing was 11%. The calculation appears to contradict the data taken with the ruthenium source in place. Here trigger pulses containing up to 200 photoelectrons are often observed and yet the afterpulse probability was only increased to 16%. Surprisingly, the collimated source gives a bimodal pulse height spectrum. In addition to the normal bell-shaped beta spectrum, there is a sharp single-photoelectron peak. About 10 times more single photoelectrons than normal betas were recorded. This result, which we confirmed with a fresh tube, reflects the interaction in the scintillator of unwanted gamma-rays and bremsstrahlung from the source.

CONCLUSION

For an RCA-4522 photomultiplier tube surrounded by a pure helium atmosphere the probability of obtaining an afterpulse was observed to grow at a rate of 11% per four weeks or 3% per week per photoelectron in the trigger pulse. Typically, in a gas Cherenkov counter the atmosphere around the tube will be maintained so as to approximate that of natural air (5 ppm of helium) and a pulse of interest might contain 30 photoelectrons. When used in this fashion, it would require 750 weeks before there was a 1% chance of generating an afterpulse.

This conclusion assumes that the poisoning of the tube proceeds linearly with increasing exposure time and with concentration of helium. Calculations support this view, but it might be checked experimentally. Also the mechanism for the complete failure of the tube after six weeks is unexplained.

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FIGURE CAPTIONS

Fig. 1a. Time distribution of afterpulses obtained when source is present.

Fig. 1b. Background time distribution.

Fig. 2a. Variation of voltage with distance from cathode.

Fig. 2b. Calculated flight time of He^+ ion versus distance of production point from cathode.

Fig. 2c. Cross section for production of He^+ ion versus distance from cathode.

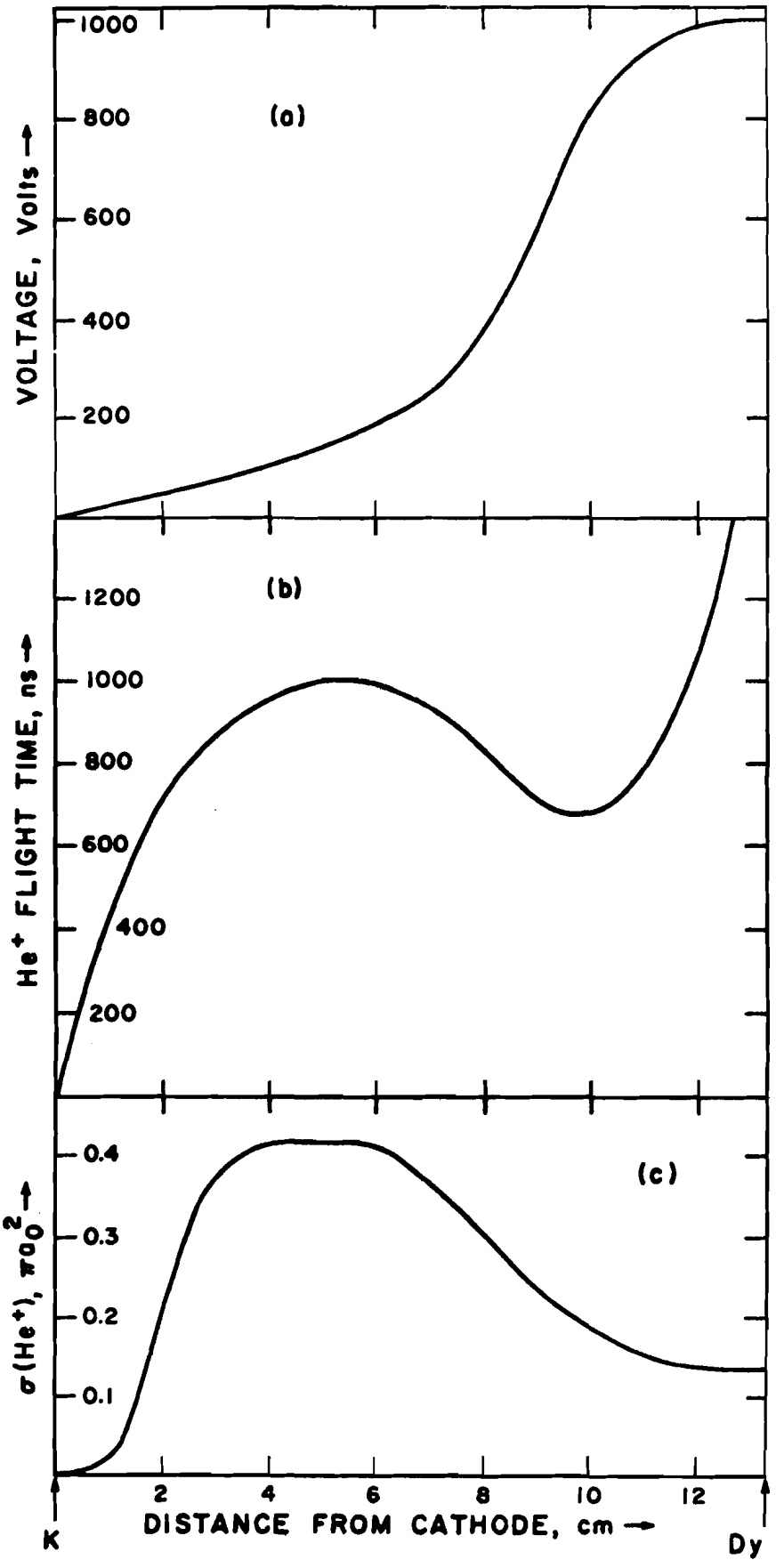
1000
800
600
400
200
(a)
VOLTAGE, Volts →
1200
1000
800
600
400
200
(b)
He+ FLIGHT TIME, ns →
0.4
0.3
0.2
0.1
(c)
σ(He+), πa0 2 →
2
4
6
8
10
12
DISTANCE FROM CATHODE, cm →
K
Dy I

Fig. 1

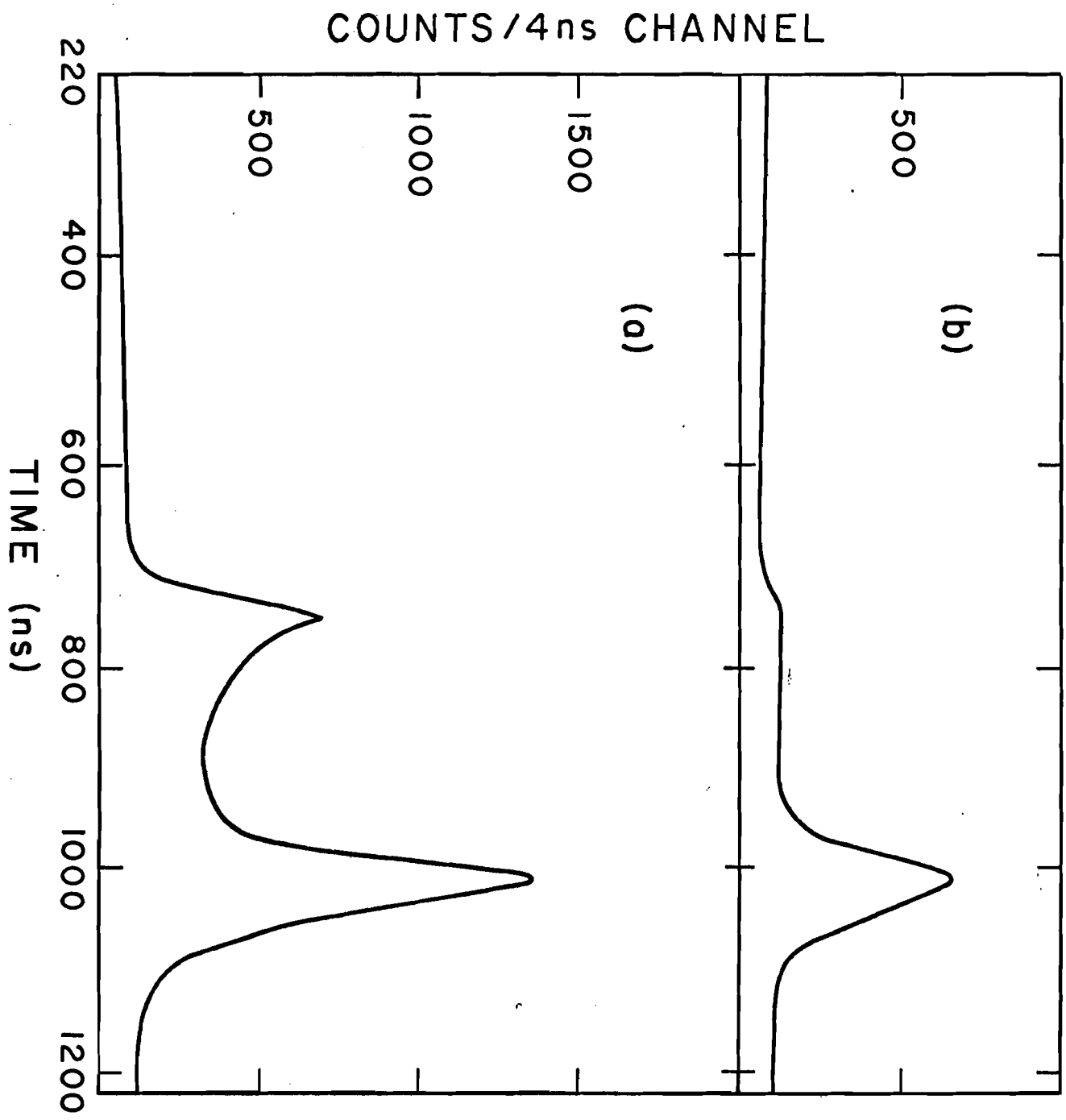
COUNTS/4ns CHANNEL
220
400
600
800
1000
1200
TIME (ns)
500
1000
1500
(a)
500
(b)

Fig. 2