TEST OF ELECTRICAL BREAKDOWN USING A POSITIVE PMT BASE IN AIR AND ARGON

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Abstract. A test has been performed to determine if the PMT dividers for the SHMS Cherenkov will breakdown in an atmosphere of argon. Paschen's Law is derived and written in terms of available constants and evaluated for inter electrode spacings in the divider. The test did not indicate any breakdown, consistent with Paschen's Law which indicates that much greater voltage must be imposed before a breakdown would occur.

1. Introduction

1.1. **Derivation of Paschen's Law.** In the late 19^{th} century, J.S. Townsend described the theory of the electron avalanche, which is the foundation on which Paschen's Law is derived. In his work, Townsend defined quantities that describe probabilities of collision in gasses, now called Townsend coefficients.

The first Townsend coefficient, α, also known as the ionization coefficient, is roughly the probability per unit length that an electron will strike and ionize a gas atom. Mathematically, this is given as $\alpha = \frac{exp\left(-\frac{\lambda_i}{\lambda_e}\right)}{\lambda_e}$, where λ_i and λ_e are the mean free paths of the ion and electron, respectively. Using simple kinetic theory, we can get an expression for λ_e. The mean free path for molecular collisions is given as the ratio of the distance traveled in the gas to the product of the effective volume of interaction and the number density of gas atoms. If the gas atoms have an effective (cross-sectional) area of σ, then the mean free path in a volume V is given as $\lambda_e = \frac{V}{N\sigma}$. Using the ideal gas law, $pV = Nk_BT$, we can write $\lambda_e = \frac{k_BT}{\sigma p} = \frac{1}{Ap}$, where $A = \frac{\sigma}{k_BT}$ is the first Paschen coefficient. Taking the electron energy at impact to be $E_e = e\lambda_e E_{br}$, where E_{br} is the (uniform) electric field at breakdown, we get a new expression for the first Townsend coefficient,

$$\alpha = Ap\, e^{-\frac{Bp}{E_{br}}}, \tag{1}$$

where $B = A\frac{E_i}{e}$ is the second Paschen coefficient.

Experiment conducted by Dr. Donal Day, Mikhail Yurov, and Dan Abrams, all affiliated with the Department of Physics at the University of Virginia.

Since we have assumed that the breakdown electric field is uniform, the breakdown voltage is given by $V_{br} = E_{br}d$, where d is the distance between electrodes. The above equation gives $E_{br} = \frac{Bp}{\log \frac{Ap}{\alpha}}$, and multiplying through by d gives the Paschen equation for the breakdown voltage

$$V_{br} = \frac{pdB}{\log pd + \log \frac{A}{\alpha d}} = \frac{pdB}{\log pd + C}, \tag{2}$$

where $C = \log \frac{A}{\alpha d}$ is the third Paschen coefficient.

In the formulation of Paschen's Law given above, the breakdown voltage is considered a function of the product of the pressure and distance, pd, as well as the distance d alone[2], since C is dependent on d; however, this dependence can be eliminated as shown below. The Paschen coefficients A, B, and C, depend on the environment through the temperature. They also depend on the specific gas and cathode used via the scattering cross-section σ, and the Townsend coefficient α. In the theory of Townsend, there is a second coefficient, γ, which is defined as the number of secondary electrons released from the cathode surface per incident ion. The Townsend coefficients are related by

$$\alpha d = \log\left(1 + \frac{1}{\gamma}\right), \tag{3}$$

an expression derived from Townsend's condition for electrical breakdown, indicated by infinite anode current density. Equation (3) allows C to be written in terms of γ by

$$C = \log \frac{A}{\log\left(1 + \frac{1}{\gamma}\right)}. \tag{4}$$

1.2. **Determination of the Townsend and Paschen Coefficients.** Determination of the Paschen and Townsend coefficients is usually done experimentally. There are a range of values for the ionization cross section σ reported in the literature. We shall use the value given by F.W. Lampe *et al.*, among others. We shall also assume that the experiment was conducted at "room temperature," given by 70 $^\circ F$. As for the nature of the electrodes, we are currently unaware of the metallic nature of the dynode pins, however, the wires that supply high voltage and read the signal from the base are soldered to it with tin.

Determination of C relies on a correct value for γ, a parameter that is highly dependent on the condition of the cathode surface[1]. Just as equation (1) gives the functional form of the first Townsend coefficient as $^{\alpha}/_{p} = f\left(^{E}/_{p}\right)$, a combination of (1) and (3) implies that γ will also be a function of the same variable, $\gamma = g\left(^{E}/_{p}\right)$. Hence, accurate determination of C would require knowledge of the functional form of $g\left(^{E}/_{p}\right)$ for our electrode material in air and argon, which could only be obtained through experiment. Hence, we must approximate a value for γ.

In the literature, authors such as Cobine give values of γ for different metals in a selection of gasses. For slow ions in argon, γ has values ranging from 0.058 to 0.22[1], for air, 0.017 to 0.077[1]. However, the CRC Handbook does list the maximum value for γ for electrons at 500 eV incident on tin at room temperature (assumed air at atmospheric pressure) as 1.35[4]. We will consider the following values for the second Townsend coefficient, $\gamma_{min} = 0.058$ and $\gamma_{max} = 1.35$. The corresponding values of C, given by equation (4), are $C_{min} = 1.375$ and $C_{max} = 3.031$. For any calculations, we shall use C_{max} as a worst-case scenario. All pertinent numerical values are listed in Table 1.

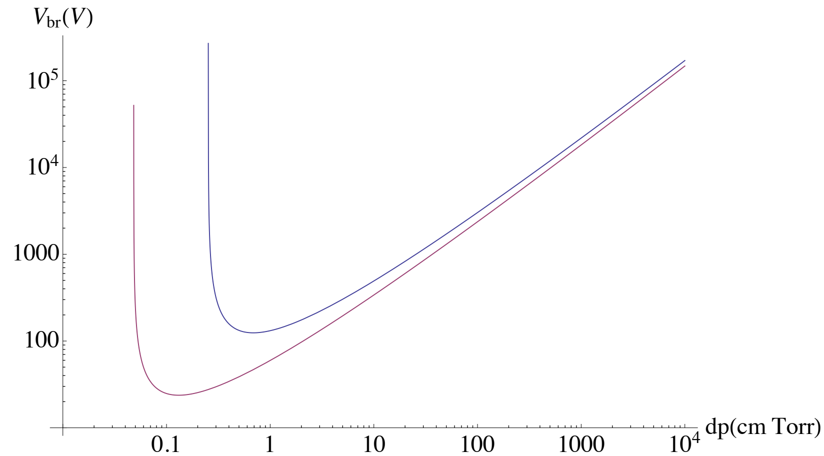

FIGURE 1. A Log Log plot of Paschen's Law with different values of C. The blue curve corresponds to C_{min}; the purple curve to C_{max}.

Quantity	Value
σ	3.5×10^{-16} cm^2 [3]
E_i	15.755 eV [4]
T	294.261 K
d_1	0.681 cm
d_2	0.781 cm
d_3	≈ 1 cm
A	11.486 Torr$^{-1}cm^{-1}$
B	180.898 V Torr$^{-1}cm^{-1}$
C_{max}	3.031

TABLE 1. Numerical values used in Paschen's Law for argon. Above, d_1 is the distance between adjacent HV dynode pins, and d_2 is the distance between the ground (green) and +HV (red) leeds, and d_3 is the distance between the ground and signal (yellow) leeds.

2. Description of Experiment

Our experimental apparatus consisted of a sealed environment within a bucket, and a plastic bag, in which we placed the positive PMT base. We customized the bucket to allow for HV and signal cables to be fed through and connected to the base. Positive high voltage was supplied to the base by a Bertan 5 kV power supply, designed to trip at 80% full scale meter range. We also placed valves in the side and lid of the bucket, allowing argon to be pumped into the interior. We recorded the voltage and current applied to the base with two multimeters connected to the front panel outputs of the Bertan power supply.

We ran two trials with the bucket, one with air inside, and one with argon. As a final test, we repeated the second trial with the PMT base inside a bag filled with a mixture of air and argon.

(A) (B) (C)

Figure 2. (A) The primary experimental apparatus. (B) The bag experiment. The bag is inflated with argon by the hose, and sealed with a plastic tie. Also pictured are the multimeters used to measure the voltage and current applied to the base. (C) An image of the base. During the experiment, the base is enclosed in a metal casing with wires soldered to the green, red, and yellow leeds. The dynode pins are arranged in a circular pattern around the edge of the circuit board.

3. Data

In the following tables, V_{mon} is the power supply voltage read by the multimeter. The next column, either I or HV, is the conversion from the panel output to the actual current or voltage supplied to the base. The voltage conversion is 10 V = 10 kV, and the current conversion is 10 V = 1 μA. The resistances were calculated using Ohm's Law.

Current		High Voltage		Resistance
V_{mon}	I [μA]	V_{mon}	HV [V]	R [MOhm]
0.014	1.4	0.01	10	7.14
0.079	7.9	0.05	50	6.33
0.157	15.7	0.099	99	6.31
0.479	47.9	0.3	300	6.26
0.793	79.3	0.499	499	6.29
1.603	160.3	1.004	1004	6.26
2.405	240.5	1.507	1507	6.27
3.2	320	2.001	2001	6.25

Table 2. Data for air.

Current		High Voltage		Resistance
V_{mon}	I [μA]	V_{mon}	HV [V]	R [MOhm]
0.011	1.1	0.01	10	9.09
0.076	7.6	0.05	50	6.58
0.154	15.4	0.099	99	6.43
0.476	47.6	0.301	301	6.32
0.792	79.2	0.498	498	6.29
1.598	159.8	1.001	1001	6.26
2.411	241.1	1.509	1509	6.26
2.561	256.1	1.602	1602	6.26
2.718	271.8	1.7	1700	6.25
2.886	288.6	1.805	1805	6.25
3.044	304.4	1.903	1903	6.25
3.209	320.9	2.006	2006	6.25

Table 3. Data for argon.

Current		High Voltage		Resistance
V_{mon}	I [μA]	V_{mon}	HV [V]	R [MOhm]
1.599	159.9	1.002	1002	6.27
2.396	239.6	1.499	1499	6.26
2.565	256.5	1.605	1605	6.26
2.71	272	1.701	1701	6.25
2.878	287.8	1.805	1805	6.25
3.046	304.6	1.904	1904	6.25
3.202	320.2	2.002	2002	6.25

TABLE 4. Data for argon bag.

4. Analysis and Conclusions

Using Paschen's Law, we can calculate at what voltage we would expect electrical breakdown to occur. Listed in Table 1 are the relevant distances between potential sparking elements on the base. For the air trial, we assume that the pressure in the bucket is atmospheric $p_{in} = 760$ Torr. For the argon trial, we estimate the internal pressure as $p_{in} = 746.43$ Torr (based on how the bucket was filled with argon). Estimated breakdown voltages and corresponding pd values are listed in Table 5. Figure 3 shows the estimated breakdown voltages on the Paschen curve, as well as the maximum voltage we applied to the base.

In our experiment, we did not achieve electrical breakdown. The HV power supply did not trip at any of the applied voltages, signaling the absence of sparking. Considering the specifics of our experimental apparatus, Paschen's law predicts electrical breakdown at voltages that are significantly higher than those used in our PMT based experiments with argon, even in the worst case scenario.

Gas	pd	Value [Torr cm]	V_{br} [V]
Air	pd_1	517.56	10088.7
	pd_2	593.56	11401.8
	pd_3	760	14225.6
Argon	pd_1	508.32	9927.8
	pd_2	582.9	11219.7
	pd_3	746.43	13997.7

TABLE 5. pd values and associated breakdown voltages for air and argon.

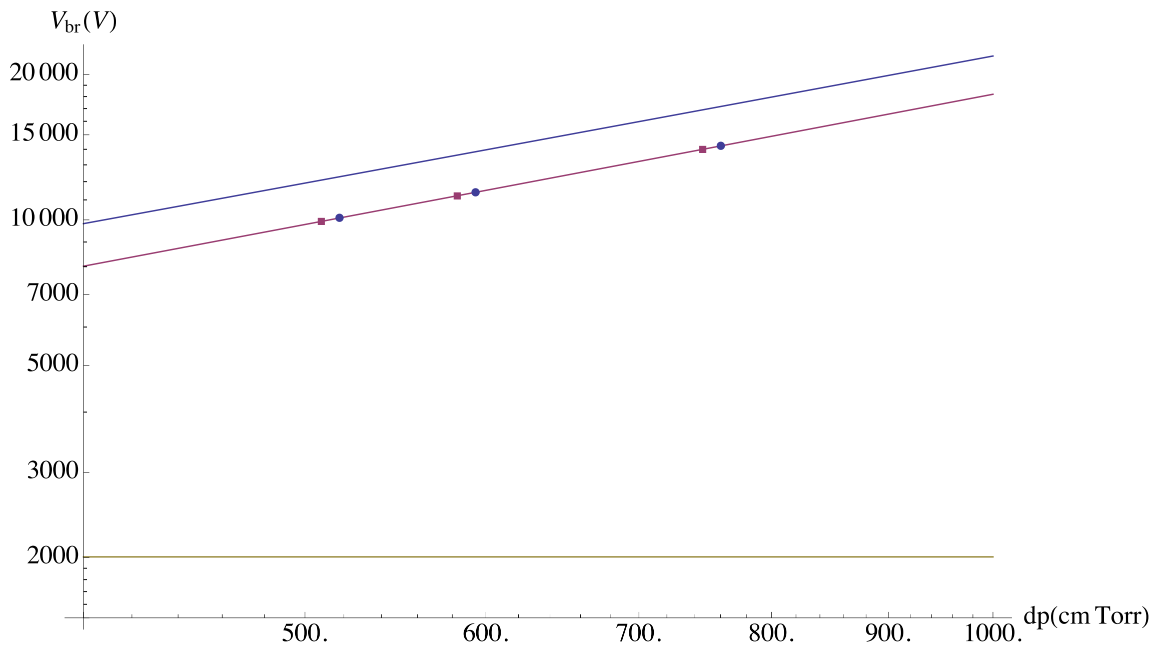

FIGURE 3. Log Log plot of Paschens Law with data points representing specific *pd* values. The horizontal line represents the largest voltage applied to the PMT base, $V_{PMT,max} = 2006$ V. Circular points represent air data, and square for argon. The blue curve is Paschen's law using C_{min}, the purple curve with C_{max}.

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