

Properties of Muon Drift Tubes

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Abstract

The Large Hadron Collider (LHC) at CERN will be used to search for the Higgs Boson. The Higgs Boson will not be detected directly, rather its decay products will be detected. One of types of decay products is the muon, which is why the ATLAS detector in the LHC will have a sophisticated muon detection system. ATLAS has about 300,000 muon drift tubes, so a detailed understanding of their properties is important. This paper examines the effects of temperature, pressure, and gas composition on the drift-time of electrons and also discusses the role of Penning ionization in enhancing the gas gain.

1 Drift-Time Dependence on Gas Properties

1.1 Introduction

GARFIELD is a computer program that simulates a particle traversing a muon drift tube. An ATLAS muon drift tube is a detector that consists of a $400\mu\text{m}$ aluminum tube filled with an Argon-CO₂ gas mixture with a $50\mu\text{m}$ gold-plated W-Re anode wire running down the axis that is held at 3080V above the tube. An electronic sensor detects currents produced in the wire due to an avalanche of electrons created from ionizations. An avalanche occurs when a small number of initial electrons are accelerated by an electric field until they have enough energy to ionize gas molecules, which creates more electrons that are again accelerated, and the process escalates exponentially.

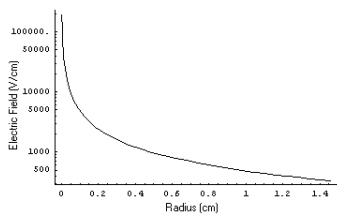


Figure 1: Electric field

These avalanches occur primarily within a few wire-diameters of the wire. As the avalanche approaches the anode wire, electrons in the wire are displaced to the sides by the repulsive force of the electrons in the avalanche. It is this displacement that causes the current in the wire that is detected, the electrons themselves are never absorbed by the wire.

Conceptually, the simulation process goes as follows. The user designs the tube by specifying its dimensions, the gas composition, the gas

pressure, the location(s) of anode wire(s), and the voltage of the anode wire(s). Then the user calculates the range of electric field that this would produce. This range and the gas properties are given to a program called MAGBOLTZ[2] that performs a Monte Carlo simulation to determine the drift velocities, longitudinal diffusion coefficients, transverse diffusion coefficients, attachment coefficients, and Townsend coefficients of electrons in such a gas with varying electric field strengths in the given range.

For each prescribed electric field strength, MAGBOLTZ drops an electron with zero velocity at the origin of a 3-dimensional space with the electric field along a particular axis, say the $-z$ axis. Then the electron is pulled up the z axis by the electric field for a fixed amount of time dt , which is chosen by the “null collision” technique. At this time, the electron undergoes a collision with a gas molecule, and the parameters of the collision are determined by random numbers. The parameters for this “Monte Carlo Simulation” include the kinetic energy loss and the 3D scattering angles. The target molecule is assumed to be stationary, which could presumably be a poor assumption for some gases, but not for our purposes. After the collision, the electron is again under the influence of the electric field for another time step dt . The pattern of being pulled by the electric field and then colliding with a gas molecule is repeated many times. The number of repetitions is given by 960,000 times the number passed to MAGBOLTZ in the ‘collisions’ parameter. After this many collisions have occurred, the final height of the electron along the z axis is divided by the total time to get the drift velocity. The output of MAGBOLTZ is a “gas file” that contains all the properties calculated from Monte Carlo simulation for each electric field strength.

GARFIELD knows that the average drift velocity must be in the direction of the electric field, so for each point in the detector, it can calculate the electric field there, then look up the magnitude of the drift velocity from the gas file, and set the drift velocity to be in the direction of the electric field with that magnitude.

An incoming muon can now be simulated by GARFIELD. The track of the muon is specified by the user in the same coordinates used to define the tube dimensions. A program called HEED is given the gas properties and it determines when the muon will ionize the gas molecules in the tube. GARFIELD then uses the drift velocity values to compute the drift-lines of these electrons and ions under the influence of the electric field.

1.2 Simulation and Results

We used GARFIELD to simulate a muon traversing a drift tube just inside the tube wall. The simulation produced ionization electrons along the muon’s track. The electrons then drifted to the anode wire starting from just inside the wall of the drift tube, forming a drift-line. After simulating 100,000 muon tracks, with many drift-lines per track, we obtained a Gaussian distribution of drift-times, where the drift-time is the time it takes for an electron to traverse its drift-line. We measured the drift-time at the center of this Gaussian distribution, which

we call t_{max} because it is the maximum time in the sense that it started as far as possible from the anode wire. This value t_{max} is affected by the gas because the gas affects the mean free path of electrons and gas molecules can absorb or contribute to the kinetic energy of electrons. This simulation process was repeated several times after tweaking either the temperature, pressure, or CO₂ fraction of the gas. The central point in parameter space was at a temperature of 20°C, a pressure of 3 bar, and a CO₂ fraction of 7%. These are the parameters that will be found in ATLAS's muon drift tubes. Temperature was varied from 15°C to 25°C in increments of 1°C, pressure was varied from 2.7 to 3.3 bar in increments of 0.1 bar, and CO₂ fraction was varied from 6.5% to 7.5% in increments of 0.1%. The results are provided in Tables 1-3. The t_{max} values are the centers of Gaussian distributions of drift-times and the errors are the widths of these Gaussian distributions. Each data point took about two days of processor time on a 3GHz Pentium 4. We exploited three machines with a total of five processors to obtain this data.

T (°C)	15	16	17	18	19	20	21	22	23	24	25
$t_{max}(ns)$	743.55	741.29	738.03	735.26	732.17	729.53	727.31	724.27	721.34	718.72	716.14
Error(σ)	8.9796	8.8852	8.8847	8.8048	8.9263	8.8626	8.9412	8.8247	8.8188	8.9291	8.8504

Table 1: Maximum Drift-Time in nanoseconds for a gas of 93% Ar, 7% CO₂, at a pressure of 3 bar, and a temperature given in the first row of the table.

P (bar)	2.7	2.8	2.9	3.0	3.1	3.2	3.3
$t_{max}(ns)$	654.24	678.39	704.18	729.53	755.54	781.15	807.00
Error(σ)	8.5604	8.8190	8.8406	8.8626	8.8702	8.9126	8.9481

Table 2: Maximum Drift-Time in nanoseconds for a gas of 93% Ar, 7% CO₂, at a temperature of 20°C, and a pressure given in the first row of the table.

CO ₂ %	6.5	6.6	6.7	6.8	6.9	7.0	7.1	7.2	7.3	7.4	7.5
$t_{max}(ns)$	685.13	693.91	702.92	711.41	720.04	729.44	738.64	748.68	756.68	766.25	774.73
Error(σ)	8.7202	8.8260	8.8943	8.8857	8.7580	8.9123	8.9526	8.9716	8.9193	8.8996	8.8998

Table 3: Maximum Drift-Time in nanoseconds for a gas of Argon and CO₂, at a pressure of 3 bar, at a temperature of 20°C, and a CO₂ fraction given in the first row of the table.

1.3 Analysis and Conclusion

The data in Tables 1-3 are all very linear, to the extent that the plots all look like straight lines. ROOT was used to compute linear fit parameters for the data. The slope for the CO₂ plot of 90.15 ± 8.4 turned out to be farther from the experimental value of 69.6 ± 0.7 than the previous GARFIELD simulations that found a slope of 83.55 ± 0.01 [1], despite the high statistics we used. However, we compiled two complete sets of data, one with 10 times more statistical

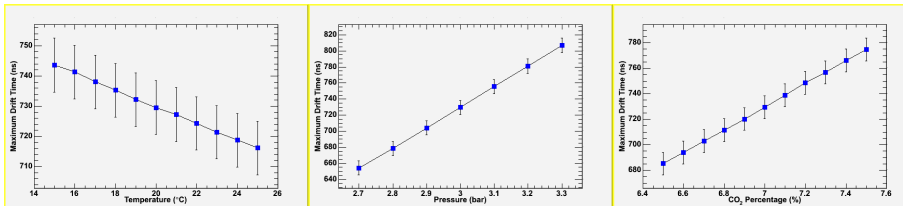


Figure 2: Maximum Drift Times for varying temperature, pressure, and CO₂ fraction of the drift tube gas.

calculation than the other, and the resulting slopes were barely affected. This seems to indicate that our current level of statistics is sufficient. Therefore it is possible that the discrepancy is due to inadequacies of the experimental measurements. Possibly the experiment's gas had contaminations or was not held at a highly stable pressure and temperature.

2 The Effects of Penning Transfer on Gas Gain

2.1 Introduction

Drift tubes detect the passage of particles through them by measuring an electric current that is generated by ionization of a gas. As the particle passes through the gas, it interacts with gas molecules and causes ionization of the gas molecules. However, for each electron that gets produced in these primary ionizations, many more get produced in the avalanche that results as the electron gets accelerated by the strong electric field near the anode wire. The ratio of total ionizations to primary ionizations is called the gas gain. It is a measure of how much an avalanche multiplies the measured number of ionizations.

We will assume a gas composed entirely of Argon and CO₂ as in the ATLAS muon drift tubes. During an avalanche, free electrons are being accelerated to the point where they have enough energy to cause an ionization. However, at the same time these electrons are causing D-Level excitations of Argon to 14.0 eV above the ground state. A D-Level excitation is an excitation in which the excited electron is found in the d orbital. CO₂ has an ionization potential of 13.77 eV, so when an excited Argon atom collides with a CO₂ molecule, it can cause ionization of the CO₂ molecule. This is known as Penning Transfer.

Our objective is to theoretically determine the probability of Penning Transfer. Only certain excited states of the gas molecules will have enough energy to cause Penning ionization, in this case only the D-Level excited state of Argon. The probability of Penning transfer will be defined as the fraction of the *energy* in these excited states that will *eventually* cause ionization by the Penning process. This probability will be written as P_p . It is important to use the words 'energy' and 'eventually' in order to allow for intermediate types of energy that can cause ionization, such as photons.

2.2 Empirical Calculation

The first step is to get an approximate value of P_p in order to guide the theoretical analysis. This is important because one starts with a whole set of neglected factors and must choose which ones to consider based on whether you want to raise or lower the current estimate. The standard technique for calculating P_p is to make an expression for the gas gain as a function of P_p and vary the parameter P_p until the experimentally determined gas gain is produced.

To create the expression for the gas gain, we first need to know the Townsend coefficient of ionization at each point in the tube. The Townsend coefficient of ionization is simply the number of ionizations per centimeter for a given electric field. MAGBOLTZ is a program that is capable of generating the time rate of excitations and ionizations per free electron[2]. Dividing by the drift velocity converts these into rates per length. If $R_{Ar}^{Ionization}$ is the Argon ionization rate, $R_{CO_2}^{Ionization}$ is the CO₂ ionization rate, and $R_D^{Excitation}$ is the Argon D-Level excitation rate, then the Townsend coefficient can be expressed as $\alpha = (R_{Ar}^{Ionization} + R_{CO_2}^{Ionization} + P_p * R_D^{Excitation})/v_d$, where v_d is the drift velocity of an electron.

Now say $n(r)$ is the number of electrons that are created by the time an avalanche reaches as close as r from the center of the tube. Then the total rate of ionization at this radius is given by $\frac{dn}{dr} = n(r)\alpha(r)$ since we must multiply the rate per electron by the number of electrons present. Therefore, $\frac{dn}{n} = \alpha(r)dr \Rightarrow \int \frac{dn}{n} = \int \alpha(r)dr \Rightarrow \log(n) + C = \int \alpha(r)dr \Rightarrow n(r) = n_0 \exp(\int \alpha(r)dr)$. Here n_0 is the initial number of electrons, which we take to be 1 so that $n(r_w)$ is the gas gain if r_w is the radius of the central anode wire. The integral is over the path of the avalanche, which is taken to be radially inward toward the wire from r_t to r_w , where r_t is the radius of the inner side of the drift tube.

According to the Diethorn formula, the gas gain of a mixture of 93% Argon and 7% CO₂ should be approximately 20,000[3]. Therefore $n(r_w)$ should equal 20,000 for an appropriate choice of P_p . Using Mathematica to perform a Gaussian integration for $n(r_w)$ and manually varying P_p between integrations by a binary search, the expected gas gain was achieved when $P_p = 0.231561$. This value serves as the starting point for a theoretical analysis.

2.3 Theoretical Considerations

In order to theoretically estimate the probability of Penning ionization, we need to consider all possible outlets of the excitation energy. An excited Argon atom is unstable, so its energy will soon to be converted to some stable form. The conceivable destinations are ionization of CO₂, kinetic energy, and escape from the tube.

First we will determine if deexcitation by photon emission is significant. We want to know if deexcitation can occur before a collision (i.e. another collision - not counting the collision that caused the excitation), so we calculate the mean free time via the mean free path equation. The mean free path of atoms in a gas is given by $\lambda = \frac{RT}{\sqrt{2}\pi d^2 N_A P}$, where d is the molecular diameter[4]. For the

gas under consideration, $T = 293K$, $P = 3bar$, and $d_{Ar} = 3.76\text{\AA}$ [5]. Therefore, $\lambda = 2.1468 * 10^{-8}m$. At a temperature of 293K, the mean kinetic energy of the gas molecules is $\langle KE \rangle = \frac{3}{2}kT = 0.04eV$. So for an Argon atom, the velocity is determined by $KE = \frac{1}{2}m_{Ar}v^2 = 0.04eV \Rightarrow v = \sqrt{\frac{0.08eV}{40/N_A}} = 14m/s$. The mean free time is the mean free path divided by the mean velocity, which is

$$t_{mft} = \lambda/v = 1.5 * 10^{-9}s.$$

The deexcitation rate of a population of any atom in any state is given by $N(t) = N(0)e^{-t/\tau}$ where τ is the natural radiative lifetime. The inverse of τ is called the Einstein A coefficient or the transition probability. Tables of transition probabilities can be found in [6] and [7]. These sources do not contain data for an emission line at 886eV, which corresponds to 14.0 eV, but [7] has information for 876eV, which is very close. The transition probability given for this energy is $A = 2.70 * 10^8/s$, which gives the natural radiative lifetime

$$\tau = 1/A = 3.7 * 10^{-9}s.$$

When we compare the natural radiative lifetime with the mean free time, we notice that they are the same order of magnitude. In fact, if every collision occurred exactly at the mean free time, then we can estimate the probability that an excited Argon atom will deexcite before a collision: $\int_0^{1.5*10^{-9}s} \frac{1}{\tau} e^{-t/\tau} dt = 0.333$. So there would be a 1 in 3 chance that an excited Argon atom would deexcite before undergoing any collisions. Therefore, we must consider the effects of photon deexcitation.

In the cases where an excited Argon atom does deexcite via photon emission before a collision, the photon basically plays the same role as the excited Argon atom. The photon will see roughly the same cross sections for collision with gas molecules because the cross sections are primarily determined by the target. A photon could excite another Argon atom, but this does not change the situation, so it will not change the probability of eventual penning transfer—it will only make it take longer. Also, a photon could potentially escape to the wall of the tube, but due to the short mean free path, this is unlikely, and even if a photon did reach the wall, it would probably be reflected since the walls are made of Aluminum, which is a highly reflective metal when not oxidized. However, if the excited Argon atom undergoes a 2-step deexcitation, then the situation changes and the energy is less likely to cause ionization. This is because the photons will leave in different directions and possibly neither one will possess the ionization energy of CO₂ on its own. But at this stage we have no evidence that we need to worry about 2-step deexcitations due to the fact that the experimental information is difficult to find.

Finally, after all this analysis we have learned that we ignore the deexcitation of excited Argon atoms and it won't affect the value of P_p . Furthermore, we learned that there is no mechanism for energy to escape from the tube, so the only two destinations for the energy initially stored in D-Level excitations of Argon are ionization of CO₂ and kinetic energy.

Excited Argon atoms will frequently collide with unexcited Argon atoms. In this case, they may undergo an inelastic collision of the second kind. This term refers to a collision in which the excitation energy is converted to kinetic energy of the atoms. This type of inelastic collision, along with the first kind in which kinetic energy is converted to excitation energy, are responsible for maintaining the relation between thermal energy and excitation energy specified in the Boltzmann factor. When a collision of the second kind occurs, the kinetic energy is quickly spread by elastic collisions and it becomes increasingly unlikely that an ionization will occur. It is possible for a collision of the first kind to cause a reexcitation, but this is thermodynamically unfavored at 293K. Therefore, we may assume that Penning transfer is ruled out after a collision of the second kind.

There are some other concerns that can influence the predicted value of P_p . The value found in the empirical calculation is not limited to just Penning ionization. Another effect is Associative Ionization, which is when two excited molecules collide and one of them is ionized. This may be worth consideration, but here we ignore it on the grounds that there are probably many more unexcited molecules than excited ones, so the probability of two excited ones colliding should be much lower. The theoretical calculation does not include associative ionization, a method for determining the concentrations of excited states in an avalanche will have to be developed before this can be analyzed. This is difficult because it requires a knowledge of the non-radial spread of the avalanche.

In the empirical calculation, only D-Level excitations were considered because this is the only excited state with enough energy to ionize CO_2 . However, if an Argon atom excited to a state with lower energy collided with a CO_2 molecule and there was enough relative kinetic energy, then ionization would still be possible. It turns out that this is not a significant effect because the kinetic energy required is so high that there is an extremely low probability that a gas molecule would possess it. The next highest energy level of Argon is the P-Level at 13.0 eV above the ground state energy. Since the ionization energy of CO_2 is 13.773 eV, an atom would need a kinetic energy of 0.773 eV to assist the ionization. However, the average energy of molecules in a gas at $T = 293\text{K}$ is $\langle KE \rangle = \frac{3}{2}kT = 0.04\text{eV}$. To determine the probability that a molecule will have enough energy, we use the Boltzmann factor $P(E) = Ae^{-E/kT}$. Normalizing, $\int_0^\infty Ae^{-E/kT} dE = 1 \Rightarrow AkT \int_0^\infty e^{-x} dx = 1 \Rightarrow AkT[-e^{-x}]_0^\infty = 1 \Rightarrow A = \frac{1}{kT}$. So the probability is $\int_{0.773\text{eV}}^\infty \frac{1}{kT} e^{E/kT} dE = \frac{1}{0.2525\text{eV}} \int_{0.773\text{eV}}^\infty e^{E/0.2525\text{eV}} dE \cong 5 * 10^{-14} \approx 0$. This demonstrates that the effect is safely negligible.

2.4 Theoretical Calculation

The last section shows that the only significant processes are Penning ionization and inelastic collisions of the second kind. Each of these processes has a specific cross section that can be measured. Collisions can occur in which neither of these processes take place, but since these don't have any measurable effect, we

can neglect them.

A Penning transfer can only occur when an excited Argon atom collides with a CO₂ molecule. Inelastic collisions of the second kind will occur with some cross section when an excited Argon atom collides with an unexcited Argon atom. They could also occur with CO₂, but Penning transfer will take precedence, so this will not happen. So P_p is just the probability that an excited Argon atom will collide with a CO₂ molecule before it collides with an Argon atom. This means that P_p can be calculated by dividing the total Penning cross section of all CO₂ molecules by the total cross section of all relevant collisions. If f is the fraction of CO₂, then the probability that an excited Argon atom will cause Penning ionization is

$$P_p = \frac{f * \sigma_{Penning}}{f * \sigma_{Penning} + (1 - f)\sigma_{Inelastic}}$$

where $\sigma_{Penning}$ is the cross section for Penning ionization, and $\sigma_{Inelastic}$ is the cross section for inelastic collisions of the second kind involving one excited atom and one unexcited atom. We can estimate $\sigma_{Inelastic}$ by πr^2 , where r is the van der Waal's radius of the atom that does the Penning ionization (typically Argon or Neon). The van der Waal's radius is calculated from the inter-atomic spacing at the critical volume of a gas and is used whenever considering unbonded atoms. This is a suitable estimate of the cross section for collisions of the second kind, though it would be better if a precise measurement could be made.

It seems that the Penning cross section for Ar*+CO₂ has never been measured, but it has been measured for Ne*+CO₂ [8]. The cross section for Ne*+CO₂ at 100 meV is about 48Å². This is the lowest energy found in the data, but it is not low enough because the atoms in the gas are at about 40 meV. However, the energy dependence is fairly low near 100 meV, with a slight upward trend for decreasing energies.

In ALICE, $f = 0.10$ and Neon has a van der Waal's radius of $r = 1.54\text{\AA}$, so the estimation equation gives $P_p = 0.41719$. Rob Veenhof used GARFIELD to empirically determine P_p and found a value of approximately 0.4[9]. In ATLAS, $f = 0.07$ and Argon has a van der Waal's radius of $r = 1.88\text{\AA}$, so if we assume that the Penning cross section for Argon is the same as for Neon, then the estimation equation gives $P_p = 0.245499$. This is close to the value of 0.231561 found by the empirical method. Both of these numbers appear to be within the expected errors, which seems to suggest that the basic concepts of the estimation equation are correct.

2.5 Conclusion

The equation is probably not yet useful as a tool, but the ideas that it represents will likely serve as the foundation for future theories of Penning transfer probability. Steps that still need to be made: quantify the effects of associative ionization, make actual measurements of the Penning cross sections, and better understand the process of inelastic collisions of the second kind.

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