TRIUMF Experiment E614
Technical Note

Muonium Formation in Helium Gas and the Choice of Whether or not to Use Central Proportional Chambers

D.H. Wright, TRIUMF

18 November 1997

Abstract

Two designs for the central region of the E614 spectrometer were re-evaluated using new information on the polarization of muons in various materials. New values of P_μ in mylar and CF_4-ISO gas were used. It was also found that P_μ in He gas was not the same as that in liquid, and had to be replaced by a rough estimate based on muonium formation in gas. The resulting overall depolarizations strongly favor the use of central PCs unless precise polarization measurements can be made before the time of the design decision.

In a previous Technical Note [1], two design options for the determination of the muon stop location in the E614 spectrometer were compared. Based on estimates of the muon depolarization in the various media near the stopping target, the option including proportional chambers (PCs) next to the target was preferred to that with helium gaps next to the target. The depolarization values used in that study are summarized in Table 1. It was also assumed that the proportional chamber inefficiency was 0.001.

Material	$1 - P_\mu$
Al Target	0.00
He gas (STP)	0.05
DME (STP)	0.05
CF_4-ISO (STP)	0.015
Mylar	1.00

Table 1. Muon depolarization values used in previous analysis.

While it has recently been determined that 0.001 is a reasonable value for chamber inefficiency, two of the depolarization values were found to be incorrect. From experience with MEGA [2], it has been found that a more reasonable estimate of the depolarization in mylar is 0.05. Also, the depolarization in helium gas was taken to be the same as that in liquid, an assumption which ignores the large effect of low density on muon depolarization. To date there have been no measurements of muon depolarization in helium gas in longitudinal magnetic fields. There is however a measurement at 1.18 atm in small transverse fields yielding a depolarization of 0.25 ± 0.03 [3].

Muonium Formation in Helium Gas

An estimate of the polarization in strong longitudinal fields requires some knowledge of muonium formation, which is the dominant depolarization mechanism in helium. A summary of work done in this field is given in [4]. When a surface μ^+ enters a gas it loses energy by Bethe-Bloch ionization. In helium this process is dominant down to about 30 keV. At 60 keV, when the muon velocity begins to be comparable with that of the atomic electrons, the first charge-exchange occurs with the formation of muonium (Mu). From 60 keV down to about 30 eV, cyclic charge exchange

$$\mu^+ + He \leftrightarrow Mu + He^+ \tag{1}$$

occurs along with elastic energy loss. Below 30 eV there is too little energy to form many muonium atoms and the μ^+ resides in a $MuHe^+$ molecule where it no longer suffers depolarization. Very little depolarization occurs while the muon is free, leaving muonium as the major cause. When a 100% polarized muon captures an atomic electron, the muonium states

$$|11>, \quad \frac{1}{\sqrt{2}}|10> + \frac{1}{\sqrt{2}}|00> \tag{2}$$

are formed with equal probability. The first state is an eigenstate of the hyperfine interaction while the second is not. For each muonium formation there is thus a 50% chance that the muon will be in a state which flips its spin and flips it back with a period of 0.224 ns. Hence the longer the muon stays in muonium, the more likely it will be depolarized. The time spent in muonium is governed by the incident muon energy and the density of the helium gas it passes through. The lower the density, the fewer charge exchange cycles (Eq. 1) occur and the longer the muon spends in muonium. This scenario is confirmed by muon polarization measurements in small transverse fields. As shown in Fig. 1, the depolarization increases as the helium pressure decreases.

In large longitudinal magnetic fields the depolarization per collision (charge exchange) is significantly reduced, but not by enough to compensate for the relatively small number of collisions in the gas. Per muonium formation the muon depolarization is given by [5]

$$P_\mu = \frac{1}{2}[1 + \frac{X^2}{1+X^2} + \frac{cos(\omega_{HF}\Delta t)}{1+X^2}] \tag{3}$$

where $\omega_{HF} = 4463$ MHz is the hyperfine oscillation frequency, Δt is the time the muon spends in muonium and

$$X = \frac{B}{B_o} = \frac{22000}{1585} = 13.88 \tag{4}$$

for a longitudinal field of 2.2 T. Due to the low density in helium gas at 1 atm, Δt is of order 0.2 ns or greater so that $cos(\omega_{HF}\Delta t)$ averages to zero. The last term in Eq. 3 can then be dropped to give

$$P_\mu/\text{collision} = 0.9974. \tag{5}$$

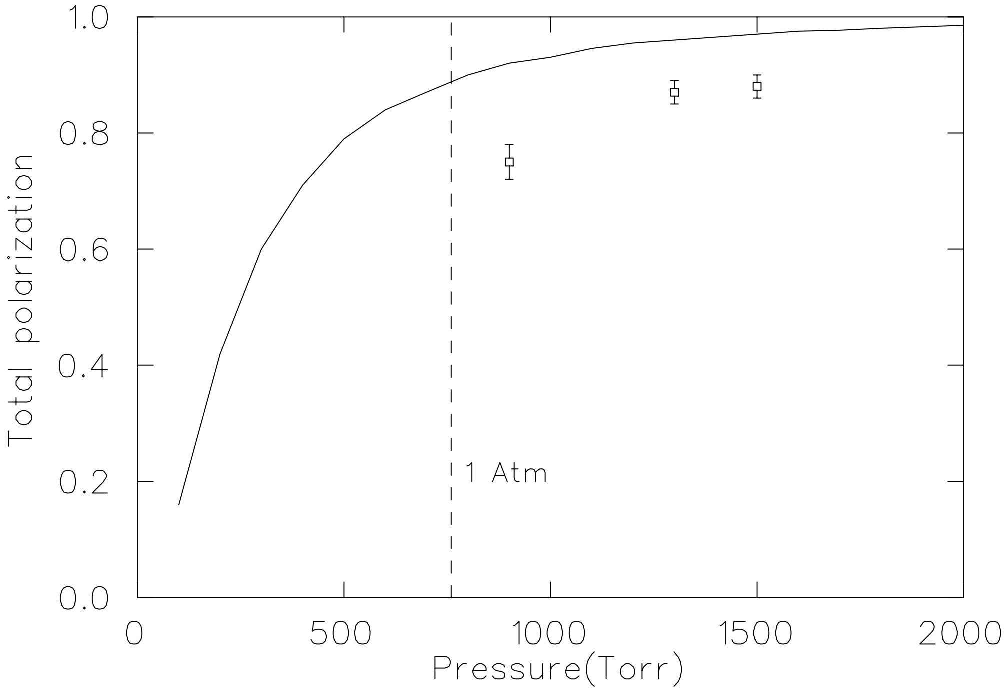

Figure 1: Muon polarization in He in small transverse magnetic fields. The calculation (solid curve) and data points are from [3].

There are roughly 100 $\pm$ 50 collisions in the muonium regime, so that an estimate of the total polarization before stopping is

$$P_\mu = 0.9974^{100\pm50} = 0.77 \pm 0.10. \tag{6}$$

The depolarization is therefore large; more importantly the uncertainty in the depolarization is large. In addition, the case of small transverse magnetic fields (Fig. 1) shows a large deviation of measurement from calculation, decreasing confidence in the estimate for longitudinal fields.

No Proportional Chambers Adjacent to Target

An earlier Monte Carlo study (see Table 1 of [1]) of the spectrometer with no proportional chambers next to the target determined an average depolarization for muons stopping in and around the target of 2.3×10^{-3}. This method tracked both the positron and incoming muon in order to determine the decay vertex. It also arranged for a symmetric stopping distribution of muons in the target. At first glance, better values of muon polarization greatly improved the situation. Taking the muon depolarization in mylar to be 0.05 instead of 1.0, and taking the depolarization in He gas to be 0.002 (Strovink, liquid) instead of 0.05, lowered the overall depolarization to 1.5×10^{-4}. However, the above estimate for polarization in He gas 0.77$\pm$0.10 raises the overall depolarization and its error to an unacceptable level,

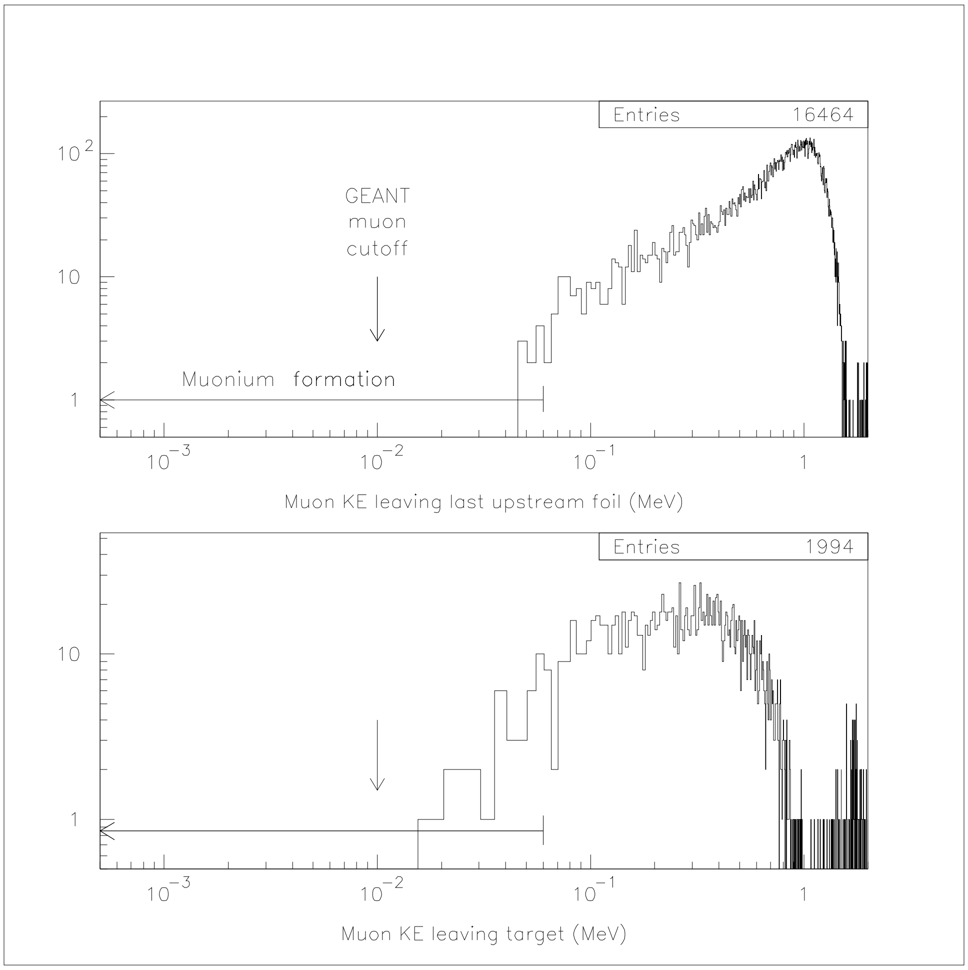

Figure 2: Kinetic energy of muons entering helium gaps upstream (top) and downstream (bottom) of the target.

0.011 ± 0.001 .

The kinetic energies of muons entering the helium gaps just upstream and downstream of the target are shown in Fig. 2, compared with the energy range over which muonium formation occurs. All but a few muons entering the helium gaps have energies above that of the first muonium formation and none have energies below that of the last muonium formation. Hence any muon stopping in the gaps must pass through the entire muonium regime, the last few cycles of which are highly depolarizing.

The roughness of the above estimate and the lack of muon polarization data in helium gas in longitudinal fields make a measurement of this parameter imperative if the no-PC option is to work. Even if such a measurement were performed the following problems arise with the no-PC option:

1) If the measured polarization in He is much different from 1.0 (such as 0.77), a sizable

correction to the measured value of $P_\mu\xi$ will be required. The precision of the polarization in He must then be very high ($\pm$ 0.0004) in order to attain an uncertainty of 3×10^{-5} in the corrected $P_\mu\xi$.

2) Muonium is much more likely to form in gases with low ionization potentials such as hydrocarbons and heavy noble elements. The He gas likely to be used in the gaps will have total impurities of about 50 ppm much of which could be hydrocarbons. Studies of muons stopping in He-Xe mixtures show that complete depolarization can occur when the Xe concentration is only a few ppm [5]. Methane, for example, which has nearly the same ionization potential as Xe, could pose a serious problem unless the He gas is first passed through a cold trap to remove hydrocarbons.

Proportional Chambers Adjacent to Target

The Monte Carlo simulation of the PC option was repeated with two additional pieces of information:

1) The muon polarization measured for the PC gas (CF_4-isobutane) was > 0.985. In the present calculation it was assumed that the measured value of $P_\mu\xi$ will be corrected for the central value of the depolarization in CF_4-ISO, with only the error bars contributing to the total error in $P_\mu\xi$. Therefore $P_{\mu CF4-ISO}$ was taken to be 0.992 ± 0.008.

2) ADCs were added to the wires of the central proportional chambers. Muons stopping in the PC just upstream of the target look as if they have stopped in the target since they satisfy the trigger condition

$$PC(-2)\cdot PC(-1)\cdot \overline{PC(+1)\cdot PC(+2)} \tag{7}$$

and hence increase the error in the overall polarization. Using ADCs to distinguish between muon and positron pulse heights, the additional condition

$$PC(-1)_\mu\cdot \overline{PC(+1)_\mu}\cdot \overline{PC(-1)_e}\cdot PC(+1)_e \tag{8}$$

removes events in which a muon stops in the upstream chamber (PC(-1)) and has a decay positron traveling downstream. In addition, tracking of the decay positron in PC(-1) will allow some events to be removed in which the positron travels upstream with initial angles $> 45°$. Together, these two methods can remove 65% of the muon stops in PC(-1), according to Monte Carlo estimates.

A Monte Carlo study of the PC option was reported in an earlier Technical Note [1], the results of which are reproduced in Table 2 along with better depolarization values.

Material	N_{stops}	$1-P_\mu$
Al Target	7212	0.000
CF_4-ISO (PC(-1))	269	0.008
CF_4-ISO (PC(+1))	338	0.008
1st Mylar foil downstream	172	0.05

Table 2. Number of Monte Carlo stops in the region $-0.4 < z < 0.4$.

That study performed 10,000 trials and assumed a symmetric distribution of muons stopping in the target. With the use of ADCs on PC wires for positron-muon discrimination and tracking, the number of muons stopping in PC(-1) which contribute to depolarization can be reduced by 65%, from 269 to 94. Using the values of Table 2 and Eq. 4 of [1], the overall depolarization and error in $P_\mu \xi$ is

$$\overline{1 - P_\mu} = \frac{94(0.008) + 0.001[338(0.008) + 172(0.05)]}{7212 + 94 + 0.001(338 + 172)} = 1.04 \times 10^{-4}. \tag{9}$$

Using a muon stopping distribution which is asymmetric in the target and shifted downstream reduces the above number to 7×10^{-5}. A better measurement of the lower limit of the depolarization in CF_4-ISO will reduce this value further.

Conclusion

Based on Monte Carlo studies and improved muon depolarization values, the spectrometer design option which includes central PCs will be sufficient to limit the systematic error in $P_\mu \xi$ due to depolarization in the PCs to a part in 10^4 or less. Before the no-PC option can be seriously considered, a very precise measurement of the depolarization of muons in He in a longitudinal magnetic field must be done. In addition, given the grade of He gas to be used in the gaps, it is also likely that impurities will contribute significant depolarization, and therefore additional error, to $P_\mu \xi$.

References

[1] D.H. Wright, E614 Technical Note 4 (1997).

[2] C. Gagliardi, private communication (1997).

[3] D.G. Fleming and M. Senba, "μ^+ Charge Exchange, Muonium Formation and Depolarization in Gases", *Atomic Physics with Positrons ed. Humbertson and Armour*, Plenum, 343 (1987).

[4] D.G. Fleming and M. Senba, "Recent results in gas phase μSR and muonium chemistry at TRIUMF",*Perspectives of Meson Science ed. Yamazaki, Nakai and Nagamine*, Elsevier, 219 (1992).

[5] M. Senba, private communication (1997).