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LOW MASS GAS MIXTURES FOR DRIFT CHAMBERS OPERATION

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ABSTRACT

Helium based gas mixtures have been investigated for lowering multiple scattering contributions to the momentum resolution for intermediate energy particles. The relevant transport parameters, namely drift velocity and diffusion have been calculated for several mixtures and compared to standard argon based mixtures. Some fast, low diffusion mixtures have been identified. The small Lorentz angle computed make them promising candidates for drift chamber operation in magnetic fields.

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1. Introduction

At high luminosity B, ϕ and τ -charm factories, where statistical errors are minimized, a good detector system should provide the best momentum resolution. For tracks with low momentum this is dominated by multiple Coulomb scattering [1],

$$\left\{ \frac{\Delta p_t}{p_t} \right\}_{ms} = \frac{\sqrt{1.43} p_t}{3BL \cos^2 \lambda} \left[\frac{13.6}{\beta p_t} \sqrt{\frac{x}{X_0} \left(1 + 0.038 \log \left(\frac{x}{X_0} \right) \right)} \right] \quad (1)$$

where p_t is the transverse momentum of the particle, β is velocity of the particle, B is the magnetic field in Tesla, L is the track length in meters, λ is the dip angle of the track, and x/X_0 is the number of radiation length of the scattering media in the form of gas and chamber materials. With some assumptions, namely $\lambda=0$ and neglecting the log term, expression (1) can be reduced to a simpler form [1]:

$$\left\{ \frac{\Delta p_t}{p_t} \right\}_{ms} = \frac{0.053}{BL\beta} \sqrt{\frac{x}{X_0}} \quad (2)$$

Argon based mixtures enjoy an almost irreplaceable position as far as operation of drift chambers is concerned. They allow high gas amplification, sufficiently fast drift velocity (4 - 10 cm/ μ s), low single electron longitudinal diffusion (100-250 μ m for one cm of drift). Our task is now to find some helium based gas mixtures which offer a longer radiation length and thus lower multiple scattering, without compromising on the attractive operating characteristics of argon based mixtures. In this paper we have attempted to identify some such gas mixtures which indeed seem promising with respect to these requirements. The next step will be to test experimentally if drift chambers can be reliably operated with these mixtures.

2. Characteristics of helium based mixtures

There has been a recent interest in helium based gas mixtures (HMs) [2-12]. One major advantage of HMs is the large radiation length of helium (5299 m) as compared to that of argon (110 m). Table 1 lists the density and radiation length of some gases and mixtures considered here. HMs exhibit a relatively low drift velocity also at high fields, thus helping in a better position resolution and two track separation. Also, the photon absorption cross section of helium is low implying low sensitivity to background x-rays from synchrotron radiation. As we will see another advantage of HMs is the small Lorentz angle in crossed E and B fields.

2.1 Primary and total ionisation

When a charged particle traverses a gaseous medium, it ionizes atoms and molecules of the gas creating electron-ion pairs. The created electrons may have sufficient energies to ionize further and create secondary electron-ion pairs. The sum of the two processes is called total ionization and the former process is called primary ionization. The number of primary electron pairs per cm (N_p) and the number of total electron-ion pairs per cm (N_t) are characteristic of a given gas or gas mixture.

The spatial resolution of a chamber depends on various factors, N_p and N_t being two important ones. They have been experimentally measured by several authors

(at STP) for a number of gases as summarized in ref. [13]; table 1 shows representative values for minimum ionizing particles. Argon based gas mixtures have also been included for comparison. For mixtures, N_p and N_t have been computed using simple weights proportional to the individual gas mass ratios [14]. The numbers given are for minimum ionizing particles; for lower energy particles the larger ionization density helps improving accuracy. Ethane, isobutane and dimethyl ether (DME) are good quenchers with helium, which help increasing also the number of primary and total ion pairs per cm. He-DME 70-30 has been reported to provide 80 to 100 μm spatial resolution in a drift chamber [7]; similar results have been obtained with He- iC_4H_{10} - CO_2 mixtures [8] and He-ethane [12].

2.2. Transport parameters

The relevant transport parameters for the operation of a high accuracy drift chamber are drift velocity, longitudinal and transverse diffusion and the characteristic energy of the electrons. All calculations of transport parameters presented here have been realized using the MAGBOLTZ program [15] that solves the Boltzmann transport equation of electron motion under the influence of electric and magnetic fields, using as input the cross-sections of various elastic and inelastic processes for the gases considered here from the data base GASSTORE [15,16]. The results presented here and elsewhere [15] agree well with experiment within errors. It may be noted that the calculations here are done up to fields of 2 kV/cm which is a reasonable assumption for an upper limit of drift fields.

2.3 Mean electron energy

The electron energy distribution is characteristic of the gas and is dependent on the electric field and pressure. For our calculations we have used STP conditions namely a temperature of 20°C and pressure of 1 bar. Diffusion in a gas mixture is directly related to the square root of the mean energy of the electrons; this implies that a small mean energy of electrons is desirable to keep diffusion low for high accuracy drift chamber operations. It is clear that gases with large elastic cross sections for rotational and vibrational collisions are favored; large molecules like DME and isobutane are good candidates. Helium itself has a large and almost energy independent elastic cross section up to electron energies of a few eV. Ternary mixtures are an advantage too in this respect as the electrons in this case keep a low mean (thermal) electron energy. In addition, it has been found that mean electron energies in all helium based gas mixtures are lower than the corresponding argon based gas mixtures. Fig. 1 shows the mean energy of some commonly used argon based gas mixtures, namely A- CH_4 (90-10) and A- C_2H_6 (90-10) as a function of the electric field, compared to some helium based mixtures. The values of the mean electron energies in argon based mixtures are $\sim 1\text{-}2.5$ eV at the highest fields relevant for drift chamber operation. The lower thermal bound of $kT=0.025$ eV is also shown as a dashed line.

For the HMs the mean electron energy as a function of field was also computed for He- CH_4 , He- C_2H_6 , He- iC_4H_{10} , He- CO_2 and He-DME mixtures, with three different percentages of quencher in each case. As expected with more quencher the mean electron energy is lower due to the additional non-ionizing cross sections available to the electrons in the gas. They are respectively cooler gas mixtures, which implies that the upper limit for mean electron energy goes from ~ 1.8 eV to ~ 0.9 eV in

going from He-CH₄ to He-DME in the order listed above, clearly being lower than for argon based mixtures. In addition the two three component mixtures studied, He-CO₂-iC₄H₁₀ (80-10-10), and He-CO₂-DME (75-25-5) also show the upper limits of the mean electron energies at ~ 0.6 and 0.3 eV respectively for electric fields ~ 2 kV/cm.

2.4 Drift velocity

Fig. 2 shows the drift velocity versus electric field for the argon based mixtures. Experimental points taken from [17-19] for the A-CH₄ mixtures are also shown in the figure. For the helium based mixtures the drift velocity is not saturated up to high fields (~ 2 kV/cm). The drift velocity of helium based mixtures is in general somewhat smaller than those of the argon based gases, but there are some exceptions. Above 1 kV/cm the drift velocities are comparable in some cases. Figs. 3 to 5 show various two component HMs, fig. 6 the two three component HMs. Fractions of the order of 10-20% of quencher to helium are sufficient to increase the drift velocity up to more than 2 cm/ μ s. The drift velocity of He-DME mixtures is low, but increases rapidly to ~ 4 cm/ μ s for a ternary mixture with CO₂, yet unsaturated. 80-20 and 70-30 mixtures of He-CO₂ are faster than those of He-CH₄ and He-C₂H₆ at fields greater than 1.2 kV/cm. Drift velocities in He-iC₄H₁₀ (90-10, 80-20 and 70-30) are all greater than 2.5 cm/ μ s at fields higher than 1.2 kV/cm. With increase in DME content the mixtures tend to slow down, but with the three component DME mixture, fig. 6, the drift velocity is increased to more than 3.6 cm/ μ s.

Table 2 shows good agreement of calculated and measured values of drift velocity for some HMs.

2.5 Longitudinal diffusion

The single electron longitudinal space diffusion, σ_L is given by $\sqrt{2D_L t}$ where σ_L is the standard deviation of the spread of the arriving swarm of electrons, D_L is the longitudinal diffusion coefficient. Figs. 7 to 9 show the single electron longitudinal diffusion σ_L for a 1 cm drift length, for the two component HMs, fig. 10 for the three component HMs. A 90-10 mixture of helium+quencher exhibits a σ_L similar to that of argon-methane and argon-ethane 90-10 mixtures for electric fields higher than 800 V/cm, argon based mixtures have $\sigma_L \sim 160$ -200 μ m [15]. He-iC₄H₁₀, He-DME and He-CO₂ are well below 165 μ m for similar fields. A 70-30 He-DME mixture has an almost constant σ_L at fields greater than 800 V/cm of 125 μ m. The two ternary mixtures studied also have promisingly low diffusion features namely σ_L of the order of 120 μ m. The 90-10 methane and ethane admixtures with helium are instead bad with σ_L higher than 200 μ m at similar electric fields. The 80-20 and 70-30 mixtures are once again comparable to argon based mixtures.

In practice however, the contribution to the measurement error due to the diffusion is a function of N_t . It should be noted that the single electron diffusion, σ_L does not directly provide the measured spatial accuracy of a drift chamber. This contribution σ_x can be estimated under certain assumptions [20,21] to be $\sigma_x = \sigma_L / \sqrt{\ln(N_t)}$ and was computed for He-DME mixtures, using the data on N_t from table 1 and scaling them [22] for pions of momentum 270 MeV. This value of momentum was chosen as an example for the hypernuclear spectrometer FINUDA at the Daphne ϕ -factory, where track momenta range from 100 to 300 MeV/c. The results

are plotted as a function of percentage of helium and electric field in fig. 11. All values with helium content less than approximately 95% are below 100 μm .

2.6 Lorentz angle

The Lorentz angle (angle of deflection of the electron swarm with respect to the electric field in the presence of a crossed magnetic field) is a function of both the electric field and magnetic field. In addition it is a characteristic of the gas. In DME for example electrons have a very small Lorentz angle, few degrees at magnetic fields between 1-2 Tesla up to rather high electric fields [23]. This characteristic of DME is interesting when optimizing chamber gases to be used in the presence of a magnetic field.

For argon based mixtures, the Lorentz angle is large at small values of electric field and almost independent of the electric and magnetic field values, but above few hundred V/cm, it starts to be dependent on both. This is an especially important source of distortions in chambers having non-uniform geometries, and also in the case of uniform field chambers where non-uniformities arise close to the anode wires.

For helium based gases the corresponding Lorentz angles are much smaller than argon based mixtures. They have been calculated for all the mixtures studied in various proportions with quenchers. Here we show in fig 12 the angles for a He-DME 70-30 case*. A comparison of values of the Lorentz angles at a magnetic field of 1.5 Tesla is given in table 3 for three different values of electric field.

2.7 Momentum resolution in He-DME

The total momentum resolution of a tracking system is given by:

$$\frac{\Delta p}{p} = \left[\left\{ \frac{\Delta p}{p} \right\}_{meas}^2 + \left\{ \frac{\Delta p}{p} \right\}_{ms}^2 \right]^{1/2} \quad (3)$$

For the high momentum particles, the error in the momentum resolution is dominated by the spatial resolution of the position detectors [24]; for the particular case of three equally spaced detectors:

$$\left\{ \frac{\Delta p_t}{p_t} \right\}_{meas} = \frac{8p_t}{0.3BL} \sqrt{\left\{ \left(\frac{\sigma_1}{2} \right)^2 + (\sigma_2)^2 + \left(\frac{\sigma_3}{2} \right)^2 \right\}} \quad (4)$$

where σ_1 , σ_2 and σ_3 are the measurement accuracies of three detectors, and B and L are the magnetic field and track length. We computed the individual contributions of the multiple scattering term and measurement accuracy term, to the total momentum resolution for pions at 270 MeV/c for He-DME and A-iC₄H₁₀. We have taken an example of a track length of 1m, a magnetic field of 1 Tesla perpendicular to the electric field, and that $\sigma_1=\sigma_2=\sigma_3=\sigma_x$ defined in sec. 2.5, is given only by diffusion and ion statistics. Also tracks contained in the plane perpendicular to the magnetic field were the only ones considered here.

The results are shown in figs. 13 and 14. Contribution of the measurement term being nearly same in the two cases, the dominant factor is multiple scattering

* Detailed tables of Lorentz angles presented here and for other gas mixtures can be obtained from the authors by those interested. Note that in the figures the electric field is not plotted on a linear scale.

responsible for worse total momentum resolution for the Argon-Isobutane case, clearly the low diffusion characteristics of DME contribute to a good total momentum resolution and partly compensate for the lower ionization yield as compared to argon mixtures. The optimum mixture is with approximately 70% of helium and 30% of DME. DME being a flammable gas (the limit of flammability in air is 3.4%), one could investigate ternary mixtures of DME with CO₂. At higher ($> \sim 0.5$ GeV) momenta however, since measurement accuracy is the dominant term, a typical Argon-Isobutane mixture provides better momentum resolution as shown in fig. 15.

3. Conclusions

The calculated parameters show that helium based gas mixtures are promising candidates for reducing multiple scattering at the same time preserving good localization accuracy for low momentum particles. In addition some mixtures exhibit low diffusion, reasonably fast drift velocity and small Lorentz angles. Also in cases where track multiplicity poses a problem, for example in heavy ion collisions, a low drift velocity and low diffusion gas mixture may be a solution for better two track separation.

4. Acknowledgement

We gratefully acknowledge S. Biagi's permission to use extensively the MAGBOLTZ program [16] for the work presented here.

Gas	Ratio	Density* (g/cm ³)	Radiation Length (m)	N _p * (cm ⁻¹)	N _t * (cm ⁻¹)
Helium		1.78x10 ⁻⁴	5299	4.8	8
Neon		9.00 x10 ⁻⁴	345	12	43
Argon		1.78x10 ⁻³	110	24.3	94
Methane CH ₄		7.17x 10 ⁻⁴	649	26.5	53
Ethane C ₂ H ₆		1.34x10 ⁻³	340	41	111
Isobutane iC ₄ H ₁₀		2.59x10 ⁻³	169	84	195
DME C ₂ H ₆ O		2.34x10 ⁻³	222	60	160
Carbon dioxide CO ₂		1.98x10 ⁻³	183	35.5	91
He-C ₂ H ₆	90-10	2.9x10 ⁻⁴	2155	8.42	18.3
	80-20	4.1x10 ⁻⁴	1353	12.0	28.6
	70-30	5.3x10 ⁻⁴	986	15.6	38.9
He-iC ₄ H ₁₀	90-10	4.2x10 ⁻⁴	1313	12.7	26.7
	80-20	6.6x10 ⁻⁴	749	20.6	45.4
	70-30	9.0x10 ⁻⁴	524	28.6	64.1
He-DME	90-10	3.9x10 ⁻⁴	1612	10.3	23.2
	80-20	6.1x10 ⁻⁴	951	15.8	38.4
	70-30	8.3x10 ⁻⁴	674	21.4	53.6
A-CH ₄	90-10	1.67x10 ⁻³	120	24.5	90.0
	80-20	1.57x10 ⁻³	132	24.7	85.8
	70-30	1.46x10 ⁻³	147	25.0	82.0
A-C ₂ H ₆	90-10	1.74x10 ⁻³	118	26.0	95.7
	80-20	1.69x10 ⁻³	127	27.6	97.4
	70-30	1.65x10 ⁻³	138	29.3	99.1
He-CO ₂	90-10	3.58x10 ⁻⁴	1396	8.0	16.3
	80-20	5.38x10 ⁻⁴	804	10.9	24.6
	70-30	7.19x10 ⁻⁴	565	14.0	32.9
He-CH ₄	90-10	2.37x10 ⁻⁴	3087	7.0	12.5
	80-20	2.85x10 ⁻⁴	2178	9.1	17.0
	70-30	3.55x10 ⁻⁴	1683	11.3	21.5
He-CO ₂ -DME	70-25-5	1.09x10 ⁻³	580	15.2	36.4
He-CO ₂ -iC ₄ H ₁₀	80-10-10	5.99x10 ⁻⁴	776	15.8	35

Table 1: Characteristics of some helium based gas mixtures

* Values at STP: 20°C, 1 Bar, for minimum ionizing particles.

Gas Mixture	Ratio	E (V/cm)	Drift Velocity (Measured) (cms/ μ s)	Reference	Drift Velocity (Calculated in this work) (cms/ μ s)
He-iC ₄ H ₁₀	90-10	225	1.125 $\pm$ 0.057	[4]	1.04
		450	1.690 $\pm$ 0.043	[4]	1.64
	80-20	168.75	0.885 $\pm$ 0.133	[4]	0.81
		337.5	1.495 $\pm$ 0.38	[4]	1.43
		562.5	2.038 $\pm$ 0.025	[4]	2.07
		560	2.04	[5]	2.06
	70-30	168.75	0.792 $\pm$ 0.048	[4]	0.8
		337.5	1.475 $\pm$ 0.049	[4]	1.46
		562.5	2.134 $\pm$ 0.055	[4]	2.18
		787.5	2.728 $\pm$ 0.152	[4]	2.67
		560	2.13	[5]	2.18
He-DME	90-10	527	1.4	[8]	1.24
		730	1.8	[8]	1.64
	80-20	560	0.87	[5]	0.78
	70-30	560	0.57	[5]	0.55
		527	0.5	[8]	0.50
		831	0.8	[8]	0.86
He-CO ₂ -iC ₄ H ₁₀	80-10-10	562.5	1.640 $\pm$ 0.026	[4]	1.74

Table 2. Calculated and measured values of drift velocity for some HMs studied here.

B=1.5 T	Lorentz angle, ψ (degrees) E=800 V/cm	Lorentz angle, ψ (degrees) E=1000 V/cm	Lorentz angle, ψ (degrees) E=2000 V/cm
A-CH ₄			
90-10	79.63	72.26	34.26
80-20	82.43	79.33	49.70
He-iC ₄ H ₁₀			
90-10	26.02	23.13	13.86
80-20	29.02	26.64	17.68
70-30	30.08	28.16	19.97
He-iC ₄ H ₁₀ -CO ₂	24.81	23.77	18.04
He-DME			
90-10	18.85	18.14	13.37
80-20	13.16	13.6	13.21
70-30	9.30	9.85	11.23
He-DME-CO ₂	14.38	14.74	15.52

Table 3: Comparison of Lorentz angles, in degrees, for some mixtures at B=1.5 T, for three values of electric fields.

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Figure Captions:

- Fig. 1: Mean electron energy distribution in argon and helium mixtures.
- Fig. 2: Drift velocity as a function of field for argon based mixtures. The open squares and solid triangles represent data from [17], solid circles are data taken from [18], and the open circles are data from [19].
- Fig. 3-6: Drift velocity as a function of field for different helium mixtures.
- Fig. 7-10: Single electron longitudinal diffusion for 1 cm of drift as a function of electric field for different helium mixtures.
- Fig. 11: Contribution of diffusion (for 1 cm drift), to the spatial accuracy for He-DME mixture, as a function of electric field and percentage of helium computed for 270 MeV/c pions.
- Fig. 12: Lorentz angle as a function of electric and magnetic field for He-DME (70-30).
- Fig. 13-14: Contributions of measurement errors and multiple scattering errors to the total momentum resolution for 270 MeV/c pions, for He-DME and Argon-Isobutane mixtures.
- Fig. 15: Total momentum resolution as a function of track momentum for He-DME (90-10),(70-30) and Argon-Isobutane (75-25) mixtures.

Fig. 7

Fig. 8

Fig. 11

Fig. 12

Fig. 15