Gas Argon Time Projection Chamber Optimization

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FERMILAB-POSTER-21-061-STUDENT

Introduction

A gaseous argon time projection chamber (GArTPC) is investigated through this project in the hope of obtaining the low energy threshold O(50keV) and spatial resolution O(100μm) required for directional tracking of low energy nuclear recoils.

In GArTPC, Electrons' transverse diffusion impairs spatial resolution but can be suppressed by multi-atom molecule. Using PyBoltz[1], this project minimizes normalized transverse diffusion, D_T, by finding the optimized pressure, dopant (fraction), and electric field while preserving the signal for low energy recoils.

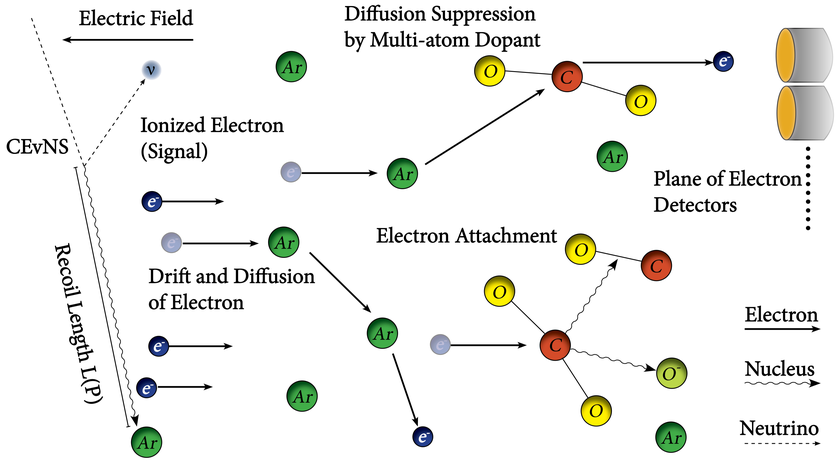

Fig. 1: Details of GArTPC is conceptualized above by selecting coherent elastic neutrino-nucleus scattering (CEvNS) as target event.

To better understand the effect of dopant type and concentration on D_T, three functions are proposed and examined, based on Blanc's law, to combine the information of component gases and predict D_T of gas mixture

$$f_1 = (2a_{1i}\frac{D_{TcM}}{W_M})^{1/2} \qquad f_2 = (\sum x_i \frac{a_{2i}}{D_{Ti}})^{-1} \qquad f_3 = (\sum x_i \frac{a_{3i}}{D_{Ti}^2})^{-1/2}$$

where D_{TcM}, W_M being the conventional diffusion coefficient, drift velocity predicted by Blanc's law, D_{Ti} the pure gas i's D_T, *a* the correction coefficients.

Other effects that could impair GArTPC's performance are also considered. Electron attachment rate is confirmed to be zero for the interested parameters. To address the pressure dependent recoil range, reduced normalized diffusion is introduced to optimize resolution: $RD_T = D_T/L(P)$ with L(P) being the average nuclear recoil length for recoil energy from 10 to 100keV at pressure P.

Acknowledgement & Reference

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

[1]Atoum, B. Al, et al. "Electron Transport in Gaseous Detectors with a Python-Based Monte Carlo Simulation Code." Computer Physics Communications, vol. 254, 2020, p. 107357.

Results & Discussion

Pressure

RD_T is simulated for dopants, including C_4H_{10}, CF_4, CH_4, CO_2, dimethyl ether (DME), ethane, and propane, in variable space: doping fraction (5-15%), electric field *E* (100-400V/cm), gas pressure *P* (1-5bar). For all dopants, minimal RD_T is reached at 1bar, which is also easy to implement in an actual setup. Thus, pressure of GArTPC is set to 1bar for all following optimization.

Dopant(s)

Under 400V/cm, f_1, W_M, f_2, f_3 are calculated and compared to simulation of argon with single dopant.

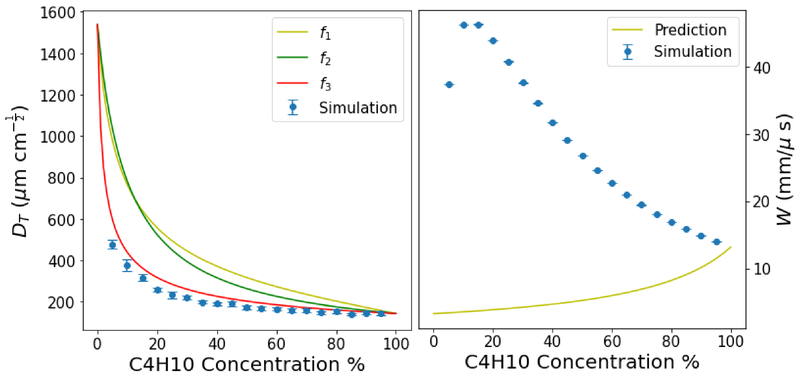

Fig. 2: Prediction functions compared with simulation results for Ar with C_4H_{10}. Left: normalized transverse diffusion; Right: drift velocity.

For most gas mixtures, f_1 and W_M differ significantly from the simulation. Thus, only f_2, f_3 are further considered. To better predict D_T for doping concentration (5-15%), f_2, f_3 are fit with simulation data to find dopant i's correction coefficient a_{2i} , a_{3i}, listed with J/N, the sum of difference square over the number of data points, in Table.1 column 2-5.

These coefficients are then used to predict diffusion for gas mixture of three: 80% Ar, one basic dopant (CO_2/DME), and another. J/N of f_2^*, f_3^* are in Table.1 column 6-9. All actual simulations match the inverse trend that f_2^*, f_3^* predict, meaning the minimal D_T will always be achieved by a single dopant at the highest-allowed concentration.

Table.1	a_2	J_2/N	a_3	J_3/N	J_2/N (CO2)	J_3/N (CO2)	J_2/N (DME)	J_3/N (DME)
C4H10	0.291	1512	0.793	190	1,473	341	1,237	179
CF4	0.166	665	0.504	37	1,741	122	1,526	68
CH4	0.41	2383	0.922	281	714	452	516	266
CO2	0.254	153	0.74	603	N/A	N/A	890	335
DME	0.199	101	0.599	726	979	310	N/A	N/A
Ethane	0.316	1920	0.767	439	978	472	1,130	146
Propane	0.287	1494	0.751	167	1,459	400	1,519	75

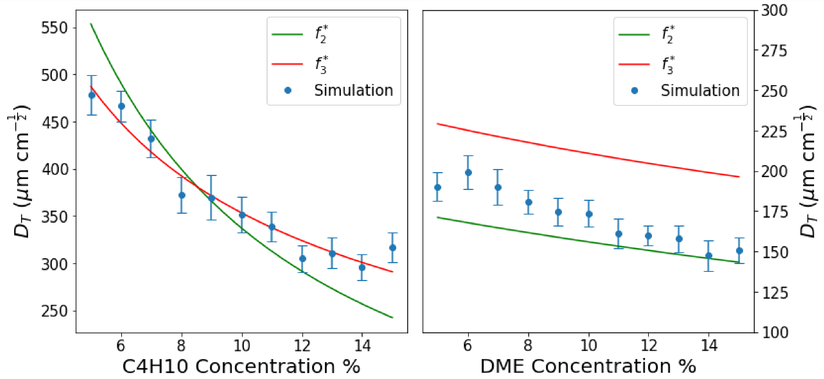

Fig. 3: Prediction functions for D_T compared with simulation results. Left: Ar with C_4H_{10}; Right: 80%Ar with DME and C_4H_{10}.

Electric Field

Lastly, simulations are carried out for doping concentration (6-20%) and *E* (25-1125V/cm). All dopants produce D_{Tmin} at 20%, with DME producing the lowest. D_{Tmin} and corresponding E_c are listed in Table.2 column 2-3. A clear linear relationship, L_{EF}, between the optimized electric fields and fraction is found for dopants that greatly suppress the diffusion. Linear fit of each gas listed in Table.2 column 4-6. Guided by L_{EF}, electric field for 80%Ar20%DME at 1bar is searched at 500 to 650 V/cm and D_T reaches minimum of 131.6$\frac{\mu m}{\sqrt{cm}}$ at 570(±5)V/cm, just as predicted.

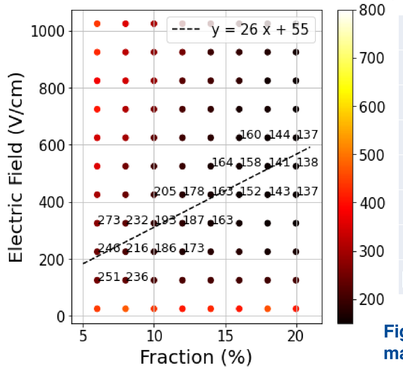

Table.2	E_c	D_{Tmin}	k	b	R
C4H10	1025	235.9	19.4	322	0.82
CF4	625	142.2	25.4	178	0.93
CH4	225	429.3	-21	657	-0.67
CO2	525	160.5	15.7	117	0.89
DME	570	131.6	25.6	54.8	0.96
Ethane	425	349.3	-3.97	610	-0.14
Propane	925	291.3	29	182	0.85

Fig. 4: 2D optimized variable search for Ar with DME, marked with L_{EF} and three lowest D_T at each fraction.

Conclusion

In this project, best settings for GArTPC are found for low-energy nuclear recoils O(50keV) to achieve the highest spatial resolution: at 570V/cm, 1bar, 80%Ar20%DME leads to minimum D_{Tmin} of 131.6$\mu m^{-1}\sqrt{cm}$. With this setting, spatial resolution could be improved by about 11 times compared to pure argon or 5 times to 90%Ar10%CH_4 under normal conditions.

Not reported in previous literature, prediction function f_3^* and linear relationship L_{EF} are discovered and investigated. Though more examination is required, these rules could potentially benefit the community by simplifying the process of finding GArTPC's best parameters.