Neutrino-hydrogen interactions with a high-pressure time projection chamber

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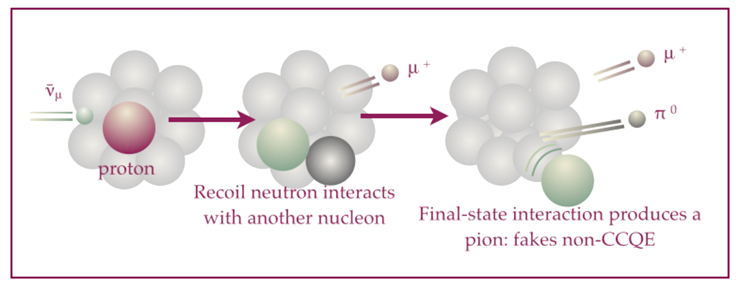
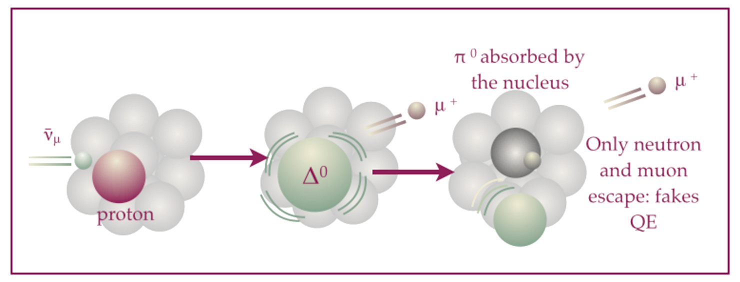
Motivation

Long-baseline neutrino oscillation experiments are currently limited by systematic error due to nuclear effects of neutrino interactions. Obtaining new input data, especially of nuclear-free neutrino interactions at MeV tracking threshold for protons, could help to reduce these uncertainties. A suitable detector that could provide a large number of neutrino-hydrogen interactions is the high-pressure gaseous time projection chamber, which is foreseen for DUNE's near-detector suite. With the projected neutrino exposure, $\mathcal{O}(10^4)$ neutrino-hydrogen events per year could be achieved with a filling of 50 % Ar+alkanes, using the transverse-kinematic-imbalance method [1]. For design and operation of such a pressurized TPC, it is essential to study microscopic tracking parameters, e.g. drift velocity, to ensure performance at large detector scales. A systematic study of hydrogen-rich argon-alkane mixtures is presented and assessed in terms of expected operational abilities and challenges.

The Problem: Intra-Nuclear Interactions

Neutrino detectors are often built from easily scaled materials and technologies, such as Water-Cherenkov or plastic scintillators, to combat small interaction rates due to vanishing neutrino cross-sections. Interactions on these target materials are predominantly on *nuclear targets* – atomic cores with a large number of protons and neutrons. Secondary interactions within the atomic cores can fake or distort signal channels.





The Solution: Neutrino-Hydrogen Interactions

Interactions on **free protons**, i.e. hydrogen, are devoid of nuclear effects. New data, especially in the MeV region, benefits modelling efforts by providing a sample free of secondary effects and thus also aid simulation of multi-nucleon interactions. Gaseous detectors, e.g. *Time Projections Chambers* (TPCs), are an ideal technology due to their scalability and very **low threshold** for particle tracking. The low target mass of a gaseous detector can be increased by operating at 10 bar pressure, which still retains the low tracking threshold of a classical TPC, compared to their liquid counterparts.

Pure hydrogen (H_2) chambers pose a too great safety hurdle for suitable laboratories with a neutrino beamline. **Alkanes** are more manageable in terms of on-site safety than H_2 and are also already established as quenchers in drift-gas mixtures for TPCs.

Extraction of ν-Hydrogen Interactions in Mixed Materials

When selecting a balanced channel, e.g. $\bar{\nu}_\mu \mathrm{CH}_4 \to \mu^+ \mathrm{p}\pi^-$, the reconstructed deviation from perfect momentum balance can be used to determine whether secondary interactions were involved in the interaction. The transverse-kinematic-imbalance method (TKI) [1] uses this property by defining the quantity

$$\delta p_{\mathrm{TT}} \equiv (\vec{p}_{\mathrm{p}} + \vec{p}_\pi) \cdot \frac{\vec{p}_\nu \times \vec{p}_\mu}{|\vec{p}_\nu \times \vec{p}_\mu|}.$$

Selection of ν-hydrogen interactions can be done event-by-event by cutting on δp_{TT}, e.g. $-3\Gamma \leq \delta p_{\mathrm{TT}} \leq 3\Gamma$, where Γ corresponds to the detector momentum resolution. Since δp_{TT} for heavy nuclei is dominated by Fermi motion with a typical width of $200\,\mathrm{MeV}/c$, a high selection purity can be achieved. For a $\nu/\bar{\nu}$-beam, a purity of 93 % could be achieved in a TPC with $5\,\mathrm{MeV}/c$ resolution filled with pure methane.

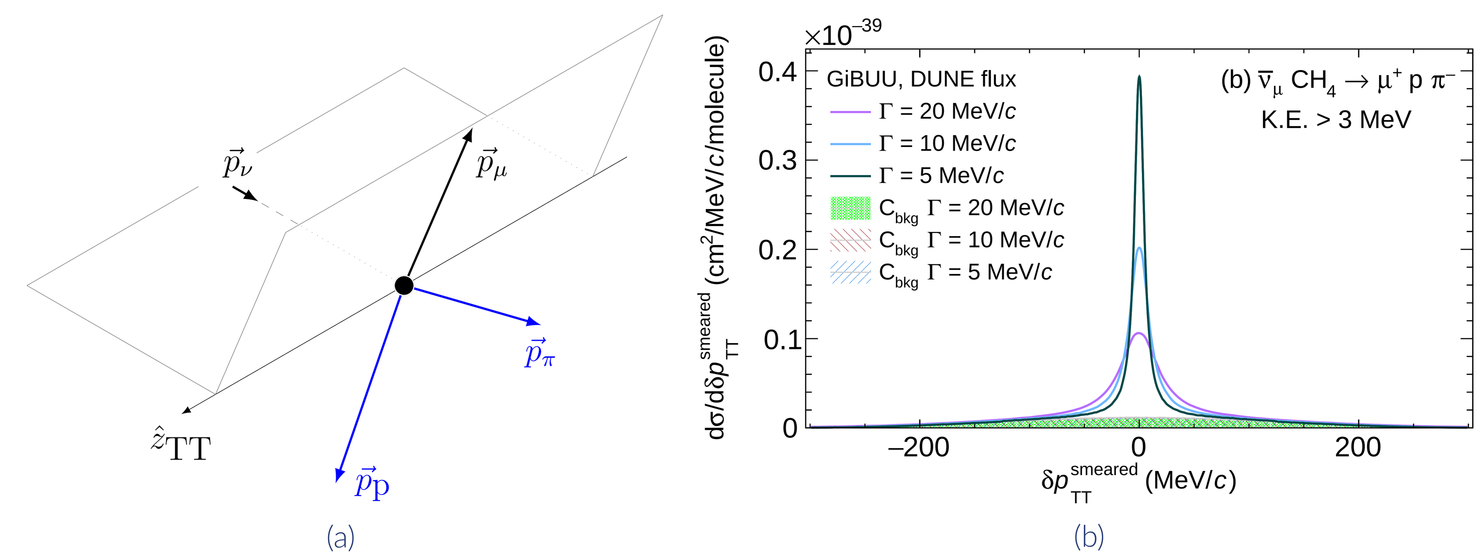


Figure 2. (a) Construction of the transverse-kinematic-imbalance quantities. (b) Spectrum of δp_{TT} for varying momentum resolution Γ. Interactions on carbon atoms are considered as backgrounds $\mathrm{C}_{\mathrm{bkg}}$.

High Pressure Gas for Time Projection Chambers

Time Projection Chambers have been predominantly operated at atmospheric conditions. To predict conditions at high pressures, common transport parameters can be scaled according to the change in gas density [2, 3].

Drift field and gas parameters	Density correction
Electric field strength	$E T/P$
Drift velocity	v_{d}
Diffusion coefficients	$\sigma_{\mathrm{L,T}} \cdot \sqrt{P/T}$
First Townsend coefficient	$\alpha \cdot T/P$

Table 1. Density corrections for the electric field and some fundamental gas parameters. At $ET/P = const.$, the drift velocity is independent of T and P, while the diffusion decreases and the gas gain increases as T/P increases.

It is desirable to verify these scaling laws by measuring the fundamental properties of drift gases (here v_{d}) anew at varying pressures. This can be done by employing a detector type originally designed for continuous detector calibration and supervision called a High Pressure Gas Monitoring Chamber [4]. Measurements have shown, that density scaling holds over a pressure range of 10 bar [4].

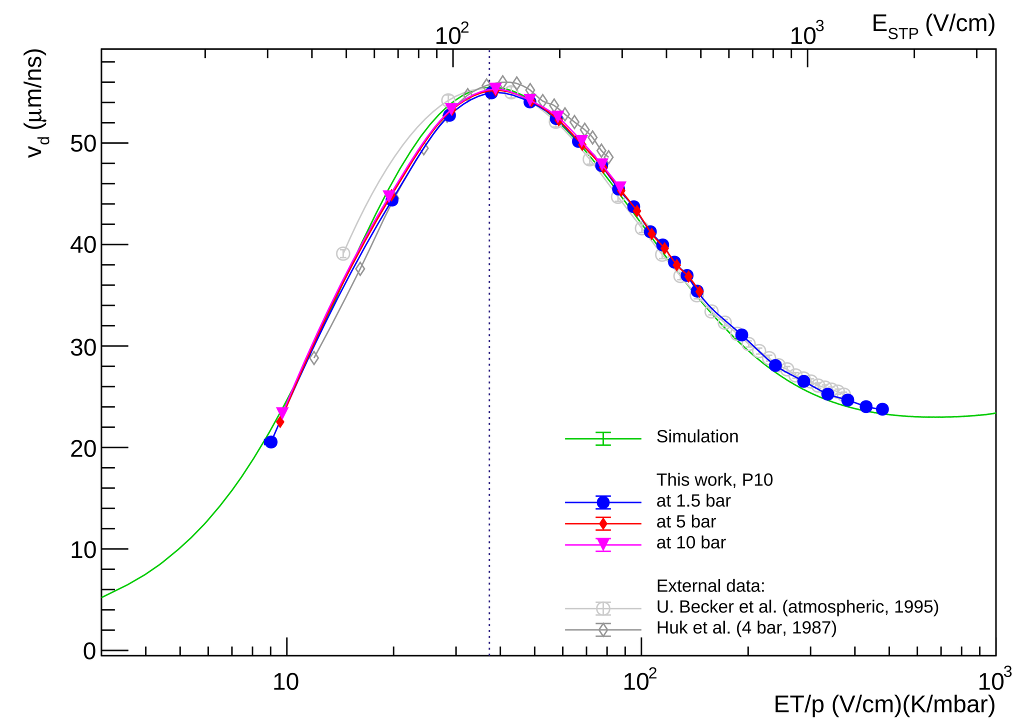


Figure 3. Measured drift velocity of 10 % CH_4 in argon (P10) at pressures from close to atmospheric up to 10 bar [4]. The data closely follows the density scaling laws. Simulation prediction produced with MAGBOLTZ.

Drift Velocity in Hydrogen-Enriched Mixtures

The currently largest, envisioned high pressure TPC is part of the near detector complex for DUNE. It has a volume of $\approx 100\,\mathrm{m}^3$ filled with the baseline mixture P10. When increasing the amount of hydrogen-rich quencher (e.g. CH_4 in P10), the drift velocity will decrease. Slow drift velocities are no concern for experiments at neutrino beam-lines, due to the low repetition rate of the neutrino pulses, typically $\mathcal{O}(\mathrm{Hz})$. A $0.5\,\mathrm{cm}/\mu s$ drift velocity still produces $\mathcal{O}(\mathrm{kHz})$ extraction rates in a 5 m TPC.

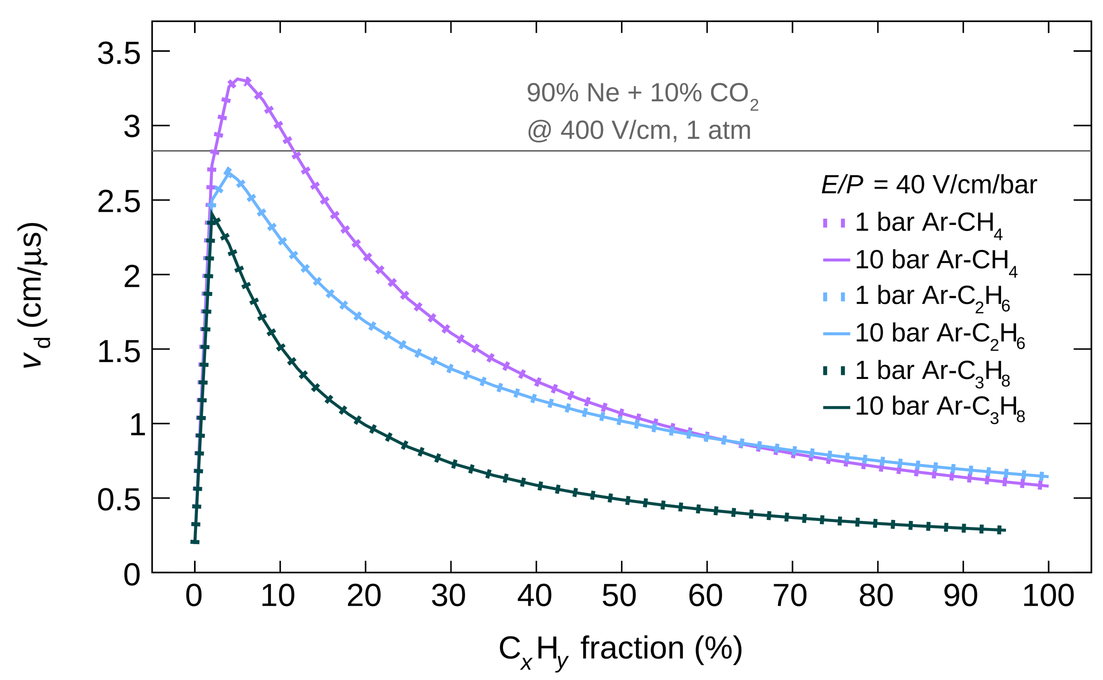


Figure 4. Increasing the alkane content in argon based mixtures decreases v_{d} at constant fields. The value for v_{d} in the ALICE gas mixture is given as a comparison. Note the perfect alignment of 1 bar and 10 bar simulations. Since $T = 298\,\mathrm{K}$ for all simulations, ET/P becomes E/P. Argon-C_3H_8 mixtures are only calculated up to 90 %, since C_3H_8 liquefies above that concentration at 10 bar.

Diffusion

Diffusion is suppressed heavily by the increased gas density, even already for relatively low concentrations of quenchers. The effect is a reduction by $\sqrt{\mathrm{P}}$ both for longitudinal and transversal diffusion. From fractions of 20 % upwards, diffusion is not further reduced, since it approaches the thermal diffusion limit. A high pressure TPC can be expected to show very clear tracks with good separation capability, even at low quencher fraction but especially for high fractions.

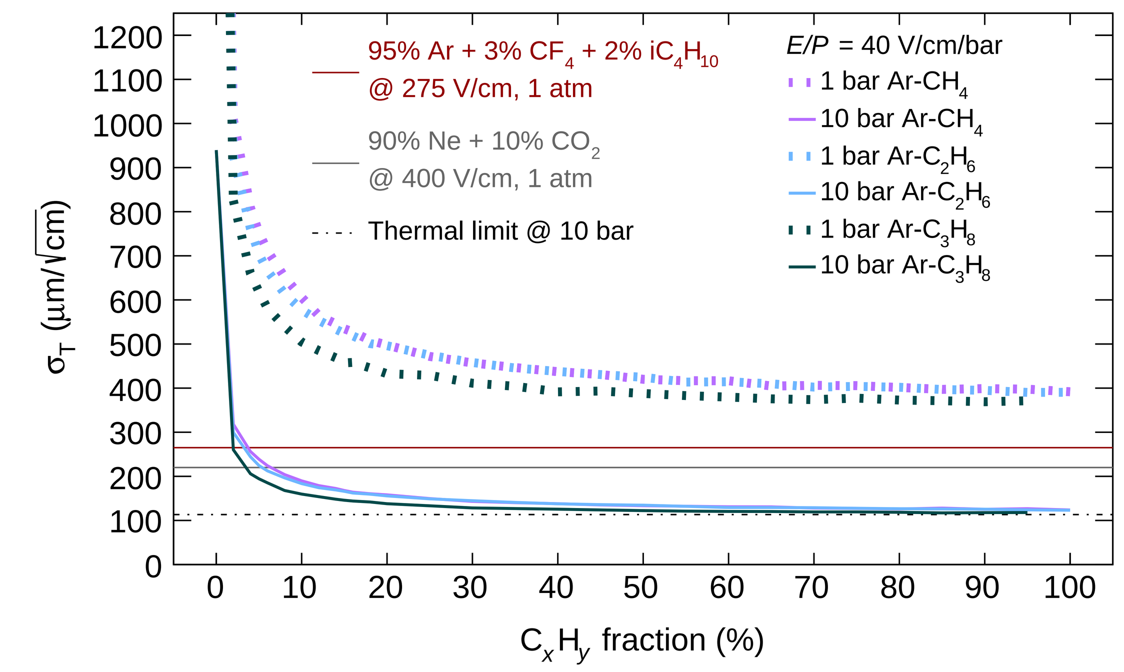


Figure 5. Increased pressure strongly reduces diffusion close to the thermal limit.

Gas Multiplication

After propagation through the drift space of a TPC, electron clouds are multiplied by avalanche ionization in strong electric fields at the readout anodes. The gas gain G can be calculated at the gas level, independent of the used anode geometry, via the first Townsend coefficient α:

$$G = \exp\left[\int_{s_0}^{s_1} (\alpha - \eta)\mathrm{d}s\right]$$

A non-negligible contribution to α comes through ionizing energy transfers between gas components known as Penning transfers. There exists some numbers for the corresponding probabilities in a few gas mixtures [5, 6], but experimental test remain indispensable. The impact on α can be calculated for the full range of possible transfer probabilities and added as uncertainty band on the simulation curves.

The first Townsend coefficient is reduced by gas density ($\propto \mathrm{p}^{-1}$). Furthermore, high percentage alkane mixtures show onset of avalanche multiplication at higher fields compared the 10 % baseline mixture.

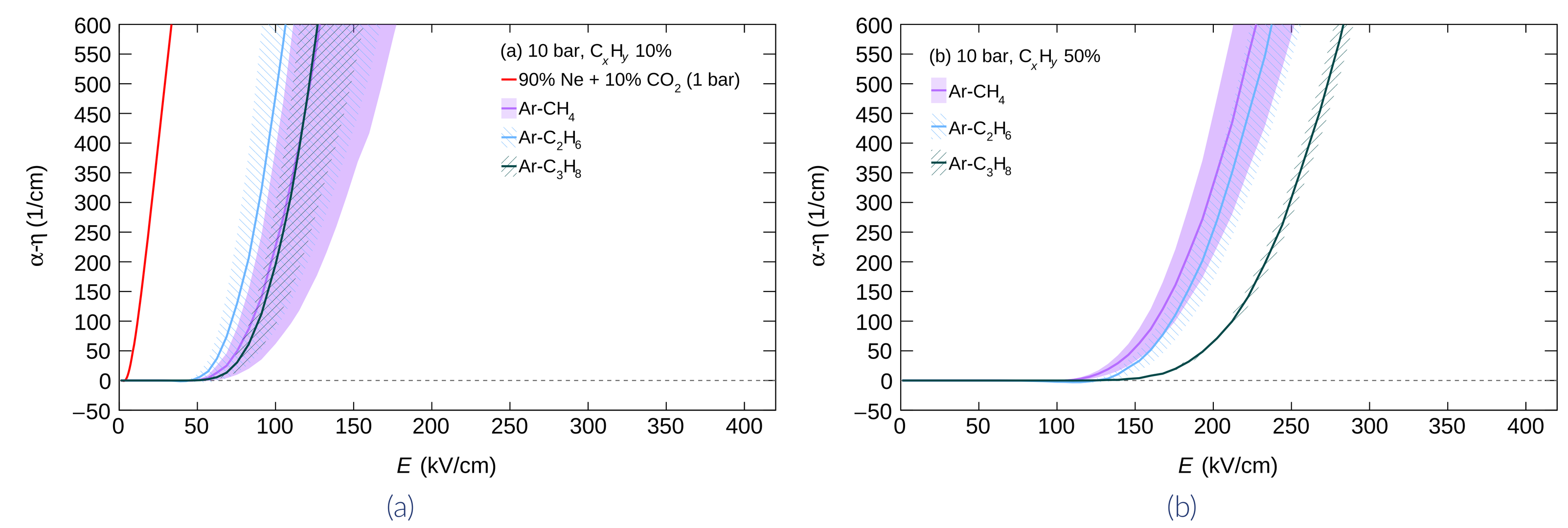


Figure 6. (a) Argon with 10 % quencher and ALICE curve for reference and (b) mixtures with 50 % quencher admixture. Error bands result from unknown Penning transfer probabilities.

References

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