Hydrogen Doping of Dual-Phase Xenon Time Projection Chambers

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1. $0\nu\beta\beta$ Detection

The theoretical process of neutrinoless double beta decay ($0\nu\beta\beta$) has several implications:

- Violation of lepton number conservation
- Neutrino is its own antiparticle (Majorana particle)
- Possible explanation of matter-antimatter asymmetry
- Highly sensitive absolute neutrino mass scale

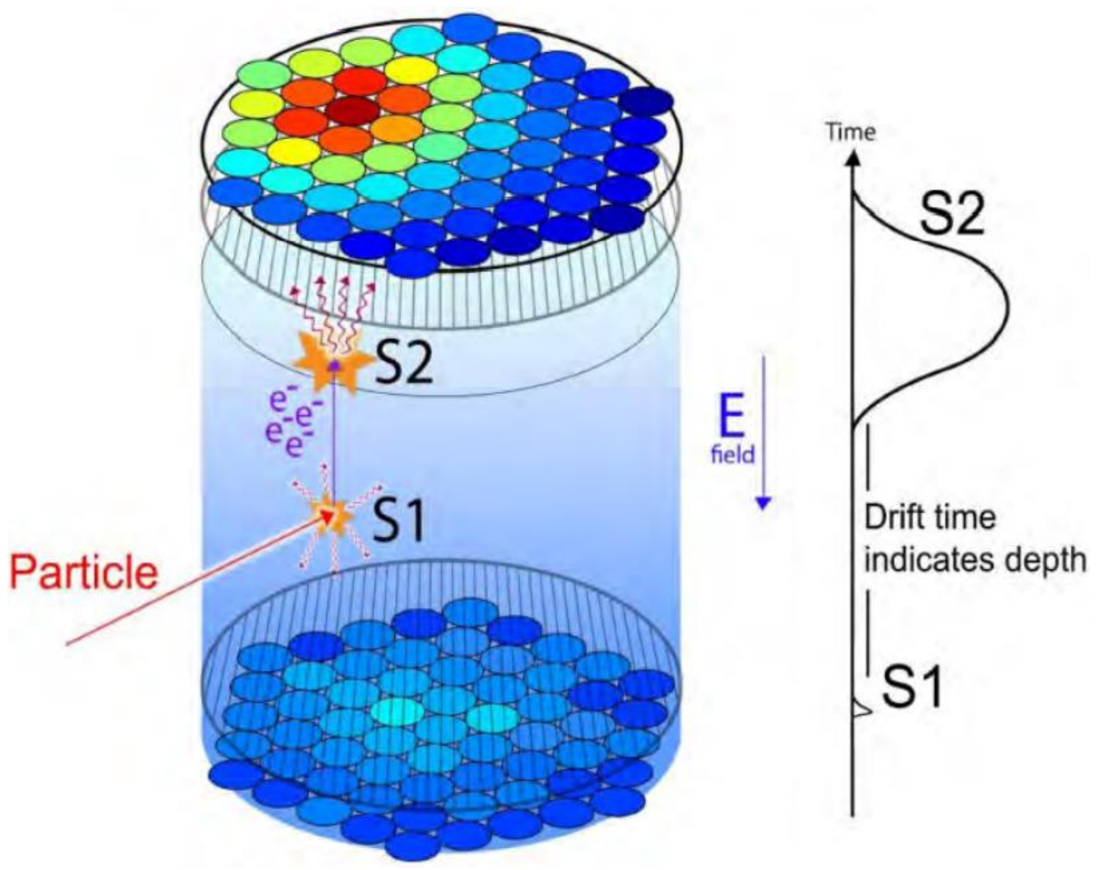

Fig.1 Signal generation within the dual-phase time projection chamber [1].

Events occur in liquid xenon (LXe) which can create electrons. The event electrons propagate and ionise further electrons.

The ionised electrons drift in an electric field. They are extracted into a gas phase where they stimulate electroluminescence (EL).

Xe-136 $0\nu\beta\beta$ decay: Q value = 2457.83 ± 0.37 keV

Bi-214 gamma background: Q value = 2447.7 keV

Insufficient energy resolution to distinguish the two events, however, their electron tracks differ slightly.

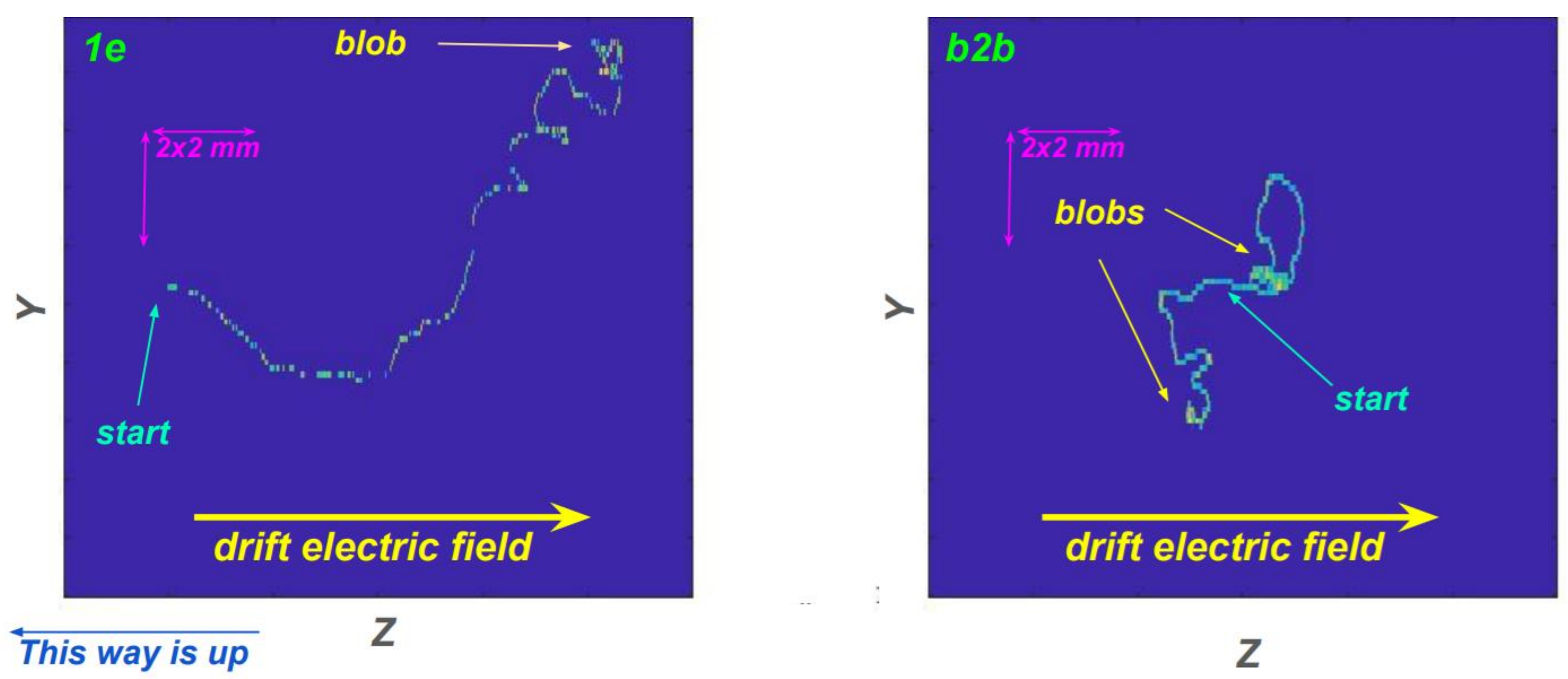

Fig.2 Electron tracks for the single electron background (left) and two back-to-back (b2b) electrons for $0\nu\beta\beta$ decay (right) [2].

Electron diffusion limits spatial resolution; reducing the energy of drifting electrons decreases electron diffusion.

Introducing a lighter dopant increases the number of electron energy loss mechanisms via both elastic and inelastic collisions.

2. Research Questions

- Can Magboltz accurately simulate electron transport in gaseous xenon (GXe)?
- Can we adapt Magboltz to accurately simulate electron transport in LXe?
- Does doping LXe with hydrogen (H_2) lead to improved sensitivity for $0\nu\beta\beta$ decay in Xe-136?
- Does doping LXe with deuterium (D_2) provide a noticeable difference compared to H_2 doping?

3. Method

Simulate electron transport in pure and doped GXe

↓

Simulate EL yield for pure and doped GXe

↓

Adjust density to simulate LXe

↓

Change cross sections for GXe to LXe

↓

Simulate electron transport for pure and doped LXe

Magboltz is software that uses Monte Carlo methods to solve the Boltzmann equation for electron transport within electric and magnetic fields. It is designed only for gas simulation.

The code within the Magboltz FORTRAN file was adapted to attempt to simulate LXe.

The interatomic spacing of LXe is comparable to the de Broglie wavelength of low energy electrons, therefore coherent scattering effects need to be considered.

- For GXe, the total elastic and elastic momentum transfer cross sections are equal.
- For LXe, the total elastic cross section is different to the momentum transfer cross section due to new effects that are present in the liquid.

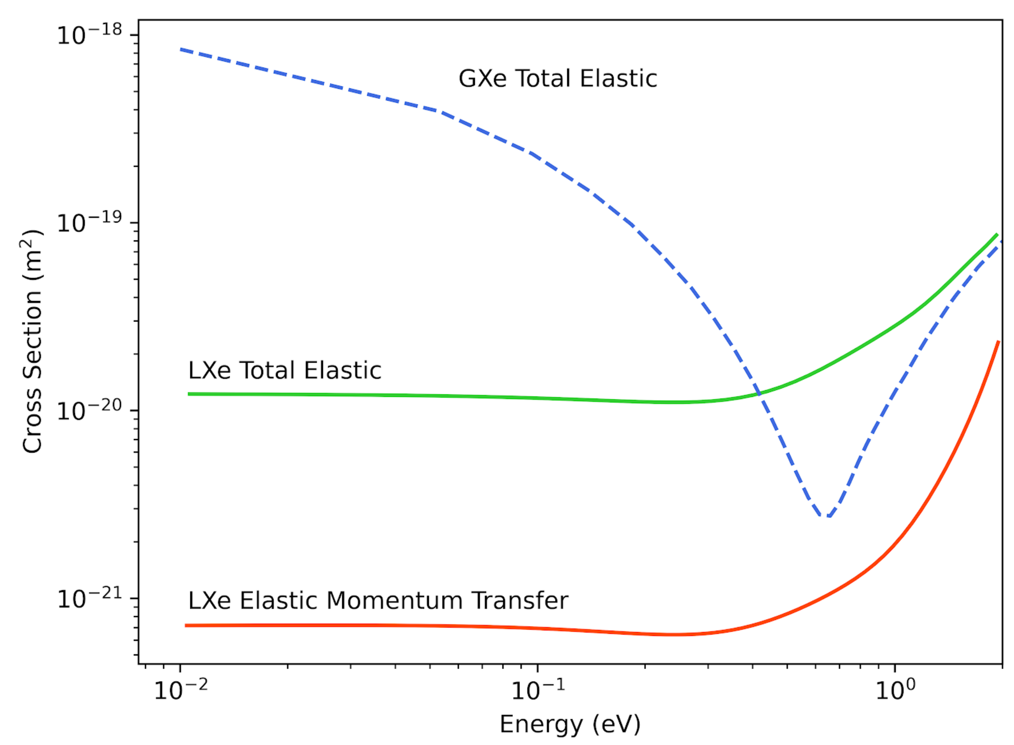

Fig.3 The total elastic and momentum transfer cross sections for LXe and the total elastic cross section for GXe.

4. Results

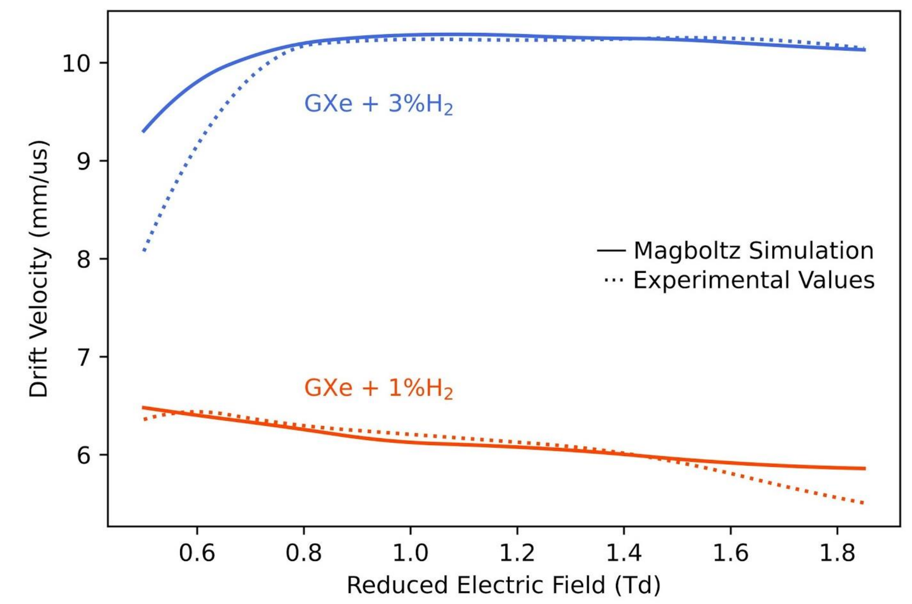

Fig. 4 Magboltz H_2 doped GXe drift velocity compared with literature.

Magboltz simulations for electron transport matched experimental data in GXe at stronger fields. There was up to ~80% loss of EL yield at greater H_2 doping percentages in GXe.

Magboltz LXe simulations gave a drift velocity that was three times smaller than literature. This result was significantly better than the result when GXe cross sections were used with the LXe density.

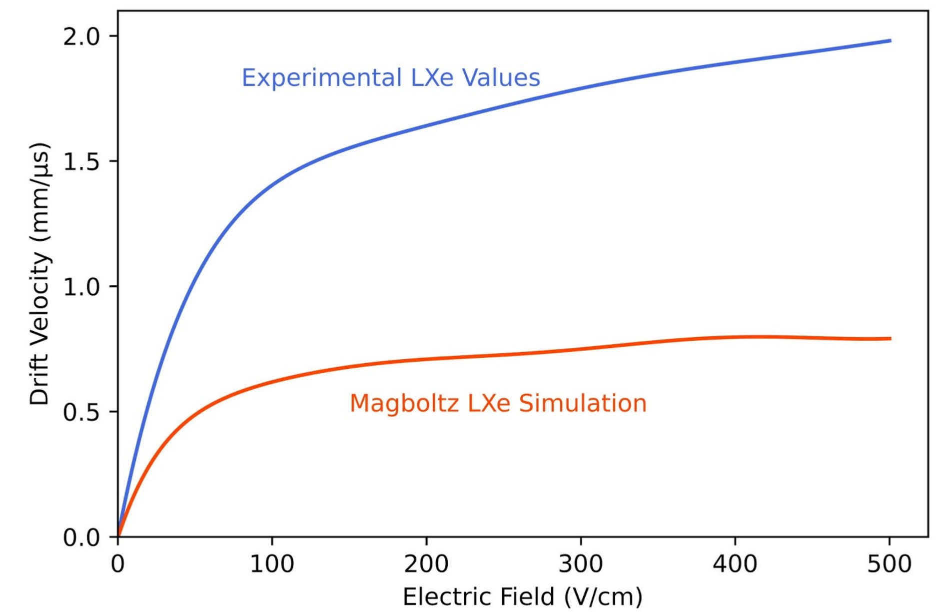

Fig. 5 Magboltz LXe drift velocity compared with literature.

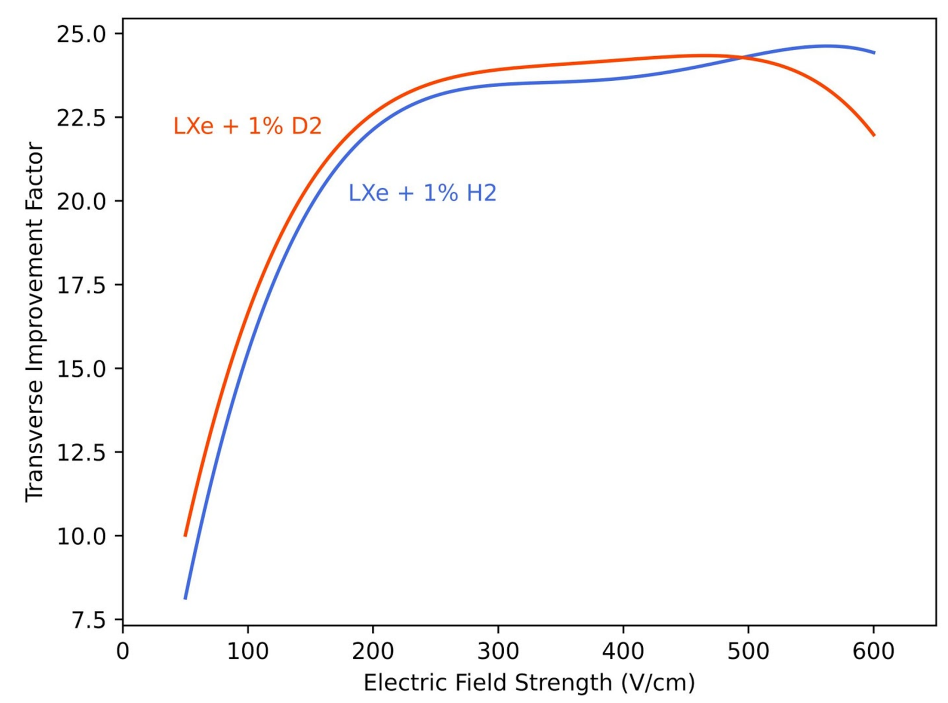

Fig. 6 Magboltz simulated improvement factor for H_2 and D_2 doped LXe in the transverse direction.

Magboltz simulations for LXe doped with H_2 or D_2 displayed reduced electron diffusion compared to pure LXe. The spatial resolution was improved for both the longitudinal and transverse directions. D_2 doping was slightly better than H_2.

5. Conclusion

- Magboltz gas simulations matched experimental data
- Magboltz liquid simulations were not accurate, but provide a useful basis for further work
- Both H_2 and D_2 doping of LXe reduced electron diffusion

6. References

[1] Akerib, D. S. "LUX-ZEPLIN (LZ) Conceptual Design Report." 2015, doi:10.2172/1251183.

[2] Solovov, A. "Neutrinoless double beta decay classification in the LUX-Zeplin TPC." 2nd BigDataHEP meeting, Braga, Feb. 13 2020.