Gaseous Xenon TPC with Germanium-like Energy Resolution

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We propose to further develop the Negative Ion Drift (NID) technique for Noble Gas Time Projection Chambers (TPC) to achieve an energy resolution near the Fano limit: this technique has the potential to make the energy resolution of Xenon TPCs competitive with germanium. The primary application of such a technique is for use in the next generation neutrino-less double beta decay ($0\nu2\beta$) search, which requires highly resolved energy measurements to distinguish the 2ν mode of the interaction from the 0ν mode: poor energy resolution will cause the tail of the 2ν energy spectrum to "leak" into the 0ν peak, limiting the detection power of the device. If $0\nu2\beta$ decay were to be detected, it would be a profound discovery demonstrating not only the Majorana nature of neutrinos, but violation of familial lepton number, both of which are not predicted in the Standard Model of particle physics [1]. It would also provide insight into the mass hierarchy of neutrinos [1]. Unless better energy resolution can be achieved, the current generation of $0\nu2\beta$ searches utilizing TPC technology will quickly reach their detection limit. Furthermore, the current generation of germanium detectors will soon reach a cost limit, as the only obvious method to increase detection capabilities for that particular technology is to dramatically increase their expensive detection material.

TPCs, in particular those which use xenon gas, are in many ways ideal for detecting $0\nu2\beta$: they offer the ability to track charged particles in 3D allowing the two β tracks from the decay to be observed, xenon itself can be easily purified to reduce background radiation within the detector volume, and they can be operated with large volumes of xenon to increase sensitivity to rare events. A xenon TPC was used by the EXO Collaboration in their recent measurement of the $2\nu2\beta$ decay in xenon, until recently the only nuclei in which $2\nu2\beta$ had been predicted to occur but not observed. However, the current state-of-the-art energy resolution in a xenon TPC is around 2.5% at the end point energy of $2\nu2\beta$, compared to the sub-percent level typical of germanium detectors. If the Fano limit to the energy resolution is achieved, a xenon TPC would have an energy resolution competitive with germanium.

The technique of NID has been demonstrated by our group in argon gas, using oxygen as an electronegative dopant [3]: by drifting O_2^- rather than electrons, the arrival times of the electrons after being stripped from the ion are spread out in time, removing the electron avalanche fluctuations in the energy measurement. The demonstration was at sub-atmospheric pressures with 78% electron recovery from oxygen achieved. Figure 1 shows the energy spectrum from an ^{55}Fe source, as well as the energy resolution as a function of the recovered electrons. In order to approach the Fano limit in energy resolution, near 100% of electrons must be recovered from the ions. Operation at pressures of one atmosphere and above must also be demonstrated for use in a $0\nu2\beta$ decay search.

There are several avenues to pursue that could increase electron recovery and the efficiency of full recovery, including the use of alternative electronegative dopants and several detector upgrades. The scope of this project is to fully characterize the electronegative dopant CS_2 at sub-atmospheres, which our research suggests may be a superior dopant compared to oxygen. If successful, we will then begin to characterize the performance of CS_2 as a function of pressure, using both argon and helium as bulk gases. In conjunction, several detector upgrades will be added to increase electron recovery. Finally, a demonstration of CS_2 in xenon will follow successful operation at pressures beyond one atmosphere. If effective recovery cannot be achieved at one atmosphere, the final task will involve characterization with additional electronegative dopants.

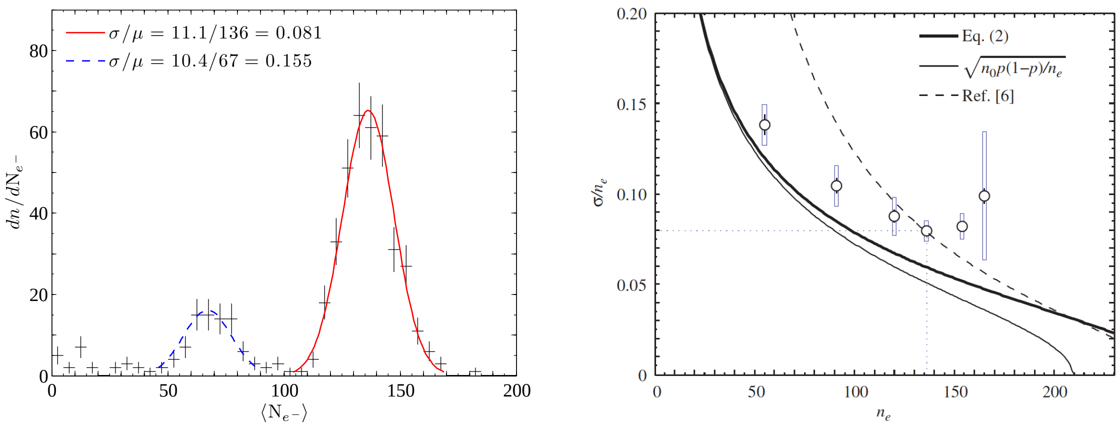

Figure 1: From [3], left: The energy spectrum obtained from counting individual electrons recovered from O_2^- ions, obtained in Ar-CO_2 at $p = 0.25$ bar with 4% O_2 dopant. The LEM was operated with $\Delta V = 880$. The full-energy peak is 5.9 keV and the argon k-shell escape peak is 3.1 keV. From [3], right: Observed energy resolution (circles) compared with the expectation for a binomial process (thin solid), the prediction from Ref. [4] and our prediction, $\sqrt{\frac{F}{n} + \frac{1-p}{n_0 p}}$ (thick solid). Statistical uncertainty is indicated by the thin vertical bars, and systematic uncertainty is indicated by the vertical rectangles.

References

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