Track imaging by direct ionization image sensing: a new method to search for neutrino-less double beta decay

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Abstract In gas-based detectors, energy resolutions achieved for electron tracks in the few MeV range have been much worse than the intrinsic limits. The extended track lengths of such events require large containment volumes and, typically, multi-wire proportional gain structures to capture the signals over a large area. The difficulties of determining accurate gain maps and stable proportional gain contribute to the challenge. As an alternative, direct sensing of track images without avalanche multiplication now appears possible due to the recent advances in ultra-low noise multi-channel integrated circuit design, at least for those circumstances where ionization density is sufficiently high. In a time projection chamber (TPC), the 3-D localization of tracks in space should also permit much better energy resolution since edge effects would be controlled. A particularly suitable application is the search for neutrino-less double beta decay in high-pressure $^{136}$Xe gas. At the 2.48 MeV Q value of the decay, an energy resolution of ~0.5% FWHM may be possible with direct ionization imaging. While only a factor of two worse than the intrinsic limit 0.25% FWHM, set by fluctuations between excitations and ionization, stability considerations suggest that direct ionization imaging may reach this level of performance, with electronic noise the dominant contribution.

1. Introduction Measurements of the squared mass differences by the oscillation experiments and the recent global picture including cosmological constraints have established an upper limit for the sum of neutrino masses around 0.17 eV. All these results have greatly increased interest in the search for neutrino-less double beta decay since one of the requirements for this decay to occur is that the neutrino have non-zero mass. As the rate for the decay depends inversely on the square of the effective neutrino mass, this mass scale constraint imposes severe challenges for the realization of greatly increased sensitivity with corresponding reduction in backgrounds and improvements in energy resolution. Rejection of the various backgrounds in previous experimental approaches at the ~10 kg level has been arguably marginal to inadequate. Future projects must confront the likely need to achieve the required performance in a system at the kilo-ton scale. Tracking systems offer advantages in the detection of background signatures, but have characteristically not met needed levels of performance [1-2].

Another novel approach is presented in another paper at this conference, also based on a time projection chamber filled primarily with high-pressure $^{136}$Xe gas [3]. In that complementary concept, each surviving electron liberated in the gas is counted individually. The counting process is assisted by electron capture and transport via negative ion, as the low ion mobility leads to an acceptably large
interval between arrival times at the readout plane. The impact of counting losses was shown to be mild, even for substantial inefficiency. Many R&D issues are suggested to explore that concept.

Here, I argue that another possibility exists as well, such that high quality imaging and energy resolution can be achieved without avalanche gain [4]. While good energy resolution is obtained in standard proportional counters with low energy x-rays such as the $^{55}$Fe 5.9 keV transition, where photoelectric conversion leads to a small spot of ionization, similar performance is not commonly obtained at higher energies. Track lengths become extended at higher energies, and several effects may enter:

- Uncompensated ballistic deficit in electronic signal processing;
- Integrated electronic noise from summing many channels in MWPC;
- Gain variations due to gas density and gas composition instabilities;
- Time-dependent gain variations due to temperature gradients;
- Gain map uncertainties;
- Space charge distortions leading to head-tail gain loss;
- Attenuation of signal due electronegative contaminants during collection.

2. Ionization Imaging

In the $^{136}$Xe decay, 2480 keV is available. Taking 21.9 eV as the average energy to produce an electron/ion pair, roughly $1.13 \times 10^5$ pairs would be produced in a neutrino-less double beta decay, taking the measured Fano factor for pure xenon as 0.13 [5], the intrinsic fluctuations lead to an energy resolution of

$$\delta E / E \sim 2.5 \times 10^{-3} \text{ FWHM}$$  \hspace{1cm} (1)

In high-pressure xenon gas at a density of $\rho = 0.1 \text{ g/cm}^3$ (~20 bars at normal temperature), the total track length would be ~ 20 cm, leading to ~5650 electron/ion pairs per cm. If the track needs N ~40 samples for adequately detailed reconstruction, then pixel sizes of ~0.5 cm diameter will be sufficient, and signal sizes of 3000 electrons will be typical. For this size pixel, with attention to stray capacitances, wire-bonds, and layout suggests that an optimized ASIC design based on CMOS technology is capable of noise levels of ~30 electrons rms [6]. The minimum noise in such designs occurs for shaping times of a few $\mu$s, a good match for a typical electron drift velocity of a few cm/$\mu$s. As the track topologies can be convoluted due to multiple scattering, it is likely that the resolution goals can be met only if the ASIC includes multi-sample capability.

If noise levels are uncorrelated and Gaussian, and no other noise sources exist, track measurements will add about $N^{1/2} \sim 7 \times 30$ electrons = 210 rms. The implied resolution would be excellent, although quite optimistic:

$$\delta E / E \sim 5 \times 10^{-3} \text{ FWHM}$$  \hspace{1cm} (2)

Ionization chambers for energy measurement purposes have traditionally incorporated grids to shield the positive ion image, which would otherwise introduce a large variable deficit in charge collection, significantly degrading energy resolution. Such grids also act as sensitive capacitive microphones and can become a serious noise source, even in the MHz frequency domain. To eliminate microphones in the TPC case, the readout plane can be safely made without grids, for several reasons. Since the TPC can provide detailed position information on the location of the event, an accurate correction for the integration deficit can be made ex post facto. And because the struck pixels will typically not represent a large fraction of the readout plane, this correction is typically quite small.

The induction of signals for the grid-less geometry has been analyzed and realized already for the detection of low-energy neutrons [7]. The absence of a grid leads to some complexity in signal
induction while the image approaches the readout plane, but no net charge complications result once collection is complete. The ionization will drift to the readout plane and be collected on the pixels lying directly on the projected image. Diffusion and topology will lead to some additional pixels receiving net charge. Pixels adjacent to the projected image, but which receive zero net charge, will experience small bipolar signals that integrate to zero net signal. Pixels further away will receive smaller bipolar signals whose amplitude diminish rapidly with distance. The main complication is the decision process of inclusion/rejection of pixels peripheral to the track image with small signals, those not clearly distinguishable from noise. Nevertheless, system stability will likely be much greater than a detector with avalanche gain, and if the ultra-low noise goal in a large system can be largely met, the energy resolution may approach (2).

The TPC offers several important advantages for background rejection, as elaborated in [3-4]. A fully active, completely closed, deadtime-free fiducial volume surface may be precisely defined, preventing undetected entry of background charged particles. Multiple Compton scattering of $\gamma$-rays will be clearly observed, as would the $\sim$30 keV fluorescence from $\gamma$-ray photoelectric conversion in xenon. In addition, the TPC offers excellent scaling behavior, with most aspects improving directly as scale increases. Only diffusion would change the character of an event detectably, scaling slowly as the square root of drift distance, and very slightly increasing the number of pixels/event.

3. Summary
Advances in multi-channel integrated circuitry design, exploiting modern high-density CMOS technology, have opened the possibility to realize high-quality tracking with high resolution energy measurements, without the complications of avalanche electron multiplication, at least in those circumstances where sufficient ionization density is present to offer good signal/noise. A particularly apt application would be the search for neutrino-less double beta decay in $^{136}$Xe, based on a high-pressure TPC. Scaling, from prototypes designed to demonstrate the expected energy resolution with MeV $\gamma$-rays, to systems at the kiloton level of active isotopic mass appears straightforward.

References
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