Simulation of electron-ion recombination in high-pressure xenon gas with TMA in pursuit of directional dark matter detection

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ABSTRACT

Dark matter is a mystery, nonetheless known to constitute the majority of mass in the universe, and current theory suggests that it takes the form of nonrelativistic weakly interacting massive particles (WIMPs) that would form a halo around the Milky Way. A high-pressure xenon gas chamber moving through this halo on Earth could be able to identify the energy deposited if a WIMP collides with a xenon atom in the detector. In order to develop this capability, we have created a Garfield++ program to simulate the behavior of the cloud of electrons ionized from their parent xenon atoms as a result of the nuclear recoil from one such collision. We are interested in maximizing the amount of recombination that occurs and learning how this quantity depends on the orientation of the nuclear recoil with respect to the external electric field. Previous data from our simulation did show a large recombination fraction with dependence on the magnitude of the electric field when 2% trimethylamine (TMA) was added to xenon gas, but upon examining the progression of individual simulations it is clear that the electron cloud quickly loses the shape of the initial recoil for short tracks. Future steps include investigating other parameters that might result in more retention of directionality information. Progress toward benchmarking the simulation with gamma ray data was also made by modeling recombination in portions of a simulated 22 keV gamma track.

INTRODUCTION

- We know that some form of non-luminous matter, termed dark matter, exists and comprises 85% of the mass in the universe.
- Weakly Interacting Massive Particles (WIMPs) are one candidate, and are thought to form non-corotating halos around galaxies.
- Earth would be moving through this halo, and thus WIMP interactions should be coming from a preferred direction.
- The dependence of columnar recombination on orientation with respect to the external electric field in the detector is key to differentiating a WIMP signal from background.

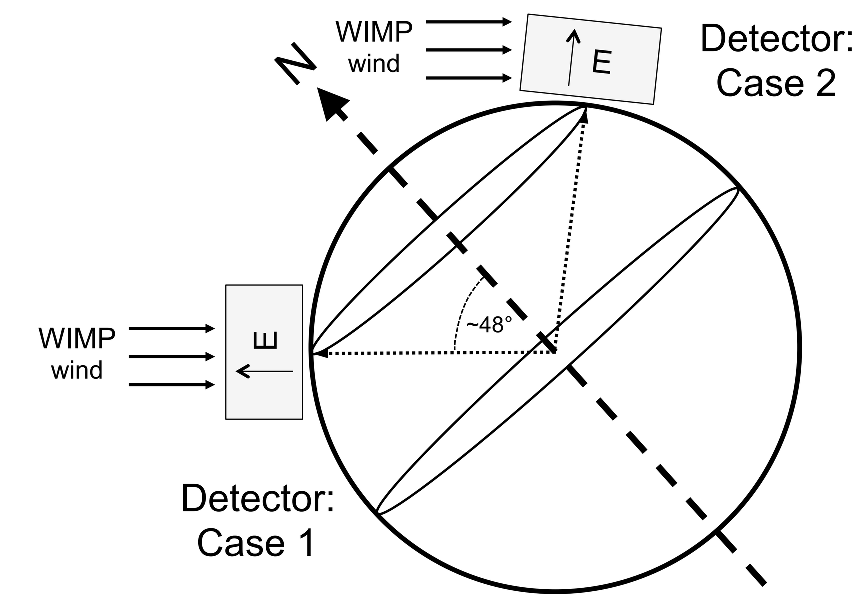


Figure 1. A stationary detector changes its orientation with respect to the dark matter wind by ~90° as the Earth rotates through the day.

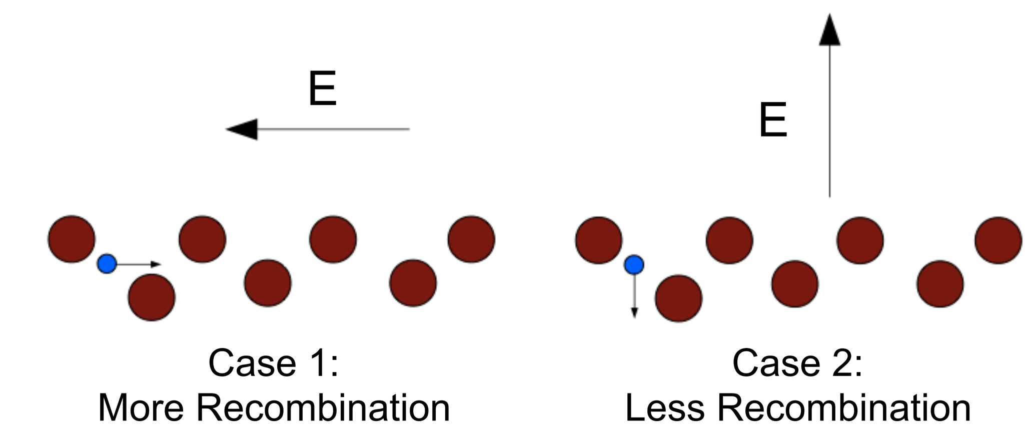


Figure 2. Columnar recombination may be used to determine nuclear recoil direction relative to an external electric field. In the Case 1 detector orientation from Figure 1 the electron moves past more xenon ions and thus has more chances to recombine.

METHOD

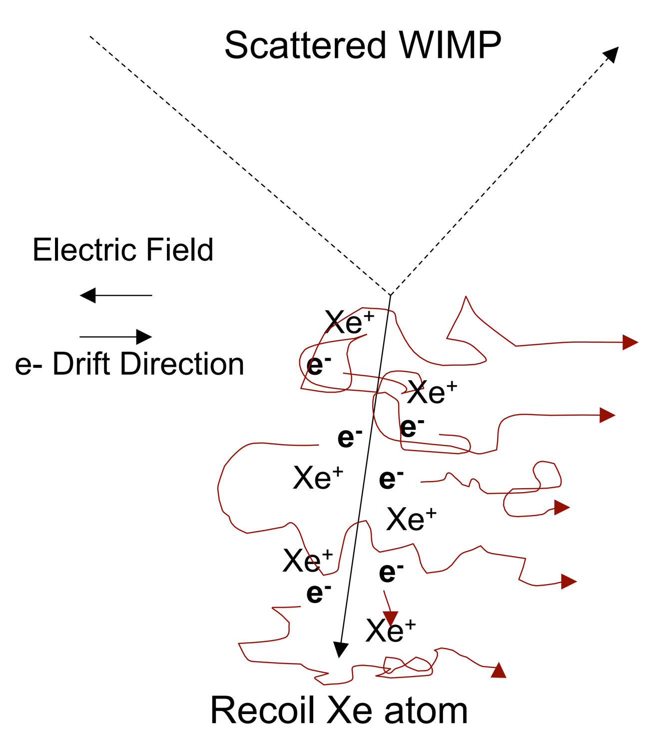
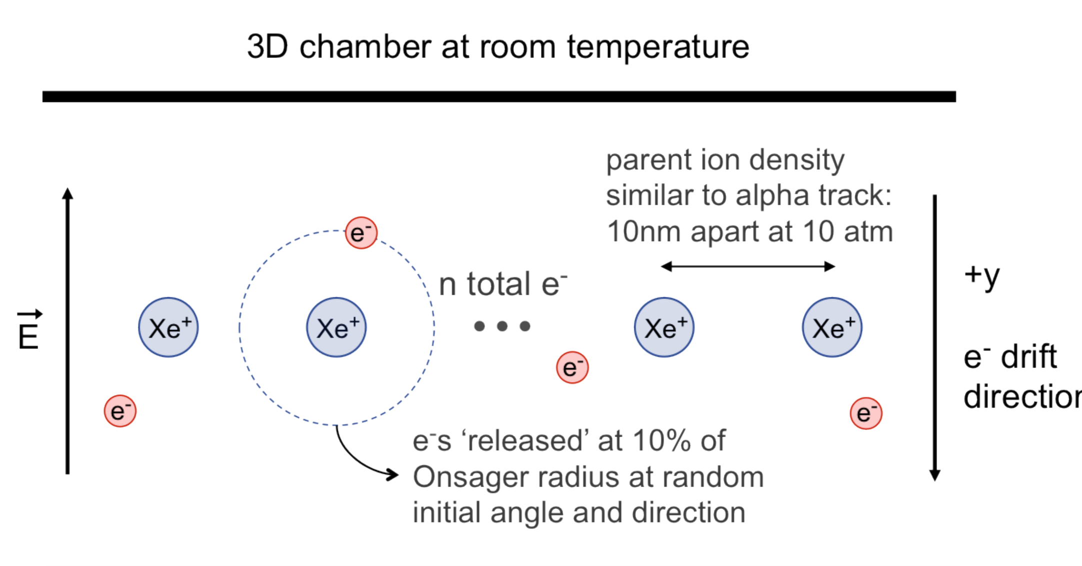


Figure 3. WIMP interactions create nuclear recoils that dissipate energy in the form of a roughly linear cloud of ionizations. The resulting electrons diffuse in the gas and either recombine with a xenon ion or drift through the detector along the electric field.



Specify: P, E, gas mix, number of e$^-$, angle of e$^-$ line w.r.t. E, runtime

Figure 4. The simulation's initial conditions in the case of a line of equally spaced electron-ion pairs.

- Simulation being developed is a modified Garfield++ program run on the Carver supercomputing cluster at NERSC. Computing hours used to date: 135,000
- Electric field due to the cloud of ions and electrons is computed and added to the external field at each advance of the electron.
- As electrons diffuse through gas, they recombine with a xenon ion if they are within the smaller of their deBroglie wavelength or the Onsager radius of an ion and their total energy is negative.

RESULTS

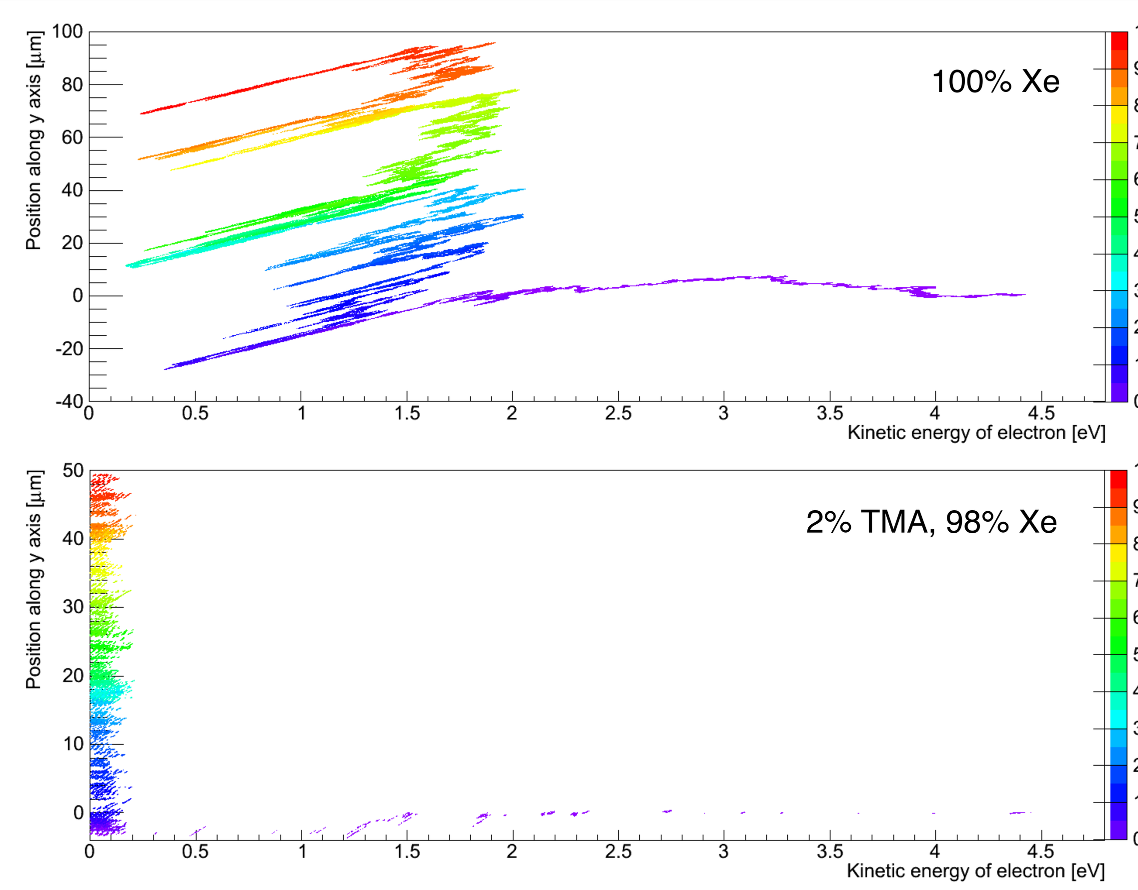


Figure 5. The position along the electric field vs kinetic energy for a 4.4 eV single electron in pure xenon (top) and 2% TMA in xenon (bottom). In 2% TMA the electron is less energetic after it reaches equilibrium with the electric field (500 V/cm in the -y direction) because it loses more energy through collisions with the TMA molecules.

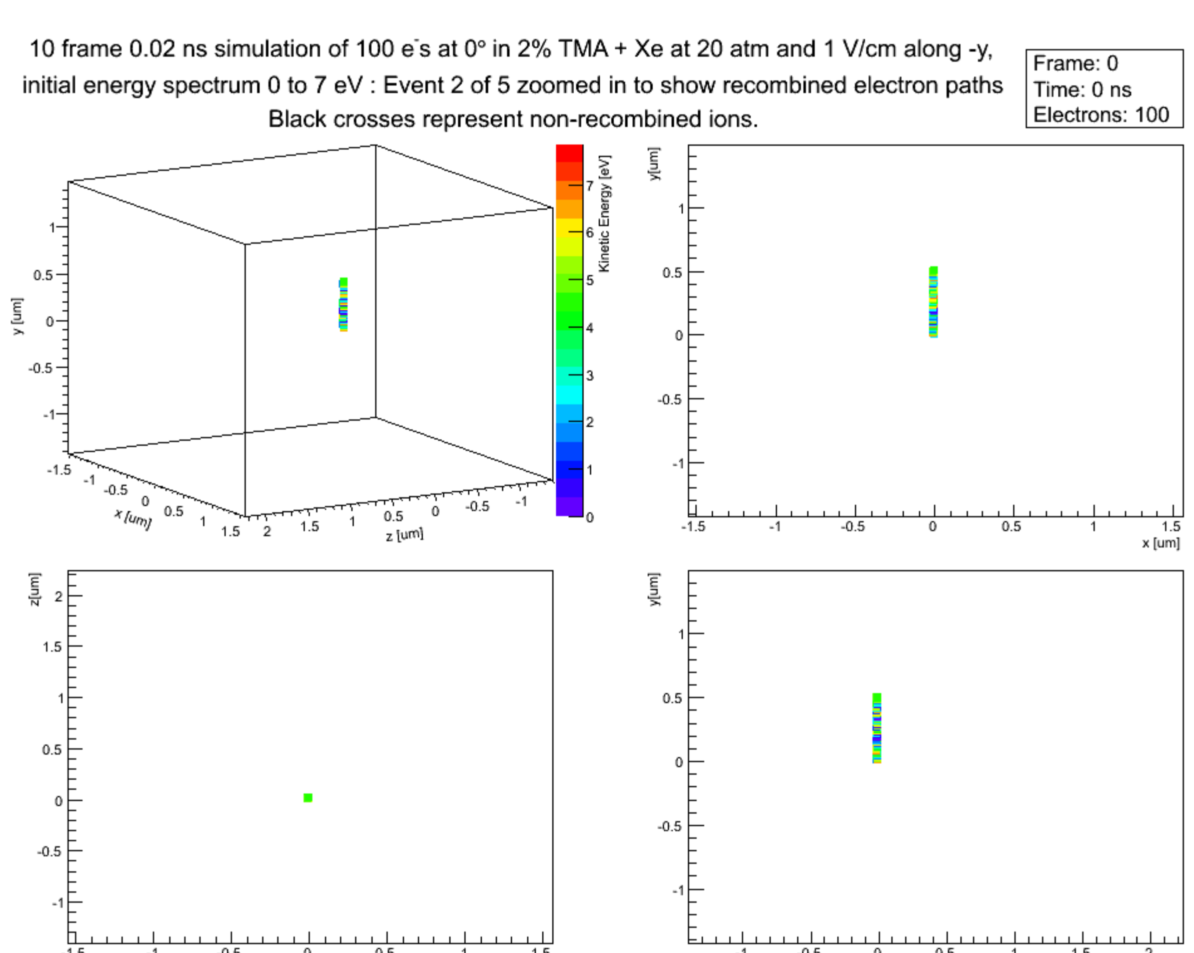


Figure 6. An animation of our model of a WIMP recoil. All animations created in this project, for an array of initial conditions, are available online at: http://portal.nersc.gov/project/hpx/recombination/

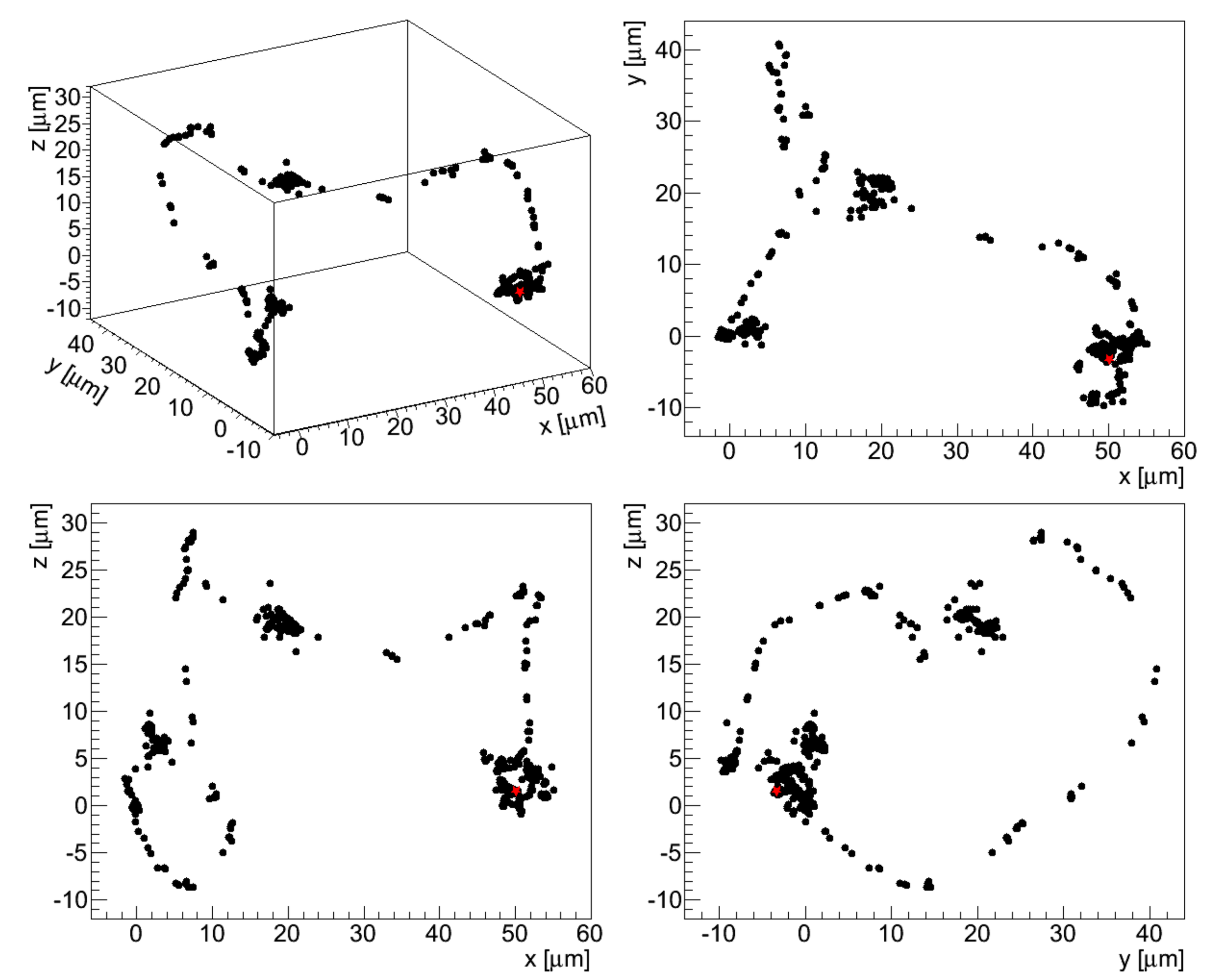


Figure 7. A 22 keV gamma ray moving through pure xenon at 10 atm creates a track of ionizations featuring several dense clusters, of up to several hundred ionizations, separated by more sparse sections. This track began at the red star and contains 980 ionizations in total.

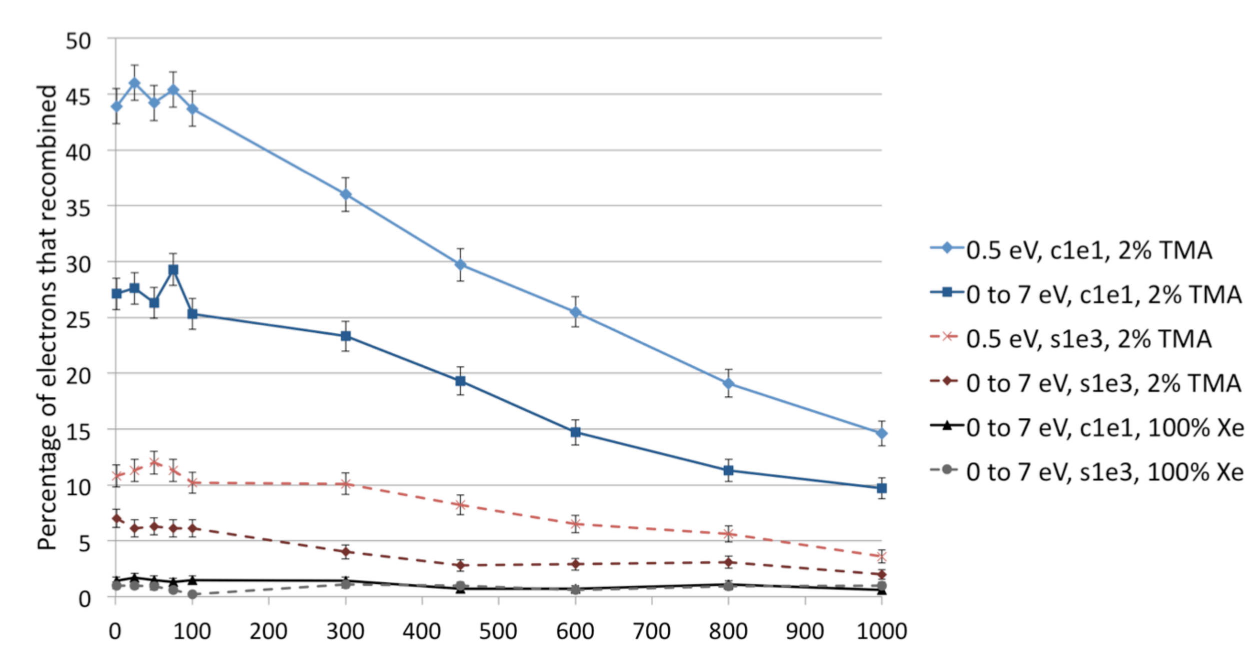


Figure 8. Recombination from a sample cluster, c1e1, and section, s1e3, (each containing 100 electron-ion pairs) of one 22 keV gamma ray track at 10 atm after 20 ns of simulation time. Recombination in pure Xe is low, but the 2% TMA case highlights the energy- and field-dependent increase in the denser clusters and the lower, but non-negligible, recombination in the more dilute sections.

CONCLUSIONS

- The animations of the electrons in our simulation (Figure 7) reveal that electrons expand to a cloud ~1 μm in width within 50 ps – when < 10% of the total recombination has taken place – and therefore quickly lose information about directionality for very short tracks.
- Goal: find a set of initial conditions for the detector that would maximize any columnar recombination seen in a real WIMP recoil (~200 electrons). Change initial electron energy, increase the distance between ions, change gas mix and/or TMA fraction.
- Simulating an entire gamma ray event (Figure 7) and modeling recombination based on samples of these events (Figure 8) brought this program much closer to results now seen in experiments using TMA. Goal: predict recombination given the average ratio of clusters to sparse track sections.
- Next: also investigate other methods of simulating more electrons per track in a non-computationally intensive manner so that results can be benchmarked against other experiments with gamma rays and alpha particles that have 1000 or more ionizations per event.

ACKNOWLEDGMENTS

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