Snowmass2021 - Letter of Interest

A next-generation LAr TPC-based MeV Gamma ray instrument

Thematic Area:
CF7: Cosmic Probes of Fundamental Physics

Additional Thematic Areas:
CF1: Dark Matter, Particle-like; IF8: Noble Elements; NF7: Applications; NF10: Neutrino Detectors

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Abstract:
We propose development of a new type of instrument to measure the Gamma-Ray sky in the largely unexplored 0.2 – 100 MeV energy range. This is based on liquid Ar (LAr) time projection chamber (TPC) technology, strongly leveraging developments in high energy physics.

We propose a new LAr TPC-based all-sky survey and transient gamma ray instrument for the poorly measured 0.2 – 100 MeV sky. This next-generation detector would leverage the substantial advances and ongoing investment in this technology area for dark matter and neutrino physics, but will require further development for this application. Such a development is motivated by the promise of substantially increased area and higher efficiency than existing detector concepts based on detectors based on Si-strip (AMEGO [1]) and Ge-strip (COSI [2]) technology.

Compared to other wavelengths, the MeV portion of the photon sky is effectively unexplored. The most complete catalogs of MeV sources include dozens of sources, as compared to the thousands of sources seen by the Fermi-LAT [3] or the billions of sources seen or expected by optical surveys such as DES [4], KIDS [5] and the VRO / LSST [6]. Extrapolation from X-ray and higher-energy gamma-ray data suggests that many sources types are expected to have spectral energy density peaks in the MeV range. Given the performance improvements expected from this type of instrument, we can expect to detect thousands of sources in the MeV band and effectively open a new window on the sky. The increased sensitivity together with the extremely large field of view offered by this design will also be key in observing a large number of transients, including the electromagnetic counterparts to gravity wave detections of compact object mergers, such as GW170817 [7]. It will also open a new window to search for signature of decaying dark matter [8]. Furthermore, given the presence of nuclear lines, as well as the 511 keV annihilation line, the bright diffuse galactic signal observed in the MeV band can provide otherwise unobtainable information about the evolution and particle content of our galaxy.

This energy range is so poorly understood precisely because accurately measuring these photons is a formidable instrumental challenge. The detector must be 10s of cm in dimension to efficiently contain multiply-scattering photons, while at the same time the positions of all scatters must be measured to sub-mm precision and with percent-level energy resolution. Uniformity of response and absence of inert material is at a premium — if any of the several scatters are lost or incorrectly measured, the event is incorrectly imaged on the sky.

There are currently active efforts to field an instrument that features fine-grained “electron tracking” readout using either Si-strips [1] or Ge-strips [2], backed by a spatially coarser calorimeter. However a liquid noble TPC has several advantages over these approaches for the same reasons that TPCs have been powerful in other contexts: they provide a large active mass with minimal inert material, and achieve 3D imaging throughout this volume with instrumentation only on the periphery. In addition, triggering afforded by the TPC may allow high resolution pixel readout of the electron recoil tracks while keeping power consumption manageable. Pixel readout is being pursued in the DUNE context [9] as a significant improvement over track (or wire) readout in its ability to disentangle complicated topologies, and should be particularly applicable here.

A LXe TPC for this purpose was pursued in the past [10]. Since that time, noble liquid technology has advanced considerably due to efforts in the dark matter and neutrino fields, and a LAr TPC in particular will benefit significantly from the worldwide HEP investment in DUNE. Still, this technology is less mature than Si or Ge, and will require development both to demonstrate its full potential and to address issues particular to deployment in space. While a compelling science program can and hopefully will be achieved soon with a Si or Ge instrument, we believe the long-term advantages of LAr and the science opportunities in this area argue strongly for an investment now in this technology.

We propose a detector with LAr in a carbon fiber vessel, with $\sim$30 cm drift length and a field of $\sim$0.5 kV/cm. If a single layer, light readout would be on the back (Earth-side) cathode surface and charge readout on the outer anode surface. Event pile-up in the relatively slow ($\sim$100 μs) TPC readout is addressed primarily by segmentation of the active fluid by low-mass light reflecting walls. These form an array of unit cells of width $\sim$15-20 cm that each function as an independent TPC. This segmentation plays another important role, achieving isolated first scatters for $\mathcal{O}(50\%)$ of events, which suppresses energy dispersion due to recombination fluctuations. The lateral size of the instrument would be set by the number of unit cells, and could reach several meters.

We are studying a charge readout consisting of two systems: a coarse-grained set of induction wires, followed by a fine-grained readout at the anode plane to image electron tracks. The $\sim$cm pitch coarse grid is used to measure the total charge, since the fine grained readout suffers from charge loss due to diffusion spreading a non-negligible amount of charge to sub-threshold elements. An attractive option is for the fine-grained readout is $\sim$200-500 μm pitch pixels similar to those used in collider experiments. This will require the development of a novel power switching scheme that keeps the pixels fully powered off until triggered by the coarse grid. Both readouts could use cold readout electronics, which for pixels would be part of the same ASIC. The total power consumption in this scheme could be at the scale of only $\mathrm{W/m^2}$, as the on-fraction of pixels would be on the scale of 10^{-5}. The theoretical noise for $\sim$15 cm long coarse grids is $\sim$20 electrons [11], equivalent to $\sim$1 keV, and is substantially lower in pixels. The pixel readout scheme is yet to be designed, but will likely implement storage of $\mathcal{O}(10^2)$ samples per pixel, with digitization of only those above threshold. Design and development of this or other readout schemes will be a core part of the overall instrument development program. We note that the charge drift triggering scheme which enables this low-power pixel readout is absent in a semiconductor readout, so the path to 3D semiconductor-only pixel readout with feasible power for a spacecraft is not obvious.

The light readout is yet to be detailed, but would likely use waveshifter-coated surfaces and SiPMs or PMTs as a readout plane that also forms the cathode. This is similar to schemes that have achieved high light collection in DM experiments [12]. A major challenge for spacecraft is dissipating the total power, which must be done through black-body radiation. We estimate a very modest few $\mathrm{W/m^2}$, which could be achieved by passive cooling if that is compatible with necessary Sun and Earth shades, and is also amenable to a cryo-cooling system with heat dissipation at higher temperatures.

We have conducted an initial look at gamma-ray reconstruction using a custom-written MC package, and are beginning more detailed studies using MEGALib [13]. The initial look supports the initial premise that a monolithic sensitive volume can provide higher efficiency than the current semiconductor approaches. Also important are upcoming studies of the ability of the TPC to reject of backgrounds of up-going photons, charged particles, and neutrons. Here the monolithic TPC active volume with only low-mass reflectors between cells should be highly beneficial. Neutrons will be readily tagged using the powerful pulse-shape discrimination of LAr [14]. Ar is intrinsically radiation hard, and while gamma rays from activation must be studied, the use of low Z, low mass materials (primarily Ar, C, Si and Al) should be advantageous. Preliminary estimates of pointing accuracy and energy resolution at 1 MeV are 1 – 2° FWHM and $\sim$2% FWHM, respectively, which is at least comparable to Si, but poorer in energy resolution as Ge. The final performance will depend on the final charge and light readout design. While it is by far premature to know the scale of a final instrument, it is worth noting that a fundamental advantage of the TPC is that it enables a very large detector mass at modest readout cost in terms of both channels and power. A $10\mathrm{m}^2$ or more detector could well be possible as a MIDEX scale mission.

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