The eBubble Detector for Solar Neutrino Detection

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• Accessing the low energy solar neutrino spectrum
• The Electron Bubble TPC concept
• R&D progress
• Next steps: towards a cubic-meter prototype

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Solar neutrinos over full (pp) spectrum

- In particular, a precision, real-time measurement of the pp neutrino spectrum down to the keV range
- Precision measurements of oscillation effect matter/vacuum dominated regimes
- SSM uncertainty on the pp flux ~ 1% → aim for “1%” measurement
- Insights into the inner working of the Sun. Comparison of the neutrino luminosity to the photon luminosity should be ≈1.
Physics Motivation cont’d

$E_x$ is the visible track energy

- $E_x = 10\text{--}30 \text{ MeV}$; isolated and “upward-going” electrons; presumably from supernovae. Little background, a single event, with $\nu$ direction measured to $\sim 1$ degree, is meaningful
- $E_x < 40 \text{ KeV}$ nuclear recoil from WIMP (Dark Matter), range very different from electron and spectrum depends on WIMP mass – similar technique used in the DRIFT experiment
Elastic scattering: measure energy and angle of recoil electrons to determine incident neutrino energy

- Most of scattered electrons are $< 100$ keV; flavor dependence $< 50$ keV
- A few hundred scatters per ton per year $\rightarrow O(25)$ ton-year exposure needed
- Cross-sections for $\nu_\mu$ and $\nu_\tau$ scattering down by a factor of $\sim 4$
- Higher energy neutrinos “for free”
Detector requirements

- \( \sim O(10) \) tons fiducial mass
- "Condensed" phase target medium to give reasonable volume for this mass
- Excellent (sub-mm) spatial resolution for low energy tracks \( \rightarrow \) range, electron ID, plus pointing, at least for higher energy recoils
- To maintain this resolution if drifting over long distances, need very low diffusion
- Good energy resolution
- Very high purity \( \rightarrow \) long drifts, and low background from medium
- Goal of reaching keV level implies need for some gain, presumably in gas phase
- (Self-) shielding
- Excellent background rejection, in particular of \( \gamma \)'s via Compton cluster ID
- Ideally, a slow drift to ease readout of large number of volumes \( \rightarrow \) feasible in principle in low-background environment underground
Detection medium: helium/neon

- In liquid phase, these low-Z materials offer good compromise between volume-to-mass consideration and desire to minimize multiple scattering
- Very low boiling points → excellent purity, since impurities freeze out
- In the case of thermal charge carriers, diffusion is proportional to $\sqrt{T}$, so low temperature is very advantageous
- In liquid phase and in dense, cold gas, electrons are localized in nano-scale electron bubbles
  - Bubble size leads to low mobilities, of order $10^{-3} - 10^{-2}$ cm$^2$sec$^{-1}$V$^{-1}$, and slow drifts
  - Electron bubbles remain thermal for E fields up to ~ 40 kV/cm, and field-ionize around 400 kV/cm
- In two-phase system, bubbles are trapped at the liquid-vapor interface, before tunneling out on a timescale dependent on T and E
Experimental approach: an electron bubble TPC

• For a homogeneous medium, one dimension must use a drift → Time Projection technique

• Slow drift (e.g. 10 cm/sec) of electron bubbles in these fluids allows high resolution in drift direction with moderate data rate

• Signals “stored” in detector volume, and read out one plane at a time in drift direction, at a rate of 10’s-100’s Hz

• Zero suppression in low-rate, low-background environment gives further large reduction in data rate

• Depth measurement from diffusion broadening of track width

• Need gain if we are to access keV energies → we have chosen Gas Electron Multipliers (GEMs) as the most promising avenue for our R&D program

• Avalanche process in the GEMs offers both charge and light as potential bases for readout schemes – we are focusing on optical readout
An Event:

1. Neutrino scatters on a target electron
2. Electron ionizes medium
3. Ionized electrons drift along Efield
4. E-bubbles form
5. E-bubbles drift to readout plane and “photographed”, one plane at a time
Backgrounds

- No radioactive isotopes in detector medium
- No solubility of heavier molecules in LHe, whereas $H_2$ dissolves in LNe (useful!) → impurities freeze out
- Micropore filters shown to be effective in removing “dust”
- Good energy and spatial resolution give powerful capability for recognizing “Compton clusters” of several scattered electrons from external $\gamma$’s in the MeV range
  - Each secondary photon from successive scatters has a lower energy, and a decreased absorption length, leading to events with a number of scattering vertices easily recognized as a Compton cluster
  - Calculations indicate rejection factors of order 100’s – 1000’s, depending on the source and the fiducial cut → ongoing studies
  - Irreducible background from MeV $\gamma$’s with (improbable) single scatters in the keV range in fiducial volume
- Self-shielding, in LNe, effective for lower energy $\gamma$’s
- 3D-reconstruction defines fiducial volume – track width from diffusion gives reasonable depth measurement, in particular at top, where backgrounds from the readout plane can be cut
Recent results from Cryogenic Test Facility at BNL

- $1 < T < 300$K; $P$ up to 10 bar
- Field cage
- Windows, transmitting from IR to UV
- Various ionizing particle sources
- Operation with LHe, LNe, or other fluids of interest
Build a Cryogenic *Fluid* Tracker

↓

Single Phase Liquid

No gain (charge/light) in Liquid

• New detector technologies

↓

2-Phase detector
Low-mobility carriers observed in liquids

- Measured drift velocities consistent with known electron bubble mobilities
- Long lifetimes! Excellent purity achieved easily
Surface behavior and trapping times

- Experimentally:
  - Establish "steady-state" with ionization charges from an alpha source being drifted to the surface, and ejected into vapor phase
  - Measured current is related to surface trapping time:

  ![Graph showing current (I) vs. Vc (V) for Helium and Neon](image)

  - Expected monotonic increase of I with $E_{\text{surface}}$ → trapping times ~ msec, and tunable
  - Periodic droplet ejections from surface (visible!) → trapping times ≥ sec

- Suitable trapping times at LHe surface, but too long for LNe at 1 Bar
Gain from GEMs in vapor

- Modest gain in He vapor; large gain (> $10^4$) in Ne vapor with addition of fraction of $H_2 \rightarrow$ operate at temperatures where finite $H_2$ vapor pressure
- With hydrogen doping, both He and Ne give gains > $10^4$ in 3-GEM configuration
- Little true temperature effect - impurities play important role at high temperatures

CERN GEMs
30x30mm
140µm hole pitch
50µm hole diameter

Purity & the addition of $H_2$ to He

- To test the impurity hypothesis, subsequent runs purified the Helium gas supply through Oxisorb + (Rare Gas) Heater Getter.
- The drop in gain could be compensated by the controlled addition of known impurity ($H_2$) at High temperatures.
- Gain still drops at LHe temperatures as the vapor pressure of $H_2$ decreases.
Build a Cryogenic *Fluid* Tracker

- **No gain (charge/light) in Liquid**
  - New detector technologies

  - **2-phase**
    - LHe: No gain < 4K
    - LNe: Gain in Ne+H₂ ~10⁴ @30K

  - **1-phase (Supercritical) Dense Gas**
    - Remove difficulty of surface
    - Possibility to use He+H₂ – retain complementarity with Ne
    - Possibility to tune density very attractive
    - Recombination losses are lower

  - Surface dynamics difficult
    - Could we manipulate this trapping
    - Optical/electrical gating of charge
GEM-optical readout concept

- Could use 2D array of amplifiers to detect charge, however electronics with good performance at low temp. are not readily accessible in standard silicon processes.
- Avalanche produces light as well as charge - triplet excitation produces significant visible (plus IR?) component.
- Calculations indicate transport efficiency of a few %, making use of lenslets matched to GEM holes.
- Use commercial CCD cameras, sitting at ~ 50K.
α tracks:

- Uncollimated alpha source, ~ 10 kHz rate, in Ne + 0.01% H₂ at 78K (charge gain ~ 10)
  
  60 sec exposure (~ 600k alphas!):

  1 msec exposure (~ 10 alphas):

- Non-optimal geometry, with ionization from many alphas occupying only a few GEM holes, limits available gain in this configuration
Light yield and spectrum

- Initially, studies with alpha tracks in neon-based mixtures at 78K
- Light registered with PMT.

- Highest charge gain achieved in Ne + 0.1% H₂
- Highest (relative) light yield for Ne + 0.01% H₂ → can obtain visible light yield from GEM holes of ≥ 1 photon per avalanche electron
- Much lower visible yield from helium-based mixtures (need to measure IR)
CCD Gas measurements:

- In this configuration charge gain limited to $O(10)$ before single damaging discharge occurs
• Use narrow band filters to look at spectrum of visible light using CCD.
• CCD QE~10% at 850nm

**Conclusions:**
• H$_2$ does not influence emission spectrum in Ne.
• Harder to get light in He even with the addition of H$_2$. 
**α tracks:**

- Collimator reduced source rate & collimated αs coming out at 35deg to the plane of the cathode
  - Rate ~ O(5-10)Hz
- Charge gain >$10^4$ achieved in a single GEM, due to reduction in charge density although in a single GEM
Single GEM in Ne+0.1%H2 @77K&7atm
14\mu m/pixel or 56\mu m/pixel_{4x4}
Projected visible track length 6.4mm

- No alignment of GEM holes on multiple GEM structures is performed
- Single vs Triple GEM did not reduce the width of the tracks.
  - Track width dominated by coulomb spread of the charge.
  - No localization of electrons in these conditions so diffusion is not thermally driven.
Summary of R&D results to date

• Localized carriers observed in LHe, LNe – long drift times (at least 200 msec) measured, confirming high purity of fluids

• Measurements of surface transfer show suitable trapping times for LHe, but inconveniently long times for LNe, at least at 27K → higher temperatures, or single-phase medium if Ne

• Large, stable gains, up to $10^4$, available in GEM structures, with small fraction (0.01 – 0.1%) of $H_2$ → operating temperatures above ~ 10K → single-phase medium if He

• Can achieve visible photon yields of > 1 photon per avalanche electron from GEM holes in neon-based gas mixtures

• Visible light yields from helium-based mixtures lower – need to measure IR yield (normal helium discharge has a bright line at ~ 1 µm)

• Successful initial CCD imaging of alpha tracks at cryogenic temperatures – individual track images very soon, followed by verification with electron tracks at T ~ 30-40K
Baseline: supercritical neon

- Initial ideas based on two-phase detector:
  - Insufficient gain in vapor phase for He
  - Trapping time at surface too long for Ne at 1 Bar
- Single-phase supercritical fluid:
  - Electrons are still localized and thermal
  - Removes difficulties of surface
  - Ability to tune density very attractive
  - Recombination losses lower
- Supercritical neon:
  - Density $\sim 0.48$ g/cc ($T \sim 45K$, $P \sim 26$ bar) $\rightarrow$ electron mobility $\sim 6 \times 10^{-2}$ cm$^2$/sec$/V/V$
  - Recoil track lengths for pp neutrinos up to $\sim 2$ mm
  - Keep option to run with supercritical helium: longer/straighter tracks, pointing for lower energies, systematic checks; but smaller target mass and reduced self-shielding
Design of cubic-meter prototype

**Goals:**

- Detect neutrino interactions
- Measure backgrounds/self-shielding performance
- Develop analysis techniques
- Explore scaling issues
Radial dependence of Irreducible Backgrounds from single Compton scatters from 2.614MeV $\gamma$ from the Th232 decay chain

1.5”SS with 0.6ppb Th232 +8” ultrapure Cu liner

Instrumented to R=100cm
Instrumented to R=50cm

Expected pp solar $\nu$ signal
Conclusion

• Good progress in measuring fundamental parameters for an electron bubble TPC detector

• Next steps:
  • Measurements and imaging in supercritical Ne (He)
    • Supercritical Ne will require an upgrade to existing infrastructure
    • But existing Test Chamber can demonstrate ebubble behavior in GEM avalanche in critical density He
  • Continued R&D on optical readout based on lenslets and CCD camera → goal is full 3D track reconstruction with electron bubbles/slow drift
  • Ongoing development of the cubic-meter prototype – small enough to be transportable, with test phase at BNL before move to an underground site
  • Techniques we are developing may be useful for a range of other applications requiring measurement (tracking) of very small signals in large volume detectors
    • Dark Matter
    • Coherent neutrino scattering
    • Double Beta decay