Outline

• Liquid state signal generation
  o Ionization
  o Thermalization
  o Recombination
  o Electron attachment & diffusion
• Signal generation in wire planes
  o Field response
  o Electronics response
• Convolution and deconvolution
• Closing comments
Ionization Nano-Physics in LAr

\[ r_{\text{ion-electron}} \sim 0.5 \text{ nm with } E_{\text{electron}} \sim 5 \text{ eV} \]

\[ r_{\text{ion}} = 23.6 \text{ eV} / (dE/dx) \]

MIP \( dE/dx = 2.1 \text{ MeV/cm} \Rightarrow r_{\text{ion}} \sim 100 \text{ nm} \)

HIP \( dE/dx \sim 25 \text{ MeV/cm} \Rightarrow r_{\text{ion}} \sim 10 \text{ nm} \)

Ref: LAr atomic spacing \( \sim 0.4 \text{ nm} = 4 \text{ Å} \)
After Thermalization

Electron mfp = 20 nm
Onsager distance 120 nm
($E_{\text{Coulomb}} = E_{\text{thermal}}$)

~10k collisions
~2 ns
$E_{\text{thermal}} \sim 0.01$ eV
$\langle r_{\text{ion-electron}} \rangle \sim 2500$ nm (2.5 μm)

Recombination Theories

**Geminate**
Small $r_{ion-electron}$
~0.1% in LAr
Onsager

**Columnar**
Large $r_{ion-electron}$
Jaffe, Thomas-Imel

**Bulk**
Debye-Smoluchowski
2. Zur Theorie der Ionisation in Kolonnen; 
von George Jaffé.

Leipzig, im Mai 1913.
(Eingegangen 30. Mai 1913.)

\[(32') \quad Y_3(X) = \frac{1}{1 + \frac{\alpha N_0}{8 \pi D} \sqrt{\frac{\pi}{z'}} S(z')} \quad z' = \frac{b^2 u^2 X^3 \sin^2 \varphi}{2 D^3}\]

Birks model (1951)

\[Y_3(X) = \text{recombination factor } R\]
\[\rightarrow \text{fraction of electrons that escape vs E field strength } X\]

Assumptions
Recombination ~ charge density
No Coulomb interactions
Ion mobility = electron mobility
Electrons & ions have the same Gaussian distribution

\[
S(z') = \frac{1}{\sqrt{\pi}} \int_0^\infty \frac{e^{-s} ds}{\sqrt{s(1+s/z')}}
\]
Recombination in Practice

\[ R_c = \frac{Q}{Q_\infty} = \frac{A}{1 + \frac{k E}{\varepsilon} \frac{dE}{dx}} \]

\[ R_L = \frac{L}{L_0} = 1 - \alpha R_c \]

\( \varepsilon \) is electric field in kV/cm

ICARUS

\[ A = 0.800 + 0.003 \]

\[ k = 0.0486 + 0.0006 \text{ kV/cm (g/cm}^2\text{/MeV)} \]


Less charge = more scintillation light

Craig Thorn, “Properties of LAr v9a”, MicroBooNE doc #412, LBNE doc #4482
Electron Attachment & Diffusion

\[ Q_o = \text{electron charge after recombination} \]
\[ Q = \text{charge arriving at the wire planes} \]

“drift electron lifetime”
\[ \tau_{\text{electron}} = \frac{1}{(\text{Rate Constant} \times \text{concentration})} \]

\[ Q = Q_o \exp(-t_{\text{drift}} / \tau_{\text{electron}}) \]

Water is bad!

Longitudinal / Transverse diffusion rms

Craig Thorn, “Properties of LAr v9a”, MicroBooNE doc #412, LBNE doc #4482
Electron Transport in Wire Planes

"Transparency" Condition

Garfield simulation
MicroBooNE
3 mm wire spacing
3 mm plane cap

\[ \rho = \frac{2\pi r}{d} \]

\[ \frac{E_P}{E_Q} = \frac{1+\rho}{1-\rho} \]

1.37 for uB

Buneman, Can. J. Res. A27 (1945) 191
Electron Transport in Wire Planes

- Drift Distance (cm)
  - $E = 0.5 \text{kV/cm}$, $v_{\text{drift}} = 1.6 \text{ mm/μs}$
  - $E \approx 0.75 \text{kV/cm}$, $v_{\text{drift}} = 1.8 \text{ mm/μs}$
  - $E \approx 1.1 \text{kV/cm}$, $v_{\text{drift}} = 2.1 \text{ mm/μs}$

Set E field ratio $\approx 1.5$

Electron Drift Velocity in LAr

- Induction 1
- Induction 2
- Collection

- $T = 87.3 \text{ K}$
- $T = 89.3 \text{ K}$
- $T = 91.3 \text{ K}$
- icarus [24]
Electron Transport in Wire Planes

Drift Distance (cm)

3 mm $\rightarrow$ $\sim$2 $\mu$s time spread

$45^\circ$ track

Time spread $\rightarrow$ slide 13

x-Axis [cm]
Important note:
This is a Garfield simulation of transport of ONE electron in 2D wire plane geometry

Real life:
1) 3D configuration of planes with different wire orientations
2) Ensemble of 20k+ electrons with varying trajectories → next slide
Convolute field response with 0.5 µs electronics shaping time

Different curves are for electrons starting at $0 < x < 1.5$ mm

Collection plane wire at $x=0$ (slide 10)

Collection plane wire at $x=0.3$

~2 µs

Leon Rochester (SLAC) for MicroBooNE
Electronics Response

Using BNL – Nevis electronics chain

Markers at 0.2 μs = 5 MHz sample rate

Gain set to 1.0

Shaping time (μs)

ENC = A + B C_{in}

Rough approximation

A_{300K} = 2 \times A_{90K}
B_{300K} = 2 \times B_{90K}

ENC (electrons)

Input Capacitance (pF)
Signal Processing Chain

Thermalization → Recombination → Diffusion → Field Response → Electronics Response → Sampling, DAQ → Deconvolution?

Time spread, comments

- 2 ns
- ~10 ns, charge loss
- ~1 µs, Gaussian
- ~2 µs, complex, $\angle$ dependent
- ~0.5 - 3 µs, ~Gaussian

Issues: sampling rate, position resolution, two-track resolution, S/N
ArgoNeuT Data
Collection plane

Big signal

50 cm

Induction plane

~no signal

Reconstructed hits on Collection wire 142
**Convolution and Deconvolution**

**Convolution**

Signal = Ionization \( \otimes \) diffusion \( \otimes \) field \( \otimes \) electronics

\[ \mathcal{F} = \text{Fourier Transform} \]

\[ \text{Signal} = \mathcal{F}^{-1} \{ (\mathcal{F}(\text{ionization}) \ast \mathcal{F}(\text{diffusion}) \ast \mathcal{F}(\text{field}) \ast \mathcal{F}(\text{electronics})) \} \]

**De-convolution & Filter**

Ionization \( \otimes \) diffusion = \( \mathcal{F}^{-1} \{ \text{Filter} \ast \mathcal{F}(\text{Signal}) / \mathcal{K} \} \)

Filter protects when \( \mathcal{K} \rightarrow 0 \) or to remove coherent noise
Generalization

- Signal for single hit e.g. induction plane
- Response Function
- Desired Output Shape, e.g. Gaussian

De-convolute hits in the ADC channel to a Gaussian form

**ADC\(_1\)**

\[ F(\mathcal{R}) = \frac{F(G_1)}{F(ADC_1)} \]

\[ G_n = F^{-1} \{ \text{Filter} * \frac{F(ADC)}{F(\mathcal{R})} \} \]

Cons

Developing convolution kernels and filters takes special effort

Computational cost
Closing Comments

• In-liquid signal formation well understood
  o Charge loss due to recombination and electron attachment are not...

• Complex field response in the wire planes
  o Motivates setting electronics shaping time >~ field response time spread

• BNL ASIC designed for LArTPCs
  o Programmable gain and shaping time
  o Peak amplitude independent of the shaping time
  o Charge injection calibration

• Deconvolute signals?
  o Bipolar induction plane signals → unipolar collection plane signals
    • Common hit finding and hit reconstruction code
  o Convert to a “standard” shape, e.g. Gaussian
  o No obvious benefit for collection plane signals for long shaping times
  o Remove coherent noise using a notch filter
  o Computational and human cost of developing kernels & filters