A study of electron recombination using highly ionizing particles in ArgoNeuT

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Outline

- Brief survey of recombination theory
- LAr – ideal liquid vs real liquid
- Application of Birks and Box model equations
  - Introduce a modification to the Box model
- Recombination simulation
  - Focus on angular dependence
- ArgoNeuT LAr TPC in the NuMI neutrino beam
  - Track and calorimetric reconstruction
- A novel(?) stopping particle ID scheme for selecting protons and deuterons
- Angular dependence – protons
- Extend to higher stopping power - deuterons
Recombination

- Geminate: ~0.1%
- Bulk: Electron lifetime
- No angular dependence
- Columnar: Angular Dependence
- E field

No angular dependence
\[ Y_3(X) = \frac{1}{1 + \frac{\alpha N_0}{8\pi D} \sqrt{\frac{\pi}{z'}} S(z')} \], \quad z' = \frac{b^2 u^2 X^4 \sin^2 \varphi}{2D^2}.

**Birks model (1951)**

\[ Y_3(X) = \text{recombination factor } R \]

\[ \rightarrow \text{fraction of electrons that escape vs E field strength } X \]

**Assumptions**

- Recombination \(\sim\) charge density
- No Coulomb interactions
- Ion mobility = electron mobility
- Electrons & ions have the same Gaussian distribution

\[ S(z') = \frac{1}{\sqrt{\pi}} \int_0^\infty \frac{e^{-s} ds}{\sqrt{s(1+s/z')}} \]
Liquid Argon
A Special Medium

- High electron mobility
- Electron MFP = 20 nm
- Onsager radius = 130 nm ($E_{\text{Coulomb}} = E_{\text{thermal}}$)
- No vibration levels available $\rightarrow$ ~1 nsec thermalization time
- Electrons in Coulomb field or strong external field, $\mathcal{E}$, are not in thermal equilibrium $\rightarrow$ diffusion equations not fully applicable

Box Model
Ignore electron diffusion and ion mobility in LAr

$$\mathcal{R}_{\text{Box}} = \frac{1}{\xi} \ln(\alpha + \xi),$$

$$\xi = k_{\text{Box}} N_0 / 4 a^2 \mu \mathcal{E}$$

$\mathcal{E} = E$ field

*Thomas & Imel, Phys Rev A 36 (1987) 614*

$\alpha = 1$ in the canonical model.
We allow it to vary in the recombination fits.

We set $\xi = \beta (dE/dx)$ and fit $\beta$ in the recombination fits.
Liquid Argon
As a Real Detector Medium

**Measurement**

Birks form

\[
\mathcal{R}_{\text{ICARUS}} = \frac{A_B}{1 + k_B \cdot (dE/dx)/E}
\]

\[
A_B = 0.800 \pm 0.003 \neq 1
\]

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


**Impurities**

Ions can attach to water molecules, screening the Coulomb field.

Debye length \( \lambda_D = \text{distance at which screened potential } E = E_{\text{thermal}} \)

\( \lambda_D = 400 \text{ – } 600 \text{ nm in ArgoNeut data} \)

Not negligible?

**Measurement**

Theory \( \mathcal{R} \to 0 \text{ as } E \to 0 \)

Heavy ions: \( \mathcal{R} = 0.003 \)

Electrons: \( \mathcal{R} = 0.35 \)


\( \delta\)-rays
Application of Birks and Box forms to reconstruction

Inverse Birks equation is $< 0$ at large $dQ/dx$

Inverse Box equation is well behaved

But Box model fails to match data at low $dE/dx$

Solution: Let $\alpha < 1$

“Modified Box Model” ala ICARUS $A_B = 0.8$

Example with $\alpha = 0.93$

$\beta = 0.32$

$$dE/dx = \frac{dQ/dx}{A_B/W_{ion} - k_B \cdot (dQ/dx)/\beta}$$

$$dE/dx = (\exp(\beta W_{ion} \cdot (dQ/dx)) - \alpha)/\beta$$
Recombination Simulation

E field

Stopping proton: \( \frac{dE}{dx} = 24 \text{ MeV/cm} \Rightarrow r_k = 10 \text{ nm} \)

MIP: \( \frac{dE}{dx} = 1.7 \text{ MeV/cm} \Rightarrow r_k = 50 \text{ nm} \)

Initial conditions:
\( r_0 = 0.5 \text{ nm}, \ E_{k0} = 5 \text{ eV} \)

After thermalization:
\( \langle r_0 \rangle \sim 2500 \text{ nm}, \ \langle E_{k0} \rangle \sim 0.01 \text{ eV} \)

Simulation includes motion due to (periodic) Coulomb field, external E field and atomic collisions, escape and recombination criteria

\[ \text{Sim with } \delta \text{-rays ICARUS} \]
Modify simulation to allow non-perpendicular $E$ field

Simulation runs for $r_k = 10, 20, 30, 40, 50$ nm and $\phi = 40^\circ, 50^\circ, 60^\circ, 80^\circ$

Ratios of escape probability, $R$, vs $dE/dx$ →

Simulation (data points) $R_{\text{ICARUS}}$ with $E \rightarrow E \sin \phi$ (curves)

Significant angular dependence expected from theory and simulation
ArgoNeuT

C. Anderson, 2012 JINST 7 P10019

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryostat Volume</td>
<td>500 Liters</td>
</tr>
<tr>
<td>TPC Volume</td>
<td>175 Liters</td>
</tr>
<tr>
<td># Electronic Channels</td>
<td>480</td>
</tr>
<tr>
<td>Electronics Style (Temp.)</td>
<td>JFET (293 K)</td>
</tr>
<tr>
<td>Wire Pitch (Plane Separation)</td>
<td>4 mm (4 mm)</td>
</tr>
<tr>
<td>Electric Field</td>
<td>481 V/cm</td>
</tr>
<tr>
<td>Max. Drift Length (Time)</td>
<td>0.5 m (330 μs)</td>
</tr>
<tr>
<td>Wire Properties</td>
<td>0.15mm diameter BeCu</td>
</tr>
</tbody>
</table>
Bethe-Bloch eqn has power law dependence with residual range (R) near the stopping point.

\[ \frac{dE}{dx}_{\text{hyp}} = A R^b \]

\[ T_{\text{range}} = \frac{A}{b+1} R^{b+1} \]

<table>
<thead>
<tr>
<th>Particle</th>
<th>( A )</th>
<th>( b )</th>
</tr>
</thead>
<tbody>
<tr>
<td>pion</td>
<td>7.9</td>
<td>-0.37</td>
</tr>
<tr>
<td>kaon</td>
<td>13.5</td>
<td>-0.41</td>
</tr>
<tr>
<td>proton</td>
<td>17</td>
<td>-0.42</td>
</tr>
<tr>
<td>deuteron</td>
<td>25</td>
<td>-0.43</td>
</tr>
</tbody>
</table>

Note the weak dependence on \( b \)

\( T_{\text{range}} \) (MeV), \( R \) (cm)
1) Reconstruct 3D tracks = cluster of 3D space points each with a measurement of charge $Q$ deposited using the area of a Gaussian fit (collection plane)

2) Find $dQ/dx$ using angle corrected distance between space points

3) Correct for electron lifetime

4) Find $(dE/dx)_{\text{calo}}$ using Birks or Box equation

5) Sum up to find kinetic energy deposited = $T_{\text{calo}}$

6) Find $T_{\text{range}}$ using track length assuming a proton hypothesis

7) Eliminate lightly ionizing ptcls by requiring $T_{\text{calo}} > 0.5 \times T_{\text{range}}$
**Algorithm**

Set $b = \text{constant} = 0.42$

Find $A_i = \frac{dE}{dx}_{\text{calo}} \times R^{0.42}$ for each space point $i$ on a track

Define $\text{PIDA} = \langle A_i \rangle = \text{average value for the track}$

Histogram $\text{PIDA}$ and look for bumps $\rightarrow$

**Requirements**

Protons: $14 < \text{PIDA} < 21$
Deuterons: $25 < \text{PIDA} < 33$

30x more protons than expected from NC $\nu$ interactions $\rightarrow$ neutrons
2900 proton candidates
170 deuteron candidates

\[(dE/dx)_{\text{deuteron}} = 25 \cdot R^{-0.43}\]

\[(dE/dx)_{\text{proton}} = 17 \cdot R^{-0.42}\]
ArgoNeut data
Proton candidates
$50 \text{ MeV} < T_{\text{range}} < 250 \text{ MeV}$

Range (cm)

Events

$40^\circ$  $50^\circ$  $60^\circ$  $80^\circ$
Angular Dependence
Protons

ArgoNeut data

No recombination model assumptions required to make this plot

\( \frac{dQ}{dx} \) from Bethe-Bloch using R
Angular Dependence

Protons

Significantly weaker than expected from theory and simulation

Debye-like screening effect?

ArgoNeut data

\( \times 10^3 \)

\( dQ/dx \) (e/cm)

\( (dE/dx)_{hyp} \) (MeV/cm)

\( \phi = 80^\circ \)

\( \phi = 60^\circ \)

\( \phi = 50^\circ \)

\( \phi = 40^\circ \)
Recombination Fits

\[ \frac{dQ}{dx} \text{ vs } \frac{dE}{dx} (\langle \phi \rangle = 80^\circ) \]

<table>
<thead>
<tr>
<th>Method</th>
<th>Parameter</th>
<th>Value</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Birks</td>
<td>( A )</td>
<td>0.7928 ± 0.01812</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( k )</td>
<td>0.0492 ± 0.002441</td>
<td></td>
</tr>
<tr>
<td>Modified Box</td>
<td>( \alpha )</td>
<td>0.9095 ± 0.03286</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \beta )</td>
<td>0.3019 ± 0.005493</td>
<td></td>
</tr>
</tbody>
</table>

\[ \chi^2 / \text{ndf} = 5.82 / 18 \]

Vertical bars include 2% systematic error
Horizontal bars \( \delta R = 1 \text{ mm} \)

\[ \frac{dQ}{dx} \text{ vs } \frac{dE}{dx} (\langle \phi \rangle = 40^\circ) \]

<table>
<thead>
<tr>
<th>Method</th>
<th>Parameter</th>
<th>Value</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Birks</td>
<td>( A )</td>
<td>0.8748 ± 0.0247</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( k )</td>
<td>0.06554 ± 0.003584</td>
<td></td>
</tr>
<tr>
<td>Modified Box</td>
<td>( \alpha )</td>
<td>1.062 ± 0.05178</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \beta )</td>
<td>0.3462 ± 0.00695</td>
<td></td>
</tr>
</tbody>
</table>

\[ \chi^2 / \text{ndf} = 3.757 / 16 \]

ArgoNeut data

Data – open circles
Birks fit – red curve
Modified Box fit – blue curve
**Fit Summary Protons**

<table>
<thead>
<tr>
<th>Angle Bin</th>
<th>Angle Bin Range</th>
<th>Box $\alpha$</th>
<th>Box $\beta$ (MeV/cm)$^{-1}$</th>
<th>Birks $A_{\text{Argo}}$</th>
<th>Birks $k_{\text{Argo}}$ (kV/cm)(g/cm$^2$)/MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>80°</td>
<td>70° - 90°</td>
<td>0.91 ± 0.03</td>
<td>0.302 ± 0.005</td>
<td>0.793 ± 0.018</td>
<td>0.049 ± 0.002</td>
</tr>
<tr>
<td>60°</td>
<td>55° - 70°</td>
<td>0.92 ± 0.04</td>
<td>0.317 ± 0.006</td>
<td>0.794 ± 0.019</td>
<td>0.052 ± 0.003</td>
</tr>
<tr>
<td>50°</td>
<td>47° - 55°</td>
<td>0.90 ± 0.04</td>
<td>0.327 ± 0.007</td>
<td>0.791 ± 0.020</td>
<td>0.053 ± 0.003</td>
</tr>
<tr>
<td>40°</td>
<td>20° - 47°</td>
<td>1.06 ± 0.05</td>
<td>0.346 ± 0.007</td>
<td>0.875 ± 0.025</td>
<td>0.066 ± 0.004</td>
</tr>
</tbody>
</table>

$\alpha \sim$ independent of angle

$<\alpha> = 0.93 \pm 0.02$

Excellent agreement with ICARUS in the 80° bin

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Trend line

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ANT 2013 Baller
Deuterons

\[ (dE/dx)_{hyp} = 25 \, R^{-0.43} \]

Extends the range of the recombination fit to 35 MeV/cm
Summary

• Introduced a modified Box model
  o Excellent agreement with data and Birks model
  o Obviates the poor behavior of the Birks model at low ionization

• Significant recombination angular dependence expected from columnar theory and simulation
  o ~25% loss of charge collected at φ ~ 40° and dE/dx ~ 24 MeV/cm compared to the same track at φ ~ 80°

• Introduced a PID scheme using the power-law behavior of stopping particle stopping power

• Charge loss is 5% - 10% in the proton sample at high dE/dx and small angle

• Extend the range of validity to 35 MeV/cm using a small sample of deuterons
Backup Slides
Deuterons or Protons?

Lower PIDA range: 23 < PIDA < 27
Contaminated by protons in the Gaussian tail
See slide 14

Deuteron: \((dE/dx)_{hyp} = 25 \cdot R^{-0.43}\)
Are the deuteron candidates really protons?

Use the (incorrect) proton hypothesis with the deuteron sample.
Estimating the Stopping Point Position

- The stopping point is usually assumed to be dx/2, where dx is the distance between the last two space points.
- Use the pattern of dE/dx in the last 5 space points to estimate the stopping point in the last wire cell.
- Step a distance δR in the last cell (1 < δR < 10 mm) in 1 mm increments.
- For each step, calculate:
  - dQ/δR for the stopping point,
  - Recombination correction $\rightarrow (dE/δR)_\text{calo}$ for the stopping point,
  - $(dE/dx)_{\text{hyp}}$ for next 4 points using residual range = δR + n dx (n = 1, 2, 3, 4).
- Find rms difference between $(dE/dx)_{\text{hyp}}$ and $(dE/dx)_{\text{calo}}$ for all points.
- Use the $\Delta$ value with the smallest rms.
Estimating the Stopping Point Position

Assume the track stops halfway in the last cell

\[ \langle \frac{dE}{dx} \rangle \sim 45 \pm 45 \text{ MeV/cm} \]

Data
Monte Carlo

After fitting to the stopping point

\[ \langle \frac{dE}{dx} \rangle \sim 25 \pm 13 \text{ MeV/cm} \]

Data
Monte Carlo
Estimating the Stopping Point Position

- Stopping point error from Monte Carlo ~ 1 mm
- \((dE/dx)_{\text{calo}}\) from the last point is not included in the recombination fits
- Stopping point fit reduces the \((dE/dx)_{\text{hyp}}\) error propagated from the equation on slide 12
  - Horizontal error bars on slide 18