Simulation and Design of a Hadron Calorimeter for Jefferson Lab Hall-A Super Bigbite Spectrometer

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SBS Collaboration

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Hall-A Super Bigbite Spectrometer

[Diagram showing the layout of the Hall-A Super Bigbite Spectrometer with various components labeled including Target, 48D48, CCT, CH2, GEM, Hadron Calorimeter, and dimensions such as 228 inch, 128 inch, and 63 inch.]
COMPASS Hadron Calorimeter

Designed for high energy experiments, hadron energy greater than 10 GeV.

Time resolution ~ 1.5 ns sigma.

Hadron energy range is ~ 2-10 GeV, needs better time resolution.
Design Goals

Intended to be used for 12 GeV nucleon Form-Factor experiments and nucleon transversity experiments.

- Position resolution ~ 3-5 cm for background rejection and track reconstruction.
- Good time resolution sigma ~ 0.5-1.0 ns to reject background in coincidence experiments (Time-of-Flight).

✓ Faster wavelength shifter is needed.
Scintillator and Wave-length Shifter

✔ Need 0.5-1.0 ns time resolution

● Only blue WLS (decay ~1.5 ns)
  ➢ ELJEN 299-27
  ➢ BC-484
  ➢ Absorption 350-400 nm
Scintillator and Wave-length Shifter

- Need 0.5-1.0 ns time resolution
- Only blue WLS (decay ~1.5 ns)
  - ELJEN 299-27
  - BC-484
  - Absorption 350-400 nm
- Need scintillator emission 350-400 nm
  - ELJEN-232 (too expensive)
  - BC-420,422 (too expensive)
Scintillator and Wave-length Shifter

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● Need scintillator emission 350-400
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● Scintillators with PVT base
  ➢ Usually 1%PPO+0.05% POPOP fluorescent dyes
  ➢ Does not work with EJ-229-27
  ➢ Only PPO, short attenuation length
  ➢ Needs some modifications to use a scintillator with short attenuation length

EJ-299-27 wavelength shifter

Scintillator Emission

- Emission
- Absorption

PPO
POPOP
BC-484 Wave-length Shifter

✔ BC-484 WLS compared to EJ-299-27 WLS

● Advantage
  ➢ Less self absorption
  ➢ Absorption spectrum is wider
  ➢ Expect more light
  ➢ Cheaper than EJ299-27

● Disadvantage
  ➢ Decay time 3 ns
# Scintillator made in Fermilab

<table>
<thead>
<tr>
<th>PPO Concentration (%)</th>
<th>Tested</th>
<th>Suitable with EJ-299-27</th>
<th>Suitable with BC-484</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>1.0</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>2.0</td>
<td>NO</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>3.0</td>
<td>NO</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Fermilab Scintillator Tests
### Light Attenuation Lengths (EJ-299)

<table>
<thead>
<tr>
<th>PPO concentration</th>
<th>Attenuation length</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5%</td>
<td>18.1 ± 1.5 cm</td>
</tr>
<tr>
<td>1.0%</td>
<td>11.5 ± 0.7 cm</td>
</tr>
</tbody>
</table>

#### Attenuation length (PPO=0.5%)

- $\chi^2 / \text{ndf}$: 5.35 / 6
- $N_0$: 9.63 ± 0.19
- $L_{\text{abs}}$: 18.15 ± 1.47

#### Attenuation length (PPO=1.0%)

- $\chi^2 / \text{ndf}$: 6.84 / 6
- $N_0$: 9.96 ± 0.23
- $L_{\text{abs}}$: 11.47 ± 0.69

#### Time Resolution (PPO=1%)

- $\chi^2 / \text{ndf}$: 23.26 / 14
- Constant: 81.68 ± 3.64
- Mean: 0.00 ± 0.04
- Sigma: 0.86 ± 0.03
Light Attenuation Lengths (BC-484)

<table>
<thead>
<tr>
<th>PPO concentration</th>
<th>Attenuation length</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 %</td>
<td>24.8 ± 4.0 cm</td>
</tr>
<tr>
<td>1.0%</td>
<td>N/A</td>
</tr>
</tbody>
</table>

About 60% more light compared to EJ-299-27 WLS!
The calorimeter has 22 x 11 modules.

Each module has 40 iron and scintillator plates.

Active length of a module is 50 cm, $3 \lambda_{\text{nucl}}$.

Light is collected by 92 cm long WLS bars.
Simulation

- Track optical photons with GEANT4 UNIFIED model.
  - Wavelength shifter and scintillator surface properties.
- Accurate timing simulation.
  - 900 single photo-electron responses of the PMT are measured and used to simulate the ADC pulse.
  - Photon PMT hit times are used to shape the ADC pulse.
  - Takes account PMT transit time spread and noise.
- Adjust scintillator photon yield to match the measured value.
- Energy is reconstructed using 4x4 size cluster.
- Hit position found from center of gravity of the cluster.

Simulated pulse
Simulation Validation

- A module of similar design as in COMPASS is tested using cosmic ray muons.
- The COMPASS module is simulated in GEANT4.
- Module time resolution is measured when the light propagation in the module is in direction of the cosmic muon and opposite to it (PMT at bottom and at top positions).

<table>
<thead>
<tr>
<th></th>
<th>Light propagation opposite to muon direction</th>
<th>Light propagation same direction as the muon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time resolution (experiment)</td>
<td>0.76 ns</td>
<td>0.62 ns</td>
</tr>
<tr>
<td>Time resolution (simulation)</td>
<td>0.77 ns</td>
<td>0.6 ns</td>
</tr>
</tbody>
</table>
Resolutions are calculated taking account light propagation in optical volume of the calorimeter.

4x4 cluster is used for energy and coordinate reconstruction.

Moderate energy resolution.
Simulated Efficiency

![Simulated Efficiency Graph]

- **Efficiency [%]**
- **Neutron energy [GeV]**
- **Threshold 1/4 of mean energy**
- **Threshold 1/2 of mean energy**
Simulated Time Resolution

PMT signal from 4x4 cluster modules are summed.

Simulate “threshold discriminator”, measure time when the amplitude of the signal reaches 5% of the average amplitude at a given energy. Apply time walk correction.

Simulated “constant fraction discriminator” gives worse time resolution compared to a threshold discriminator.

Neutron energy 5 GeV

Entries 8658
$\chi^2$/ndf 841.6/37
Constant 452.2 ± 6.7
Mean 9.077 ± 0.011
Sigma 0.6765 ± 0.0065

Neutron energy [GeV] vs Time resolution (sigma) [nm]
Summary

✔ A hadron calorimeter is simulated for JLab Hall-A SBS spectrometer.

✔ A PVT based scintillator with 0.5% PPO as fluorescent dye is found suitable.

✔ BC-484 WLS gives more light compared to EJ-299.

✔ Placing the WLS in the middle of the module allows to use scintillators with short light attenuation lengths (~20 cm).

✔ Simulated energy, coordinate and time resolutions meet SBS hadron calorimeter requirements.

✔ Detection efficiency is > ~90%.