Performance of FOREST calorimeters in response to the proton

Calorimeters of Interest
- Pure CsI crystal -
- Lead/scintillating fiber module -

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• Calorimeters of the FOREST experiment at ELPH
  • Pure CsI crystal
  • Lead scintillating fiber module
  • Lead glass
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Motivation

- Meson photoproduction: Photon + Nucleon → (X) → Meson(s) + Baryon
  \[(p, n) \rightarrow \left(\pi^0 \rightarrow \gamma\gamma, \eta \rightarrow \gamma\gamma, K^0 \rightarrow \pi^0\pi^0 \rightarrow \gamma\gamma\gamma\gamma\right)\]

- Multi-photon detection
  -> 4π electromagnetic calorimeter
  AND detecting the residual baryon
  1) Identification
  2) reconstruction of its kinematical values
  play an important role for selecting clear events
Motivation

- Meson photoproduction: Photon + Nucleon -> (X) -> Meson(s) + Baryon

\[ \gamma p \rightarrow \pi^0 p \]

- Multi-photon detection
  - > 4π electromagnetic calorimeter

1) Identification of the remaining baryon
2) Reconstruction of its kinematical values

**Motivation**

\[ E_\gamma = 1150 \text{ MeV} \]
\[ E_\gamma = 550 \text{ MeV} \]
FOREST experiment @ ELPH

• An electro-magnetic calorimeter complex FOREST

<table>
<thead>
<tr>
<th>Scintillator</th>
<th>Type</th>
<th># of modules</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure CsI</td>
<td>LNS</td>
<td>144</td>
<td>16.2 $X_0$</td>
</tr>
<tr>
<td></td>
<td>INS</td>
<td>48</td>
<td>13.5 $X_0$</td>
</tr>
<tr>
<td>Lead/SciFi</td>
<td></td>
<td>252</td>
<td>13.8 $X_0$</td>
</tr>
<tr>
<td>Lead glass</td>
<td>SF5</td>
<td>10</td>
<td>11.8 $X_0$</td>
</tr>
<tr>
<td></td>
<td>SF6</td>
<td>52</td>
<td>14.7 $X_0$</td>
</tr>
</tbody>
</table>

$E_\gamma = 550\sim1150$ MeV
Pure CsI crystals and lead glass

<table>
<thead>
<tr>
<th></th>
<th>W</th>
<th>H</th>
<th>Dep</th>
<th>Density</th>
<th>PbO : SiO2</th>
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<tbody>
<tr>
<td>SF5</td>
<td>150</td>
<td>150</td>
<td>300</td>
<td>4.075 g/cm³</td>
<td>0.538:0.462</td>
</tr>
<tr>
<td>SF6</td>
<td>75</td>
<td>75</td>
<td>250</td>
<td>5.20 g/cm³</td>
<td>0.687:0.313</td>
</tr>
</tbody>
</table>
Lead/Scintillating fiber (Lead/SciFi) module

A Sampling calorimeter

- Lead: absorber
- Scintillating fibers (Ø 1mm): detector

~5000 fibers/module
Energy resolutions of the pure CsI crystals, Lead/SciFi module, and Lead Glass

All of the test experiments for studying the performances of the detector were carried out in the ELPH (LNS) positron (electron) beam line.

The incident electron/positron energy ranges from 100 to 800 MeV.

Reference documents can be found in the “Research Report of Laboratory of Nuclear Science, Tohoku Univ”.

Performance of the FOREST calorimeters in response to the proton
Estimation of the proton detection efficiencies

• Analyzed reactions:
  \[ \gamma p \rightarrow \pi^0 p \rightarrow \gamma \gamma p \]
  \[ \gamma p \rightarrow \eta p \rightarrow \gamma \gamma p \]
  \[ \gamma p \rightarrow \pi^0 \pi^0 p \rightarrow \gamma \gamma \gamma \gamma p \]

• Missing momentum technique:
  The proton momentum \( p_p \) was reconstructed by the partner meson(s) and incident photon energy
  \(-\rightarrow\) The proton is treated as a missing particle

• Kinematic fit:
  The reconstructed momentum resolution was improved by the kinematic fit method
  Kinematic constraints:
  \[ \text{The } \gamma \gamma \text{ invariant mass is equal to the mass of the photo-produced meson(s): } \pi^0 \text{ or } \eta \]
  \[ \text{The missing mass of the meson(s) is equal to the proton mass} \]
The missing momentum resolution

- Estimated by a GEANT4-based Monte Carlo (MC) simulation
- The reconstructed polar angle resolutions of the proton

\[ \Delta \theta = \theta_p (p_p) - \theta_p^{\text{gen}} \]

\[ \theta_p \geq 40^\circ \]

- Pure CsI (LNS)
  \[ \theta_p = [10^\circ, 15^\circ] \]

- Lead/SciFi

\[ \sigma = 2.0 \pm 0.0 \]

\[ \sigma = 31.3 \pm 0.0 \]
Proton detection efficiencies

\[
\frac{N_{\text{meson(s)}+\text{charge detected}}(p_p)}{N_{\text{meson(s)}\text{detected}}(p_p)}
\]

**Pure CsI**

- \( p_p \sim 500 \text{ MeV/c} \)
- \( K_p \sim 125 \text{ MeV} \)

**Lead/SciFi**

- \( \gamma p \rightarrow \pi^0 p \)
- \( \gamma p \rightarrow \eta p \)
- \( \gamma p \rightarrow \pi^0 \pi^0 p \)
Performance of the FOREST calorimeters to the proton
- In a GEANT4 based simulation -
Energy spectra of the FOREST detectors

Measured energy of a FOREST detector in the simulation reproduces the realistic energy by smearing the deposit energy of the incident particle. The smearing parameters were determined by the test experiment with $e^\pm$ beam. The energy spectrum of the FOREST detector do not reproduce the realistic energy spectrum when the proton goes into them.
Reproduction of the energy deposit of the proton to the calorimeters

- Energy deposit of the proton is recomputed in every ‘step’ $dr$ as
  \[ dE \leftarrow dE \times \frac{P_{\text{random}}(Pdr)}{Pdr} \alpha \]
  where $P$ is a probability whether the proton is detected or not in the $dr$

- Total energy deposit $E$ is calculated by integration of $dE$s

- Then $E$ is smeared by use of the detector resolution determined by the photon

The determined parameter $P$ is consistent with the mass ratio of the SciFi

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![Graphs showing real data and simulation results for different energy bins.]
Mean and RMS of the energy spectrum by the real data and simulation

Introduction of the complicated structure of the Lead/SciFi to the GEANT4 based MC simulation

Real structure

Consists of Lead, SciFi, and glue

Density: 5.5 g/cm³
Mass ratio
Lead : SciFi : Opt. cement 84.5% : 11.6% : 3.9%

No prescription for the proton energy deposit
Proton detection performance of the pure CsI crystal and Lead/SciFi module in the GEANT4 simulation

\( \gamma p \rightarrow \pi^0\pi^0 p \) photoproduction reaction
Summary

• The FOREST experiment at ELPH uses three types of calorimeters
  Pure CsI crystals – the LNS type and INS type ($\sigma_E/E \sim 3\% @ 1\,\text{GeV}$)
  Lead/Scintillating fiber module ($\sigma_E/E \sim 7\% @ 1\,\text{GeV}$)
  Lead glass Cerenkov counters
    – the SF5 type and SF6 type ($\sigma_E/E \sim 5\% @ 1\,\text{GeV}$)

• The proton detection efficiency of the FOREST calorimeters reach to about 100% for $p_p \geq 500\,\text{MeV/c}$ ($K_p \geq 120\,\text{MeV}$).

• Performance FOREST calorimeters to the proton in a GEANT4 based simulation well reproduce the real data.