Lead Tungstate Crystals for a High Performance Electromagnetic Calorimeter

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Motivation

- A large number of particles is produced in the heavy ion collisions.
- Our purpose: to measure electromagnetic particles accurately at energy range from hundred MeV to a few GeV under a high particle multiplicity environment.

**Calorimeter**
- high position resolution
- high energy resolution

- A lead-tungstate (PWO) crystal is the best candidate for the calorimeter material.
A lead-tungstate (PWO) crystal is the best candidate for the calorimeter material.

**Measurements**

**Optical property**
Transmittance  
(contributed to energy resolution)

**Scintillation properties**
Light Yield  
( contributed to energy resolution)  
Decay time  
( limited time resolution)

**Energy Resolution**
Beam tests at REFER and KEK-PS
Calorimetry
How to measure total energies for electromagnetic particles

- **Electromagnetic shower**
  Bremsstrahlung, pair creation, ionization
  Radiation length : $X_0$, Moliere radius : $R_M$

- **Scintillation**
  Light originated from the atom de-exitation

- **Electromagnetic Calorimeter**
  Absorb the energies of all electrons/gamma-rays, produce signals proportional to those energies.

**signals**
Scintillation light
PWO crystal
dense, fast and radiation-hard scintillator

Y-doped PbWO₄

<table>
<thead>
<tr>
<th>Crystal</th>
<th>Density [g/cm³]</th>
<th>Radiation length [cm]</th>
<th>Moliere radius [cm]</th>
<th>Decay time [nsec]</th>
<th>Light yield [% NaI]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWO</td>
<td>8.28</td>
<td>0.89</td>
<td>2.2</td>
<td>5 ~ 15</td>
<td>1</td>
</tr>
<tr>
<td>BGO</td>
<td>7.23</td>
<td>1.12</td>
<td>2.4</td>
<td>300</td>
<td>15</td>
</tr>
<tr>
<td>NaI</td>
<td>3.67</td>
<td>2.59</td>
<td>4.5</td>
<td>250</td>
<td>100</td>
</tr>
<tr>
<td>CsI</td>
<td>4.53</td>
<td>1.85</td>
<td>3.8</td>
<td>565</td>
<td>40</td>
</tr>
</tbody>
</table>

reference to Particle Data Book
Optical property  
measurement of transmittance

- Slightly yellowish due to the absorption bands in the blue region of lead oxide
- Internal attenuation coefficient: \(0.018 \text{ cm}^{-1}\) at 420 nm
Scintillating properties
measurements of Light Yield & Decay Time

Typical PWO signal of single photoelectron

PMT
Hamamatsu R7056
one photon sensitive
(Gain : $10^7 @ -1900V$)

PWO crystal
(Covered with Aluminum)

Black box

PMT trigger

$^{60}$Co source

Plastic scintillator
Scintillating properties
measurements of Light Yield & Decay Time

60Co spectrum

- single photoelectron peak
- two p.e. peak
- 60Co photo peak (1.2MeV)

Scintillation decay curve

<table>
<thead>
<tr>
<th>Crystal</th>
<th>Light Yield [p.e/MeV]</th>
<th>Decay Time [nsec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWO(A)</td>
<td>4.5</td>
<td>1.7(30%), 5.6(70%)</td>
</tr>
<tr>
<td>PWO(B)</td>
<td>8.2</td>
<td>1.2(17%), 6.0(83%)</td>
</tr>
<tr>
<td>BGO</td>
<td>404</td>
<td>185</td>
</tr>
</tbody>
</table>

~PWO(B) crystal~
Scintillating properties
Cosmic-ray test

PWO(A)
PWO(B)

deposit energy $\sim$ 35 MeV

The light yield of two samples had the difference with factor of 2

PMT
Hamamatsu R7056
one photon sensitive
(Gain : $10^7$ @ - 1900V)

Trigger
PMT(Hamamatsu R3478)
Plastic scintillator

counts
0 20 40 60
Number of photoelectrons
0 200 400 600

PWO(A)
PWO(B)
Beam test @ REFER
Relativistic Electrons Facility for Education and Research

150MeV electron beam

beam exit

electron storage ring

BM(×8)
inj.septum
inj.BM
ext.BM
ext.septum
ext.QM

microtron
injection bending magnet

Beam time
Sep.11~14, 26~28
Oct.2~3
Beam test @ REFER
Setup & Results

Single electron peak
$E_e = 116$ MeV

Two electrons peak
$E_e = 231$ MeV

Deposit energy 77 %
Due to energy leakage
Energy resolution 16 %
Beam test @ KEK - PS
KEK 12 GeV Proton Synchrotron 2 beam line

2 beam line
unseparated beam
proton, pion or electron
1 GeV/c ~ 3 GeV/c
Beam test @ KEK - PS
PWO calorimeter test in T496

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R. Kohara
Y. Furuhashi

Hiroshima group of T496 collaboration

PWO Calorimeter
Gas Cerenkov Counter
Start Counter

Veto Counter

1*1

5 m

2 m

beam

PWO Calorimeter

5*5

2*4

10*20 (2 2)

beam
Beam test @ KEK - PS
PWO calorimeter results

 Deposit energy distribution
PWO(B)+PMT(Hamamatsu R7056)
Energy Resolution

Results
Single PWO crystal

5.4%/√E(GeV) experiment
4.6%/√E(GeV) simulation

9 PWO crystals in a 3 × 3 matrix
2.1%/√E(GeV) expectation

The difference:
• Fluctuation of scintillation photons
  PMT intrinsic resolution
  ~ 1%/√E
• Beam momentum
  ~ 1%/√E

Single PWO Crystal
PWO(B)+PMT(Hamamatsu R7056)
Conclusion

- Optical property
  attenuation coefficient $0.018$ [cm$^{-1}$] at the wavelength of 420 nm

- Scintillating properties
  * Small light output but fast scintillation
    Light yield $4.5 \sim 8.2$ [p.e./MeV]
    Decay time $1.2 \sim 1.7$ and $5.6 \sim 6.0$ [ns]
  * Two samples have different properties, although manufactured in the same method

- $78\%$ of the incident energy was deposited in one PWO crystal.

- Energy resolution is $5.4\% / \sqrt{E}$ on the single PWO crystal.
  *Consisted with the simulation
  *Will be up to $2.1\% / \sqrt{E}$ on the nine crystals in a 3 $\times$ 3 matrix
My next step at doctor course

- **Calorimeter**
  * 3 × 3 matrix
  * Avalanche Photo Diode (APD) instead of PMT

- **Physics in heavy ion collisions**
  * Measurement of “single photons”
  * \( J/\psi \) production and suppression
Photon emission in heavy ion collisions

$\begin{align*}
&\sim 10^{-23} \text{ seconds} \\
&\text{QGP creation} \\
\end{align*}$

$\begin{align*}
&\begin{array}{c}
\text{Au} \\
\end{array} \to \begin{array}{c}
\text{Au} \\
\end{array} \\
\end{align*}$

$\begin{align*}
&\begin{array}{c}
\text{q} \quad \text{g} \quad \text{g} \\
\end{array} \\
\end{align*}$

$\begin{align*}
&s_{NN} \sim 100 \text{ GeV} \\
&\text{Ultra relativistic} \\
&t \sim 3 \text{ GeV/fm}^3 \\
\end{align*}$

$\begin{align*}
&\text{Thermal equilibrium} \\
&T \sim 170 \text{ MeV} \\
&\text{Black body radiation} \\
&q\bar{q} \to g, qg \to q \\
\end{align*}$

$\begin{align*}
&\text{Hadronic decay} \\
&\pi^0 \to \eta, \phi, \omega \\
\end{align*}$

$\begin{align*}
&(\text{total } \pi^0 \text{ yield}) - (\text{decay } \pi^0 \text{ yield}) = (\text{single } \pi^0 \text{ yield})
\end{align*}$
$\pi^0$ reconstruction

Simulation

$\pi^0 / \pi^0$ separation
High Energy Resolution
High Mass Resolution

Mass resolution

$$\frac{\sigma_m}{m} = \frac{\sigma_1}{E_1} \oplus \frac{\sigma_2}{E_2} \oplus \frac{\sigma_\theta}{\tan(\theta / 2)}$$

Invariant mass

$$M_{\gamma\gamma} = \sqrt{2E_1E_2(1 - \cos\theta)}$$

$\pi^0$ (99 %)

$c \pi^0 = 25.1$ nm
$m = 134.9$ MeV
## Photon emission in heavy ion collisions

| Before Collision | Au $\rightarrow$ Au | $\bar{s}_{NN} \sim 100$ GeV
|                 |                   | Ultra relativistic |
| First           | Parton Scatter    | prompt photon $q\bar{q} \rightarrow g, qg \rightarrow q$ |
| $T \sim 170$ MeV | Quark Gluon Plasma | thermal photon $q\bar{q} \rightarrow g, qg \rightarrow q$ |
| $\bar{s} \sim 3$ GeV/fm$^3$ | Hadron gas | thermal photon $\pi^0, \pi^\pm$, etc. |
| Phase transition |                      |                      |
| Final           | decay photon $\pi^0, \pi^\pm$, etc. |                      |

$\sim 10^{-23}$ seconds
# Survival Charmonium

| Before Collision | Au | Au | $\Delta s_{NN} \sim 100$ GeV  
Ultra relativistic |
|---|---|---|---|
| First | Parton Scatter  
$q\bar{q} \rightarrow c\bar{c}$,  $gg \rightarrow c\bar{c}$  
$c\bar{c}$-pair produced |
| $T \sim 170$ MeV  
$\sim 3$ GeV/fm$^3$ | Quark Gluon Plasma  
Some $c\bar{c}$-pairs disassociated.  
(Color screening) |
| $\sim 10^{-23}$ seconds | Hadron gas  
$J/\Psi (c\bar{c}) + h \rightarrow D\bar{D} + X$  
(Absorption) |
| Final | decay  
$J/\Psi \rightarrow \phi \pi^+ \pi^-$,  $J/\Psi \rightarrow e^+e^-$ |
Avalanche Photo Diode

Si APD (Hamamatsu S5345)
Short wavelength enhanced type

Preamp (Hamamatsu H4083)
Charge sensitive

Output signal for scintillation light

Prototype
Monte Carlo Simulation
GEANT4

GEANT is used most widely at high energy physics for detector simulation.

Injection beam: 150 MeV electron
Momentum: constant

Electron, positron, gamma

\[ E_e = 117 \text{ MeV} \]
\[ \frac{\sigma}{E} = 13\% \]

Not take into account;
photo statistics, fluctuation of beam momentum,
PMT intrinsic resolution, noise of electronics, etc.
Photon statistics & PMT resolution

- $a_{pe}$: stochastic term of photon statistics
- $N_{pe}$: Light Yield [p.e./MeV]
- $F$: Excess Noise Factor

$$a_{pe} = \sqrt{\frac{F}{N_{pe}}}$$

- Expected stochastic term

$$a_{exp} = a_{sim} \oplus a_{pe}$$