Development of Nuclear Emulsion for Cosmic Ray Radiography
-Thick supporting base type emulsion-

Yuta Manabe, Kunihiro Morishima, Nobuko Kitagawa, Akira Nishio, Mitsuaki Kuno
Department of Science, Nagoya University

ICMaSS 2017/09/30
Cosmic-Ray Radiography

- Archeology remains
- Blast furnace
- Nuclear power plant
- Non-destructive inspection for large structure.
- Detect CR muon, calculate energy loss.
- Estimate target’s material density

Detect particle trajectory

Mt. Showahshinzan

Alfred Tang et al. PHYSICAL REVIEW D 74, 053007 (2006)
We need high angular accuracy.

Final imaging resolution is decided by detector’s resolution.

Estimate material density by detected muons.

Red: High material density
Blue: Low material density

Cosmic-Ray Radiography

- Archeology remains
- Blast furnace
- Nuclear power plant

Alfred Tang et al. PHYSICAL REVIEW D 74, 053007 (2006)
Structure of Nuclear Emulsion

Microscopic view

High spatial resolution (< 1μm)

Emulsion Layer
Supporting base (Polystyrene)
Emulsion Layer

Producing in Nagoya University
Emulsion Cloud Chamber (= ECC)

Estimate momentum by multiple coulomb scattering

\[ \theta_{\text{scat}} = \frac{13.6}{\beta cp} z \sqrt{\frac{x}{X_0}} \left\{ 1 + 0.038 \ln \left( \frac{x}{X_0} \right) \right\} \]

\[ \theta_i = \sqrt{\theta_{\text{scat}}^2 + \Delta \theta_i^2} \]
Detection Principle of Nuclear Emulsion

- Taking slice images of emulsion layers
  → Judge particles tracks by developed grains linearly.

- Connecting both side tracks
  → Reconstruct tracks with corrected distortion of emulsion layer (gelatin).
Definition of Angular Accuracy

\[
\tan \theta_x = \frac{x_2 - x_1}{l} \\
\left(= \frac{x_2 - x_1}{z_2 - z_1}\right)
\]

\[
\delta \tan \theta_x = \sqrt{\frac{1}{l^2} \delta x^2 \times 2 + \left(\frac{x_2 - x_1}{l^2}\right)^2 \delta l^2}
\]

\[
= \frac{\sqrt{2}}{l} \sqrt{\delta x^2 + \delta z^2 \times (\tan \theta_x)^2}
\]

We expect to improve angular accuracy by using thick type base.
(From optical design of scanning machine, the limit of all thickness is 1mm.)
## Base Candidates

<table>
<thead>
<tr>
<th>Base Materials</th>
<th>PS (㎛)</th>
<th>TAC (㎛)</th>
<th>PMMA (㎛)</th>
<th>COP (㎛)</th>
<th>PC (㎛)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Thickness</td>
<td>70</td>
<td>175</td>
<td>90</td>
<td>200</td>
<td>500</td>
</tr>
<tr>
<td>[㎛]</td>
<td></td>
<td></td>
<td>205</td>
<td>800</td>
<td>300</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Water Absorption [Wighet%]</th>
<th>PS</th>
<th>TAC</th>
<th>PMMA</th>
<th>COP</th>
<th>PC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.01~0.03</td>
<td>3.3~3.8</td>
<td>0.1~0.4</td>
<td>&lt;0.01</td>
<td>0.15</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Refractive index</th>
<th>PS</th>
<th>TAC</th>
<th>PMMA</th>
<th>COP</th>
<th>PC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.59</td>
<td>1.49</td>
<td>1.53</td>
<td>1.53</td>
<td>1.59</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Birefringence [nm]</th>
<th>PS</th>
<th>TAC</th>
<th>PMMA</th>
<th>COP</th>
<th>PC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1.4</td>
<td>3.5</td>
<td>3.6</td>
<td>7.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Experiments</th>
<th>WA75</th>
<th>Now</th>
<th>CHORUS, DONUTS</th>
<th>OPERA</th>
<th>CHORUS, DONUTS</th>
<th>CHORUS, DONUTS</th>
<th>Under Investigation</th>
<th>Under Investigation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Using</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Start of Experiments</th>
<th>WA75</th>
<th>Now</th>
<th>CHORUS, DONUTS</th>
<th>OPERA</th>
<th>CHORUS, DONUTS</th>
<th>CHORUS, DONUTS</th>
<th>Under Investigation</th>
<th>Under Investigation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Emulsion thickness [㎛]</th>
<th>PS</th>
<th>TAC</th>
<th>PMMA</th>
<th>COP</th>
<th>PC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>350</td>
<td>44</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

Water Absorption is literature data.
Improvement of Angular Accuracy Test 1

- **Beam**: $\pi^-$
- **Energy**: 5GeV
- **Density**: $10^3/cm^2$
- **Exposure area**: $5 \times 12.5\, cm^2$
- **Emulsion Base Type**: 175$\mu$mPS, 500$\mu$mCOP

**2D Histogram of test beams**

**1D Histogram of test beams**
To investigate base thickness dependence of angular accuracy, I use the beam spot of $\tan \theta = 0.0 \pm 0.02$

Angular accuracy is expected near to be inversely proportional to the base thickness.
Angular Accuracy of Vertical Tracks
175$\mu$mPS • 500$\mu$mCOP Emulsions

Solid Line
: 500$\mu$mCOP Emulsion
$1\sigma = 0.972 \pm 0.006 \times 10^{-3}$

Dashed line
: 175$\mu$mPS Emulsion
$1\sigma = 2.62 \pm 0.016 \times 10^{-3}$

<table>
<thead>
<tr>
<th></th>
<th>PS</th>
<th>COP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base thickness</td>
<td>175</td>
<td>500</td>
</tr>
<tr>
<td>Angular accuracy</td>
<td>$2.62 \pm 0.016 \times 10^{-3}$</td>
<td>$0.972 \pm 0.006 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Ratio of base thickness: $\frac{500\mu m}{175\mu m} = 2.86$

Ratio of angular accuracy: $\frac{2.62 \times 10^{-3}}{0.972 \times 10^{-3}} = 2.70$

Not contain base material effects
Improvement of Angular Accuracy Test 2

Location: Outdoor tent
Direction: Horizontal to the ground
Period: 3 days

Investigate base dependence of angular accuracy, using same angle as the beam,

\(-0.02 < \tan \theta < 0.02\)

- 175\(\mu\)m PS base emulsion
- 300\(\mu\)m PC base emulsion
Angular Accuracy of Vertical Tracks
175μmPS • 300μmPC Emulsions

Solid Line: 300μmPC Emulsion
\(1\sigma = 1.49 \pm 0.10 \times 10^{-3}\)

Dashed Line: 175μmPS Emulsion
\(1\sigma = 2.53 \pm 0.18 \times 10^{-3}\)

<table>
<thead>
<tr>
<th></th>
<th>PS</th>
<th>PC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base thickness</td>
<td>175</td>
<td>300</td>
</tr>
<tr>
<td>Angular accuracy</td>
<td>(2.53 \pm 0.18 \times 10^{-3})</td>
<td>(1.49 \pm 0.10 \times 10^{-3})</td>
</tr>
</tbody>
</table>

\[
\text{Ratio of base thickness} = \frac{300\mu m}{175\mu m} = 1.71
\]
\[
\text{Ratio of angular accuracy} = \frac{2.53 \times 10^{-3}}{1.49 \times 10^{-3}} = 1.70
\]

Not contain base material effects
Summary of Angular Accuracy of Vertical Tracks

\[\sqrt{2} \times \delta \tan \theta_x \times 10^{-3}\]

Red: 175\(\mu\)m PS_CR
Black: 175\(\mu\)m PS_Beam
Blue: 300\(\mu\)m PC_CR
Green: 500\(\mu\)m COP_Beam

\[\delta \tan \theta_x = \frac{\sqrt{2}}{l} \sqrt{\delta x^2 + \{\delta z^2 \times (\tan \theta_x)^2 = 0\}}\]

Power approximation curve is

\[y = 7.75 \times 10^{-7}x^{-0.936}\]

It is approximately inversely proportional.

And, \(\delta x\) is calculated \(~0.55\ \mu m\) from this value, which is in agreement with the known value in the order.
Angle Dependence of Angular Accuracy Test

\[ \tan \theta_x = 0.0, 0.2, 0.4 \ldots 1.0 \]
\[ \tan \theta_y = 0.0 \]
Each points \( \pm \tan \theta = 0.05 \)

\[ \tan \theta_x = 0.0, 0.1, 0.2 \ldots 1.0 \]
\[ \tan \theta_y = 0.0 \]
Each points \( \pm \tan \theta = 0.05 \)
Angle Dependence of Angular Accuracy Test Result, Consideration

**Results**

1. Thick base type emulsion’s angular accuracy is better than more thin one.

2. Angular accuracy is deferent between same base emulsion.

**Consideration of Result 2**

- Deference of angular distribution
- Deference of set up
- Deference of statistics
## Base Candidates (New Beam Test Samples)

<table>
<thead>
<tr>
<th>基材素材</th>
<th>PS (Polystyrene)</th>
<th>PMMA (PolyMethyl MethAcrylate, Acryl)</th>
<th>COP (CycloOlefin Polymer)</th>
<th>PC (PolyCarbonate)</th>
<th>Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refractive index</td>
<td>1.57</td>
<td>1.48</td>
<td>1.53</td>
<td>1.58</td>
<td>1.52</td>
</tr>
<tr>
<td>Birefringence [nm]</td>
<td>-</td>
<td>3.5</td>
<td>3.6</td>
<td>7.5</td>
<td>-</td>
</tr>
<tr>
<td>Water Absorption [Wt%]</td>
<td>0.01~0.03</td>
<td>0.1~0.4</td>
<td>&lt;0.01</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>Coefficient of thermal expansion [cm/cm°C]</td>
<td>$5.0\sim8.3 \times 10^{-5}$</td>
<td>$5.0\sim9.0 \times 10^{-5}$</td>
<td>$7 \times 10^{-5}$</td>
<td>$6.8 \times 10^{-5}$</td>
<td>$7.2 \times 10^{-6}$</td>
</tr>
<tr>
<td>Base Thickness [μm]</td>
<td>175</td>
<td>500</td>
<td>500</td>
<td>300</td>
<td>300 500 700</td>
</tr>
</tbody>
</table>

Water Absorption & Coefficient of thermal expansion is literature data,
Conclusion

• We are developing thick supporting base type nuclear emulsion for improvement of angular accuracy to use cosmic-ray radiography.

• In beam test and observation of cosmic-ray, We confirmed improvement of angular accuracy by using thick type base.

• Next step, using new beam test samples, we’ll evaluate several base type emulsion’s performance inclusive angle dependence of angular accuracy.
角度精度の角度依存性評価

1D Histogram of test beam

1D Histogram of Detected Cosmic Ray

$tan\theta_x = 0.0, 0.2, 0.4 \ldots 1.0$
$tan\theta_y = 0.0$
のピーク+-0.05で切り出す

$tan\theta_x = 0.0, 0.1, 0.2 \ldots 1.0$
$tan\theta_y = 0.0$
の点+-0.05で切り出す
屈折率・副屈折率の違いによる見え方の差

PC（ポリカーボネート） 300μm
屈折率 = 1.58
複屈折率 = 7.5nm

COP（シクロオレフィンポリマー） 500μm
屈折率 = 1.53
複屈折率 = 3.6nm

* コンプトン電子の飛跡が見える
* コンプトン電子の飛跡は殆ど見えない

* 支持体と乳剤層の屈折率差の効果
  （乳剤層の屈折率〜1.5）
* 複屈折率が高いことによる像のボケ
散乱効果による画像のボケ

溶鉄10mを貫通したミューオンの散乱による画像ボケ

散乱されやすい低運動量のミューオンを識別する必要がある
Glass 500μm
屈折率 = 1.52
複屈折率 = 未測定
COP 500μm
屈折率 = 1.53
複屈折率 = 3.6nm
PC 300μm
屈折率 = 1.58
複屈折率 = 7.5nm
PMMA 500μm
屈折率 = 1.48
複屈折率 = 3.5nm
PS 175μm
屈折率 = 1.57
複屈折率 = 未測定