The cosmic ray flux of about ~1 particle per cm² per minute at the earth’s surface is composed predominately of mu-mesons (μ±). E. P. George was the first to use cosmic ray muons for radiography. George measured the stopping rate of muons in order to determine the overburden of a mine tunnel. This technique has since been used for a variety of geological and archeological investigations. We have researched using the multiple scattering of muons for radiography. In addition to providing much more sensitivity than stopping, multiple scattering provides 3-d information, enabling tomography. This technology has recently been chosen for use in studying the damaged cores of the Fukushima Reactors.
Radioactivity, three discoveries-three Nobel prizes

Wilhelm Conrad Roentgen
Discovered x-rays in 1895
First Nobel prize in physics 1901

Antoine Henri Becquerel
Discovered Radioactivity in 1896
shared the Nobel prize in physics with Pierre and Marie Curie, 1903

Victor Franz Hess
1910-1913 showed cosmic rays come from outside the solar system.
Shared the Nobel prize in 1936 with C.D. Anderson

Flux at earth's surface is predominately muons
• Letons
• Time dilation
Muon Interaction with Matter

Kinematics

<table>
<thead>
<tr>
<th>particle</th>
<th>mass (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+$</td>
<td>0.5</td>
</tr>
<tr>
<td>$\mu^+$</td>
<td>105</td>
</tr>
<tr>
<td>p/n</td>
<td>940</td>
</tr>
</tbody>
</table>

Coulomb Interaction

$$\frac{d\sigma}{d\Omega} = \left( \frac{Z_1 Z_2 e^2}{8\pi\epsilon_0 m v_0^2} \right)^2 \csc^4 \left( \frac{\Theta}{2} \right).$$

'LA-UR-13-26416
Energy Loss

\[
\frac{dN}{dx} = \frac{dN}{dE} \frac{dE}{dx}
\]
\[
\frac{dE}{dx} = K z^2 \frac{Z}{A} \beta^2 \left[ \frac{1}{2} \ln \left( \frac{2 m c^2 \beta^2 \gamma^2 T_{\text{max}}}{I^2} - \beta^2 - \delta(\beta \gamma) \right) \right]
\]

Multiple Scattering

\[
\frac{dN}{d\theta} = \frac{1}{2 \pi \theta_0^2} e^{-\frac{\theta^2}{\theta_0^2}} d\Omega
\]
\[
\theta_0 = \frac{14.1}{p \beta} \sqrt{\frac{L}{X_0}}
\]
\[
\frac{1}{X_0} = \frac{K}{A} \left\{ Z^2 \left[ L_{\text{rad}} - f(Z) \right] + Z L'_{\text{rad}} \right\}
\]

\[\text{\textsuperscript{1}LA-UR-13-26416}\]

<table>
<thead>
<tr>
<th>Material</th>
<th>dx/dE [cm/GeV]</th>
<th>x [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor Core</td>
<td>731.9</td>
<td>8.7</td>
</tr>
<tr>
<td>Concrete</td>
<td>254.1</td>
<td>15.8</td>
</tr>
<tr>
<td>Fe</td>
<td>88.4</td>
<td>9.5</td>
</tr>
<tr>
<td>water</td>
<td>502.5</td>
<td>36.0</td>
</tr>
</tbody>
</table>
Cosmic Rays
Measure
Overburden
of Tunnel

Geiger counter telescope used for mass determination at Gudhaga project of Snowy Scheme. Equipment described.

Search for Hidden Chambers in the Pyramids

The structure of the Second Pyramid of Giza is determined by cosmic-ray absorption.


Method of probing inner-structure of geophysical substance with the horizontal cosmic-ray muons and possible application to volcanic eruption prediction

K. Nagamine ab, *, M. Iwasaki a, K. Shimomura a, K. Ishida b

* Measun Science Laboratory, Faculty of Science, University of Tokyo (UT-MSL), Hongo, Bunkyo-ku, Tokyo, Japan
b Muon Science Laboratory, The Institute of Physical and Chemical Research (RIKEN), Wako, Saitama, Japan

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Scattering Cosmic Radiography

• Technical approach:
  – Measure passive radiation
  – Use muons to generate “scattering density” image
    » Built in momentum measurement
    » Automatic calibration using flux through empty detector
  – Combine signals to identify threats

• Advantages over other methods
  – No radiation
  – Simple technology
  – Inexpensive
  – Can penetrate thick cargos
  – Automatic Identification
It really works!
Decision Sciences
Decision Sciences First Installed Commercial Muon Scanner at Freeport in the Bahamas
Radiography of Fukushima reactors
11 March 2011 Tohoku Great Earthquake

18500 Deaths due to the earthquake and tsunami.
Economic loss ~$275 billion

2 weeks after the earthquake
Cas Milner suggesting using muon scattering to look at the cores.

Three reactors melted down.
Clean up estimated to take 40 years.
(No prompt deaths due to radiation exposure;
No increased cancer rate; radiation deaths estimated to be negligible. Clean up cost ~$15-100 billion
Scattering and Stopping radiography can be used to image the damaged cores. Stopping radiography is much more difficult.
Results from Toshiba Nuclear Critical Assembly (NCA) Radiography (350 hrs exposure)
NCA Results
**Summary**

- Cosmic ray radiography
  - Apparatus is simple and robust.
  - In use for border protection (Bahamas)
  - Potential for treaty verification
  - Radiography of Fukushima cores is approved
  - Cosmic rays allow precise assessment (~several %) with 8 weeks of exposure