Measurement of the cosmogenic neutron seasonal variations with LVD

LVD collaboration

Presenter: Irina Shakiryanova (INR RAS)

ECRS, 2016, Torino, Italy
• Introduction
  ➢ Temperature and barometric effects
  ➢ The set of the available muon intensity variation measurements

• Large Volume Detector

• Data analysis (muon events selection, neutron detection)
  ➢ Methods of determination of neutron seasonal variation
  ➢ Epoch folding method
  ➢ Residual method

• Conclusions
\[ E_{p} \approx 10^{14} \text{eV} \]

\[ E_{\pi} \approx \frac{1}{10} E_{p} \approx 10^{13} \text{eV} \]

\[ I_{\mu_{1}}^s > I_{\mu_{1}}^w \]

\[ I_{\mu_{2}}^s < I_{\mu_{2}}^w \]

\[ E_{(\mu)}^s > E_{(\mu)}^w \]
The temperature effect of the muon component is caused by a competition between decay of $\pi/\kappa$ and $\mu$ and their interaction with the atmospheric nuclei due to the change of geometric atmosphere dimensions.

With atmosphere heating and its consequent expansion the number of $\pi/k$ decays is increasing and this results in positive temperature effect. Simultaneously with the atmosphere expansion the $\mu$ path to the detector is increasing what results in the negative temperature effect as $\mu$ decay becomes more possible.
The set of the available muon intensity variation measurements:

2. AMANDA (225 days 1997)
3. MINOS (1096 days)
4. LVD (2001 - 2008)
5. BOREXINO (2007 - 2011)
6. IceCube (18 month 2007-2008)
MINOS (E.W. GRASHORN for Minos coll.,
Observation of Seasonal Variations with the
MINOS Far Detector, 30ICRC, arXiv:0710.1616)

IceCube (Serap Tilav for IceCube coll.,
Atmospheric Variations as observed by
IceCube, arXiv:1001.0776)

MACRO Coll (M. Ambrosio, Seasonal
variations in the underground muon
intensity as seen by MACRO, Astroparticle
Physics, 7 (1997) 109-124)

AMANDA Coll. (A. Bouchta for
Amanda coll., Seasonal variation of the
muon flux seen by Amanda, 26 ICRC, 1999)

Borexino (Davide D'Angelo for
Borexino coll. Seasonal modulation in the
Borexino cosmic muon signal, arXiv:1109.3901)

LVD (M. Selvi for LVD Coll., Analysis of the seasonal modulation of the cosmic muon flux in the LVD detector during 2001-2008, 31 ICRC, 2009)
The main goal: detection of neutrinos from the collapse of stellar cores

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length $\times$ Width $\times$ Height</td>
<td>22.7$\times$13.2$\times$10 m</td>
</tr>
<tr>
<td>Iron mass</td>
<td>1020 $\tau$</td>
</tr>
<tr>
<td>Scintillator mass</td>
<td>1008 $\tau$</td>
</tr>
<tr>
<td>Amount of scintillation counters</td>
<td>840</td>
</tr>
<tr>
<td>Number of PMTs</td>
<td>2520</td>
</tr>
<tr>
<td>Average depth minimal</td>
<td>3620 m w.e.</td>
</tr>
<tr>
<td>Mean muon energy</td>
<td>280 GeV</td>
</tr>
<tr>
<td>$E_\mu$ on see level (min.)</td>
<td>1.3 TeV</td>
</tr>
<tr>
<td>Muon rate (on 1 tower)</td>
<td>$\sim$ 120 h$^{-1}$</td>
</tr>
<tr>
<td>Threshold $\varepsilon_{th}$</td>
<td>5 MeV</td>
</tr>
</tbody>
</table>
Muon selection and neutron detection:

An event is selected as ‘muon event’ if there are at least 2 distinct counters with $E_{tr} > 10$ MeV and time difference $\Delta t < 250$ ns.

We have selected from muon events the inner counter triggers having energy $E_{tr} > 50$ MeV.

- Neutron searching for in the same counter where muon trigger is produced ($E_{tr} > 50$ MeV);
- Energy of gamma pulses: 1 – 12 MeV;
- Time window: 50 – 550 microseconds

\[
\begin{align*}
n+p &\rightarrow D + \gamma, \quad E_\gamma = 2.2 \text{ MeV} \\
n+Fe^{56} &\rightarrow Fe^{57} + \gamma, \quad \Sigma E_\gamma = 10.16 \text{ MeV} 
\end{align*}
\]
Methods of the $N_n/N_{tr}$ determination:

Specific number of muon-induced neutron is the determined number of neutrons divided by number of triggers in the same counter.

**Epoch folding method**

- Background determination
  - $N_n = N_{tot} - N_{bg}$
  - $N_n/N_{tr}$ (during 180 months)
  - $F(t) = 1 + \delta \cdot \cos(2\pi(t-\varphi)/T)$

**Residual method**

«summer» - «winter»

- Winter: 3 mon. x 15 year = 45 months
  - $n_w$ = $f(t) = N_0 \cdot \exp(-t/\tau) + B$
- Summer: 3 mon. x 15 year = 45 months
  - $n_s$
  - $\delta = (n_w - n_s)/(n_w + n_s)$
Specific neutron number $N_n/N_{tr}$

Rate of trigger pulses per month, $<N_{tr}> \approx 2.5 \times 10^5$

Rate of neutron pulses ($N_{tot} - N_{bg}$), $<N_n> = 0.63 \times 10^3$

Specific neutron number divided by average per year $<N_n/N_{tr}> \approx 2.5 \times 10^{-3}$
We analyzed the whole available data set with the detector in its final configuration (T1+T2+T3), starting in 1 January 2001 and ending in 31 December 2015.

\[ \delta \equiv \delta \left( \frac{N^n}{N_{tr}} \right) \propto \delta \ N_n \left( \overline{E}_\mu \right) \]
Here the T value is fixed: $T=12$ month.
If all three parameters are fitted:
$T=11.99$, 
$f=7.153$, 
$\delta=0.078$

Epoch folding curve

$F(t) = 1 + P_1 \cdot \cos\left(2\pi(t-P_3)/P_2\right)$

$= 1 + 0.080 \cdot \cos\left(2\pi(t - 7.14)/12\right)$

$= 1 + 0.082 \cdot \cos\left(2\pi(t - 7.65)/12.59\right)$

Here the T value is fixed: $T=12$ month.
If all three parameters are fitted:
$T=12.59$, 
$f=7.165$, 
$\delta=0.082$

$\delta N_n = 0.08 \pm 0.02$
\[ N_{n}/N_{tr} (s)= 246.3 \times 185/10464715 = 4.35 \times 10^{-3}; \]

\[ N_{n}/N_{tr} (w)= 203.8 \times 185/10006669 = 3.77 \times 10^{-3}; \]

\[ \delta N_{n} = (s-w)/(s+w) = (N_{n}/N_{tr} (s)- N_{n}/N_{tr} (w))/ (N_{n}/N_{tr} (s)+ N_{n}/N_{tr} (w)) \]

\[ \delta N_{n} = 0.072 \pm 0.002 \pm 0.008 \]

\[ <N_{n}/N_{tr}> = (4.35+3.77) \times 10^{-3} / 2 = 4.06 \times 10^{-3} \]
Changing energy muons 10% leads to a change 8% in the specific number of neutrons.
Conclusions:

- The seasonal variations of the average energy of muon flux underground has been found using number of muon induced neutrons:
- The characteristics of the muon induced neutron variations are defined using different methods
  - residual method (summer - winter): variation magnitude is 
    \[ \delta N_n = 0.072 \pm 0.002 \text{ (stat)} \pm 0.016 \text{ (sys)} \];
  - epoch folding method: 
    \[ f(t) = 1 + \delta \cdot \cos(2\pi(t-\varphi)/T) \],
    \[ \delta N_n = 0.08 \pm 0.02, \varphi = 7.15 \pm 0.5 \]
- The measured characteristics of the neutron variations indicate seasonal variations in the average energy of muons at the LVD depth of 280 GeV with an amplitude of 10%: 
  \[ \bar{E}_\mu = 280 \pm 28 \text{ GeV} \].
- The neutron flux produced by muons underground undergoes seasonal variations with the amplitude 
  \[ 1 + \delta \Phi_n = (1 + \delta I_\mu)(1 + \delta N_n) = 1.076 \times 1.015 \]
  \[ \delta \Phi_n(I_\mu N_n) = 9.2\% \]
- It was assumed that the neutron flux is proportional to the intensity of muons with an amplitude variation of 1.5%. We have shown that the neutron flux has an amplitude of seasonal variations in 6 times more, because the energy muons also varies with the amplitude of \(~10\%).
Thank you!
The definition uncertainties of the modulation amplitude value

- **For residual method:**

  Statistic uncertainty – 2.6 %
  number of triggers: \( N_{tr} = 1.0 \times 10^7 \),
  number of neutrons: \( N_{\gamma} = 1.5 \times 10^3 \),

  \[
  \delta \delta = \delta \left( \frac{n_s - n_w}{n_s + n_w} \right) = \sqrt{\delta^2 (n_s - n_w) + \delta^2 (n_s + n_w)}
  \]

  \[
  \delta^2 (n_s + n_w) = \delta^2 (n_s - n_w) = \sqrt{\delta^2 n_s + \delta^2 n_w}
  \]

  \[
  n_s \approx n_w \Rightarrow \delta \delta = \sqrt{4 \delta^2 n_s}
  \]

  \[
  \delta n_s = \delta (N_0 \times \tau / N_{tr})
  \]

  \[\delta = 0.072 \pm 0.002 \text{ (stat)} \pm 0.016 \text{ (sys)}\]

- **For epoch folding method:**

  From fitting procedure – 20.0 %

  \[\delta = 0.08 \pm 0.02 \text{ (sys)}\]
Muon-induced neutron yield $Y_{sc}$ and $Y_{Fe}$ using value of the specific neutron number:

$$Y_n \sim \frac{N_n}{N_\mu} \frac{1}{\rho l_i} \frac{q_i(\eta_{sc}, \eta_{Fe})}{\varepsilon_1 \varepsilon_2}$$

<table>
<thead>
<tr>
<th>$Y_{sc}$, n/μ/(g/cm²)</th>
<th>$Y_{Fe}$, n/μ/(g/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3.24 \times 10^{-4}$</td>
<td>$16.3 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

$\rho l_{sc} = 65$ g/cm²,
$\rho l_{Fe} = 59$ g/cm²,
$q_{sc} (E_{th}>1.5$ MeV $)= 1.084$
$q_{Fe} (E_{th}>1.5$ MeV $)= 4.940$
$\varepsilon_1 = 0.24$ (geom.factor),
$\varepsilon_2 = 0.87$ (tay-Bruno effect)
$\eta_{sc} = 0.33$
$\eta_{Fe} = 0.13$

$q_{sc} = \frac{Q}{Q \eta_{sc} + (1-Q) \eta_{Fe}}$,
$q_{Fe} = \frac{(1-Q)}{Q \eta_{sc} + (1-Q) \eta_{Fe}}$

$Q = 0.18$
### Quasi-Vertical Muons

E_{\mu} > 100 \text{ MeV}

<table>
<thead>
<tr>
<th>Muons</th>
<th>2428151</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrons</td>
<td>9858</td>
</tr>
<tr>
<td>Length</td>
<td>65 g/sm$^2$</td>
</tr>
<tr>
<td>$Y_{sc}$, n/\mu/(g/sm$^2$)</td>
<td>3.2\times10^{-4}</td>
</tr>
</tbody>
</table>

\[
\frac{N_n + \delta N}{N_n} \sim \left( \frac{E_{\mu} + \delta E}{E_{\mu}} \right)^{0.78} \Rightarrow \frac{\delta E}{E} = (1 + 0.33)^{1/0.78} - 1 = 0.44
\]

\[
\Rightarrow 280 \text{ GeV} + 280 \times 0.44 \approx 400 \text{ GeV}
\]

### Quasi-horizontal muons

E_{\mu} > 100 \text{ MeV}, level L=\pm1

<table>
<thead>
<tr>
<th>Muons</th>
<th>11510</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrons</td>
<td>71</td>
</tr>
<tr>
<td>Length</td>
<td>75.6 g/sm$^2$</td>
</tr>
<tr>
<td>$Y_{sc}$, n/\mu/(s/sm$^2$)</td>
<td>4.3\times10^{-4}</td>
</tr>
</tbody>
</table>
Backup slides
F(t) = 1 + P1 \cdot \cos(2\pi(t-P3)/12.0)
Epoch folding method

To determine the variation phase we use the fitt:

\[
F(t) = 1 + P_1 \cos(2\pi(t - P_3)/P_2)
\]

- \( P_1 = 0.09 \pm 0.02 \) – modulation value,
- \( P_2 = 12.0 \pm 0.5 \) – period,
- \( P_3 = 7.2 \pm 0.5 \) – phase (month),
Muon events selection:

An event is selected as 'muon event' if there are at least 2 distinct counters with $E_{tr} > 10$ MeV and time difference $\Delta t < 250$ ns.

We have selected from muon events the inner counter triggers having energy $E_{tr} > 50$ MeV.

We analyzed the whole available data set with the detector in its final configuration (T1+T2+T3), starting in 1 January 2001 and ending in 31 December 2015.
\[ F(t) = 1 + P1 \cdot \cos\left(2\pi\left(t - \frac{P3}{P2}\right)\right) \]

\[ \frac{N_{\text{tot}}}{N_{\text{tr}}} \text{ per month} \]
\[ \langle \frac{N_{\text{tot}}}{N_{\text{tr}}} \rangle \cong 8.5 \times 10^{-3} \]

\[ \frac{N_{\text{bg}}}{N_{\text{tr}}} \text{ per month} \]
\[ \langle \frac{N_{\text{bg}}}{N_{\text{tr}}} \rangle \cong 6 \times 10^{-3} \]

\[ \frac{N_{\text{n}}}{N_{\text{tr}}} \text{ per month} \]
\[ \langle \frac{N_{\text{n}}}{N_{\text{tr}}} \rangle \cong 2.5 \times 10^{-3} \]
Specific number of muon-induced neutrons is the determined number of neutrons divided by number of triggers in the same counter.

The specific number is the averaged magnitude over a muon flux. Then the specific number is proportional to a number of neutrons produced by muon at mean $E_{\mu}$ energy of muon flux underground:

$$\frac{N_n}{N_{tr}} \propto N_n(\bar{E}_\mu)$$

$$\delta \equiv \delta \left( \frac{N_n}{N_{tr}} \right) \propto \delta \ N_n(\bar{E}_\mu)$$
Atmosphere density: $\rho_w > \rho_s$

Atmosphere height: $h_w < h_s$

Sea level

observation level $H=3650$ m w.e.
Specific neutron number $N_n/N_{tr}$

Rate of trigger pulses per month, $\langle N_{tr}\rangle = 2.3 \times 10^5$

Rate of LET pulses per month, $\langle N_{tot}\rangle = 1.99 \times 10^3$

Rate of neutron pulses ($N_{tot} - N_{bg}$), $\langle N_n\rangle = 0.63 \times 10^3$

$\frac{(N_{tot} - N_{bg})}{N_{tr}}$ per month