Neutrinos and other searches at the Gran Sasso Underground Laboratory

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Outline

The Gran Sasso Laboratory:
Ø location, characteristics, facilities, ...

Fundamental research at the Laboratory:
Ø Solar neutrinos (GALLEX/GNO, Borexino)
Ø dark matter (DAMA, CRESST, XENON, WArP)
Ø double beta decay (HDMS, CUORICINO, CUORE, GERDA)
Ø nuclear astrophysics (LUNA)
Ø CNGS project (OPERA, ICARUS-T600)
Ø Cosmic rays (LVD, MACRO)
Ø Supernovae neutrinos (LVD, Borexino, ICARUS-T600)

* stopped experiments
Laboratory location and characteristics
A little bit of history [1]

1979: A. Zichichi as president of I.N.F.N. proposes the construction of the Gran Sasso Underground Laboratory

In Zichichi’s summary are reported the scientific aims of the new laboratory:
- nuclear stability (proton decay)
- neutrino astrophysics (solar and supernova neutrinos)
- neutrino oscillations (a sketch of the CERN-GS beam is reported)
- biologically active matter
- ground stability
A little bit of history [2]

1987: activities at the lab get started
Radioactivity measurements underground

Large Volume Detector (LVD) and MACRO: the first experiments underground

An Air Shower Array is built at the top of the mountain to correlate muons on surface with those underground

2003: new constructions underground take place for safety and ground water
Location

lat. 42.45° N
long. 13.57° E
130 km from Rome
~ 1000 m above sea level
The underground laboratory

mean depth: 3800 m.w.e.
min. depth: 3000 m.w.e.
Rock properties

composition:
Ca 26%, Si 1%, Mg 9%,
o 51.5%, C 12.5%

\[ \langle \rho \rangle = (2.71 \pm 0.05) \text{ g cm}^{-3} \]
\[ \langle Z \rangle = 11.4 \]

radioactivity in rocks:

<table>
<thead>
<tr>
<th></th>
<th>Gran Sasso (Bq/kg)</th>
<th>Mont Blanc (Bq/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{238}\text{U})</td>
<td>5</td>
<td>80-500</td>
</tr>
<tr>
<td>(^{232}\text{Th})</td>
<td>0.25-0.5</td>
<td>~90</td>
</tr>
<tr>
<td>(^{226}\text{Ra})</td>
<td>4.5</td>
<td>30-300</td>
</tr>
<tr>
<td>(^{40}\text{K})</td>
<td>5-50</td>
<td>100-2000</td>
</tr>
</tbody>
</table>

neutron flux:
fission and (\(\alpha, n\))
\[ \Phi_{th} \approx 3 \times 10^{-6} \text{ cm}^{-2} \text{ s}^{-1} \]
\[ \Phi_{cr} < 0.3 \times 10^{-6} \text{ cm}^{-2} \text{ s}^{-1} \]
Cosmic muon flux

*muon flux:*

\[ \approx 1 \text{ } \mu/(m^2 \cdot \text{h}), \ E_\mu > 1 \text{ TeV} \]

(10^6 reduction with respect to surface)
Laboratory facilities
Projects at the Laboratory

- GERDA, LVD, CRESST, CUORE
- ICARUS-T600
- WArP
- BOREXINO, OPERA
- DAMA
- XENON
- Low backg. Lab.
Neutrino physics
Neutrino sources for the GS lab [1]

- Neutrinos as dark matter particles
  - Cosmological neutrinos $\sim 110 \text{ cm}^3$

- Neutrinos from Supernovae
  - Relic neutrinos $\sim 2.5 \text{ cm}^2 \text{ s}^{-1}$

- Solar neutrinos $\sim 6.4 \times 10^{10} \text{ cm}^2 \text{ s}^{-1}$

- Terrestrial neutrinos $\sim 10^6 \text{ cm}^2 \text{ s}^{-1}$

- Neutrinos from accelerators
  - $\sim 6 \times 10^6 \text{ cm}^2 \text{ yr}^{-1}$

- Atmospheric neutrinos $\sim 1 \text{ cm}^2 \text{ s}^{-1}$
<table>
<thead>
<tr>
<th>Source</th>
<th>Mean Energy ($&lt;E&gt;$)</th>
<th>Neutrino Flux ($\phi_v$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun</td>
<td>$\sim 0.3$ MeV</td>
<td>$6 \times 10^{10}$ cm$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>Earth</td>
<td>$\sim 1$ MeV</td>
<td>$10^6$ cm$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>Nuclear reactor</td>
<td>$\sim 1$ MeV</td>
<td>$I_v \sim 10^{20}$ $\nu$ s$^{-1}$ (1800MW)</td>
</tr>
<tr>
<td>Supernovae</td>
<td>$\sim 20$ MeV</td>
<td>$N_v \sim 10^{58}$ in $\sim 10$ sec.</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>$\sim 1$ GeV</td>
<td>$\phi_v \sim 1$ cm$^{-2}$ s$^{-1}$ at sea level</td>
</tr>
<tr>
<td>Accelerator</td>
<td>$\sim 10$ GeV</td>
<td>$6 \times 10^6$ cm$^{-2}$ yr$^{-1}$</td>
</tr>
</tbody>
</table>
Neutrinos from the Sun

\[ 4p + 2e^- \rightarrow \alpha + 2\nu_e + Q \]

\(Q=26.7\text{ MeV}) \quad L = 2.4 \times 10^{39}\text{ MeV/s (0.42 mW/cm}^2\text{)} = \text{ solar constant}

\(2\nu_e\) for each \(Q\) of radiated energy (on Earth)

\[
\phi_{pp} = 2 \cdot \frac{2.4 \cdot 10^{39}}{26.73\text{MeV} - 0.53\text{MeV}} \cdot \frac{1}{4\pi (\text{A.U.})^2} \approx 6.5 \cdot 10^{10}\text{ cm}^{-2}\text{s}^{-1}
\]
Solar Neutrino Spectrum

The diagram shows the solar neutrino spectrum with the following contributions:

- $^{8}\text{B}$ (10%)
- $^{17}\text{F}$ (25%)
- $^{13}\text{N}$ ($^{+20}_{-15}$%)
- $^{7}\text{Be}$ (6%)
- pep (1.3%)
- $^{15}\text{O}$ ($^{+23}_{-16}$%)

The vertical lines indicate the energy thresholds for each contribution.
Detection of Solar Neutrinos

a) $\nu_e + (A,Z) \rightarrow e^- + (A,Z+1)^*$ above threshold
   radiochemical detection
   real-time

b) $\nu_x + e^- \rightarrow \nu_x + e^-$
   real-time
   no strong tagging: background issue
   easy for water Cherenkov (since 1985)
   needs strong background suppression with organic liquid scintillators (only after 2007)

c) $\nu_e + d \rightarrow e^- + p + p$ ($E>1.4$ MeV)
   $\nu_x + d \rightarrow \nu_x + p + n$ ($E>2.2$ MeV)
## Solar Neutrino Measurements

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Detection Technique</th>
<th>Threshold (MeV)</th>
<th>Start</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homestake Radioch.(Cl)</td>
<td>0.814</td>
<td>1968 stopped</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kamiokande Cherenk. (H₂O)</td>
<td>7.0</td>
<td>1985 stopped</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SAGE Radioch.(Ga)</td>
<td>0.233</td>
<td>1990 stopped</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GALLEX Radioch.(Ga)</td>
<td>0.233</td>
<td>1991 stopped</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Super-Kamiokande Fasi: I, II, III Cherenk. (H₂O)</td>
<td>5.0</td>
<td>1996 in operation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GNO Radioch.(Ga)</td>
<td>0.233</td>
<td>1999 stopped</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SNO Phase: I, II, III Cherenk. (D₂O)</td>
<td>5.0 6.4 7.2</td>
<td>1999 stopped</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BOREXINO Scin.(C₉H₁₂)</td>
<td>0.2</td>
<td>2007 in operation</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Detection of sub-MeV solar Neutrinos

a) Homestake in South Dakota: radiochemical detection in Cl above 0.8 MeV
b) Gallex at Gran Sasso/SAGE at Baksan: radiochemical detection on Ga above 0.2 MeV
c) Real time detection
   a) In 1988 it was proposed to make use of massive (100 ton scale) organic liquid scintillators to detect sub-MeV (7Be) solar neutrinos in real time
   b) The scintillator can reach a better radiopurity than water (lower detection threshold)
   c) The scintillator has a large light yield (better for low energy and pulse shape discrimination)
   d) 1994 the Counting Test Facility (prototype of Borexino) starts data taking with 4 tons of liquid scintillator
Counting Test Facility
Neutrino Oscillations
Neutrino Mixing

If neutrinos are massive one can distinguish between mass and flavour eigenstates

\((\nu_e, \nu_\mu, \nu_\tau)\)
\((\nu_1, \nu_2, \nu_3)\)

\[
\nu_{L,\alpha} = \sum_{i=1}^{3} U_{\alpha i} \nu_i
\]

\[
\sum_{i=1}^{3} U_{\alpha i} U_{\beta i}^* = \delta_{\alpha \beta}
\]
Consider a neutrino source and a detector located a distance \( L \) away.

\[
A(\alpha \rightarrow \beta) = \langle \nu_\beta \mid \text{propagator} \mid \nu_\alpha \rangle = \sum U_{\beta i}^* U_{\alpha i} \text{Prop}(i)
\]
The case of two-neutrino oscillations

\[
\begin{pmatrix}
\nu_\alpha \\
\nu_\beta 
\end{pmatrix} =
\begin{pmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta 
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 
\end{pmatrix}
\]

\[P_{\alpha\beta} = \sin^2 2\theta \sin^2 \left( \frac{\Delta m_{12}^2}{4E} L \right) = \sin^2 2\theta \sin^2 \left( \frac{k_{12}}{2} L \right) =\]

\[\Delta m_{12}^2 = m_2^2 - m_1^2\]

We can define an oscillation length: \[\lambda = \frac{2\pi}{k_{12}} = \frac{4\pi E}{\Delta m_{12}^2}\]

\[P_{\alpha\beta} = \sin^2 2\theta \sin^2 \left( \pi \frac{L}{\lambda} \right)\]

Maximum sensitivity to oscillations phase when \[L \sim \lambda/2\]
Including detector properties:
detector finite energy resolution
source energy spectrum

Smearing of oscillation term
\[ \langle P_{\alpha\beta} \rangle = 1 - \frac{1}{2} \sin^2 2\theta \]

\[ \Delta m^2 = 0.1 \text{ eV}^2 \text{ and } \sin^2 2\theta = 0.6 \]
Effective interaction potential in matter

Taking into account both CC and NC processes and averaging over many interactions

\[
V = \begin{pmatrix}
\sqrt{2} G_F n_e + V_Z & 0 & 0 \\
0 & +V_Z & 0 \\
0 & 0 & +V_Z
\end{pmatrix}
\]
Survival probability for solar neutrinos

\[ P_{ee} = \frac{1}{2} + \left( \frac{1}{2} - e^{-\frac{\pi}{2} \gamma} \right) \cos 2\theta M \cos 2\theta \]

For \[ n_e(r) = n_e(0)e^{-r/r_o} \] with \( r_o = \frac{R_{Sun}}{10.54} \)

\[ \gamma = kR_{Sun} \frac{\sin^2 2\theta}{\cos 2\theta} \frac{1}{10.54} = 0.167 \cdot 10^9 \frac{\sin^2 2\theta}{\cos 2\theta} \left( \frac{\Delta m^2}{eV^2} \right) \left( \frac{E}{MeV} \right) \]

Solid line: \( \sin^2 2\theta = 0.87 \) and \( \Delta m^2 = 7 \times 10^{-5} \text{ eV}^2 \)

Dashed line: \( \sin^2 2\theta = 0.005 \) and \( \Delta m^2 = 5 \times 10^{-6} \text{ eV}^2 \)
GALLEX/GNO: radiochemical solar neutrino detector

Neutrino detection:

\[ \nu_e + ^{71}\text{Ga} \rightarrow e^- + ^{71}\text{Ge} \rightarrow \text{EC} \rightarrow ^{71}\text{Ga} \ (T_{1/2} = 11.4\text{d}) \]

- Target mass = 30.3t of Ga
- Neutrino rate expectation: 0.5 cpd
- Ge atoms at the end of an exposure (~4 weeks) is about 10
  - Ge (in solution as volatile GeCl\textsubscript{4}) is extracted through ~ 3,000 m\textsuperscript{3} of N\textsubscript{2} and converted in GeH\textsubscript{4} (gas)
Double beta decay search
Neutrinoless Double beta decay

$\beta\beta(0\nu) : \ 2n \rightarrow 2p + 2e$

$2\beta\beta$ decay is a second-order process detectable when $\beta$ decay is energetically forbidden.

$0\nu\beta\beta$ can be a background source for $0\nu\beta\beta \Rightarrow$ high energy resolution needed.

$\beta\beta$ observed in many isotopes.
GERDA: GERmanium Detector Array for $0\nu\beta\beta$ of $^{76}\text{Ge}$

- Water tank (650 m³ H₂O)
  Equipped with 66 PMTs for $\mu$-veto

- Cryostat (70 m³ LAr)
  LAr scintillation light readout can be implemented

Cleanroom

Lock for detector insertion

Detector Array
GERDA: inside the WT
CUORE will be a closely packed array of 988 detectors
M = 741 kg of TeO₂

19 towers with 13 planes of 4 crystals each
Nuclear astrophysics
Nuclear Interactions in the Sun

Nuclear time scale \( \sim \delta \cdot 0.1 \cdot M_{\text{Sun}} c^2 / L_{\text{sun}} = 10^{10} \text{ yr} \)
\( \delta = M(^4\text{He}) / 4 m_p = 0.7\% \)

Coulomb barrier:
\[
\frac{e^2}{2r_0} = \frac{\hbar c}{\hbar c} \cdot \frac{\hbar c}{2r_0} = 0.6 \text{ MeV with } r_0 = 1.2 \text{ fm}
\]

In the core \( kT \sim 1 \text{ keV (T} \sim 10^7 \text{ K) } \)
Average energy \( \ll \) Coulomb barrier

Reaction rates:
\[
R_{12} = \frac{n(1)n(2)}{1 + \delta_{12}} \langle \sigma v \rangle_{12}
\]
\[
\sigma(E) = \frac{S(E)}{E} e^{-2\pi n} \text{ with } S(E) = S(0) + E \left. \frac{dS}{dE} \right|_{E=0}
\]
LUNA (Laboratory for Underground Nuclear Astrophysics)

LUNA2 (LUNA1): 50-400kV (1-50kV) electrostatic accelerator
Output current: 1mA (1mA)
Gas/Solid target + silicon detector, HpGe detector, $4\pi$ BGO summing crystal for particles and for $\gamma$'s detection
# Measurements of $S(0)$

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$S(0)$ in keV b</th>
<th>$S(0)$ in keV b</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p(p, e^+\nu_e)d$</td>
<td>$(4.01 \pm 0.02) \times 10^{-22}$</td>
<td>$(4.01 \pm 0.04) \times 10^{-22}$</td>
</tr>
<tr>
<td>$^3\text{He}(^3\text{He}, 2p)^4\text{He}$</td>
<td>$(5.4 \pm 0.4) \times 10^3$</td>
<td>$(5.21 \pm 0.27) \times 10^3$</td>
</tr>
<tr>
<td>$^3\text{He}(\alpha, \gamma)^7\text{Be}$</td>
<td>$(0.53 \pm 0.05)$</td>
<td>$(0.56 \pm 0.03)$</td>
</tr>
<tr>
<td>$^3\text{He}(p, e^+\nu_e)^4\text{He}$</td>
<td>$2.3 \times 10^{-20}$</td>
<td>$(8.6 \pm 2.6) \times 10^{-20}$</td>
</tr>
<tr>
<td>$^7\text{Be}(p, \gamma)^8\text{B}$</td>
<td>$0.019^{+0.004}_{-0.002}$</td>
<td>$(2.08 \pm 0.16) \times 10^{-2}$</td>
</tr>
<tr>
<td>$^{14}\text{N}(p, \gamma)^{15}\text{O}$</td>
<td>$3.5^{+0.4}_{-1.6}$</td>
<td>$1.66 \pm 0.12$</td>
</tr>
</tbody>
</table>
Supernova Neutrinos
Stellar collapse and $\nu$ emission

4 phases:

**Infall:** free-fall time scale: $(3\pi/32G\rho)^{1/2} \sim 100\text{ms}$

Falling material on inner stiff core and bounce
- Shock wave in outer core
- Early emission of $\nu_e$: $e^-p \rightarrow n\nu_e$

**Accretion and delayed shock revival** $\sim 500\text{ms}$
- $e^+ + n \rightarrow p + \text{anti-}\nu_e$
- $e^+ + e^- \rightarrow \nu_i + \text{anti-}\nu_i$

**Cooling** $\sim 10\text{s}$
- $e^+ + n \rightarrow p + \text{anti-}\nu_e$ and $e^- + p \rightarrow n + \nu_e$
- $e^+ + e^- \rightarrow \nu_i + \text{anti-}\nu_i$

PROMPT EMISSION

LATE THERMAL EMISSION
Neutrino Luminosities
Borexino
Other neutrinos probes underground: Geoneutrinos ...
Performances of the low background lab.

- for our standard HpGe detectors: U and Th $\sim 10^{-10}$ g/g where
  $1\text{Bq}(\text{U})/\text{kg} = 81\times 10^{-9}$ g/g
  $1\text{Bq}(\text{Th})/\text{kg} = 245\times 10^{-9}$ g/g

- for a special designed HpGe detector: U and Th $< 10^{-11}$ g/g

- for K: $< 10^{-7}$ g/g ($1\text{Bq}(^{40}\text{K})/\text{kg} = 30\times 10^{-10}$ g/g)

Lab. performances are good enough for shielding materials; could not be enough for target materials and in some cases for the inner parts of detectors where ppt levels are required.

Higher sensitivity accessible through
- ICP-MS: $\sim 1$ppt
- NAA+\(\gamma\)-spectroscopy ($^Z\text{A} + \gamma \rightarrow ^{Z+1}\text{A} + \text{g}$): $\sim 1$ppt
- Isomeric Spectroscopy of Activated Nuclei
  ($^{238}\text{U} + n \rightarrow ^{239}\text{U} \rightarrow ^{239}\text{Np} \rightarrow \beta\gamma$ Delayed Coincidences): $\sim 10^{-3}$ppt

**OPERA: appearance of $\nu_\tau$**

**Main idea:** proof of $\nu$-oscillations by appearance of a $\nu_\tau$ from a $\nu_\mu$ beam

**Technique:** massive target (~2kton Pb) + decay topology by emulsion sandwich

![Diagram of OPERA setup](image)

- 2 SuperModules
- 31 walls/SuperModule
- 52x64 bricks/wall
- 206 336 bricks

**Expected ~ 25 $\nu_\tau$ CC / kton / yr with $\delta m^2$ ~ 2.5 x $10^{-3}$ eV$^2$ (but only a few observed)**

**OPERA is under construction at present. Data taking starts 2006**