State-of-the-art in underground physics experiments (Borexino)

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ITALY

Synergies in Low Background Radiation Techniques
University of Minnesota
Minneapolis MN, USA
July 25th, 2005

Underground laboratories
SSM Neutrino Spectrum on Earth

Low Energy Solar neutrinos …

- Low energy solar neutrinos… a MUST!
- Asks for BIG experimental effort
- Low energy (<1 MeV) asks for scintillation techniques (upcoming experiments)
- Borexino collaboration has addressed important milestones: CTF showed for the first time that organic liquid scintillators have the right radiopurity
- For low energy on the road liquid noble gases and metal loaded organic scintillators
Organic liquid scintillators:

1. $\rho \sim 1\text{g/cm}^3$ (efficient self shielding), $\sim 10^4$ photons/MeV, 5% energy resolution @ 1MeV, sigma $\sim 10\text{cm} @ 1\text{ MeV}$ for vertex reconstruction
2. Expected 1.3 ev/day/ton for pp and 0.5 for $^7\text{Be}$ in full energy range
3. 10 t target mass for pp gives about 10 counts/day
4. ONLY ES channel (rely on detection of single electron)
5. $^{14}\text{C}$ (with 156keV) limits low energy sensitivity to only $^7\text{Be}$ with achieved $^{14}\text{C}/^{12}\text{C} \sim 10^{-10} (=0.2\text{ Bq/ton background below end-point})$
6. $^{238}\text{U}$, $^{232}\text{Th}$, $^{40}\text{K}$, $^{85}\text{Kr}$, $^{39}\text{Ar}$, $^{210}\text{Pb}$ sources of important background
7. Needed U,Th $< 1\text{mBq/ton}$ to get S/B$>1$ … possible!
8. Needed $< 0.5\mu\text{Bq (Kr,Ar)/m}^3$ of $N_2$ … possible!
9. Needed $^{210}\text{Pb} < 1\text{ mBq/ton}$ … rely on distillation of scintillator!
10. Deep location to measure pep and avoid cosmogenic $^{11}\text{C}$ background: expected 0.03 pep/day/ton vs 0.15 $^{11}\text{C}$/day/ton @ Gran Sasso depth; a factor 100 less @ SNO!

What about solar neutrinos?

Find smoking-gun for LMA
- use low energy solar neutrinos or Mton detector
- measure day-night asymmetry

Test new physics from neutrino interactions with low energy neutrino
- in the Sun with low energy neutrinos in a high density matter
- Light sterile neutrino
- Neutrino magnetic moment ($< 10^{-11}\mu_B$)
- Flavour changing interactions with sub-weak strength

Test solar physics with sub-MeV solar neutrinos
- Neutrino luminosity = light luminosity
- Time variation in the Sun with neutrinos (neutrinos bring information from the interior of the Sun in ~real time!)
- CNO luminosity (predicted 1.5%, measured < 6%)
More …

- Neutrinos from the Earth
- Neutrinos from supernovae in the galaxy
- Relic supernovae neutrinos

Goals for Borexino

- Measure $^7$Be solar neutrinos
- Smoking gun for LMA (Yes/No)
- Search for sub-dominant effect with new physics
- With $5\%$ $^7$Be measurement test solar standard model better than $1\%$
- Study CNO luminosity and pep neutrinos
- Time variation of solar signal, neutrino magnetic moment
- Neutrino from the Earth
- Neutrino from supernovae
Counting Test Facility (CTF)

- CTF is the prototype of Borexino. Its main goal was to verify the capability to reach the very low-levels of contamination needed for Borexino.

**CTF campaigns**
1. **CTF1:** 95-97
2. **CTF2:** 2000 (PXE)
3. **CTF3:** 2001 still ongoing

- 100 PMTs
- ~4 tons of scintillator
- 4.5 m thickness of water shield
- Muon-veto detector

**CTF high mass and very low levels of background contamination make it a unique detector to search for rare or forbidden processes with high sensitivity**

- $^{14}\text{C}/^{12}\text{C} \sim 10^{-18}$ (measured: $(1.94 \pm 0.09) \times 10^{-18}$)
- $^{238}\text{U} \sim 10^{-16}$ g/g (measured: $(3.5 \pm 1.3) \times 10^{-16}$ g/g, Rn daughters)
- $^{232}\text{Th} \sim 10^{-16}$ g/g (measured: $(4.4^{+1.5}_{-1.0}) \times 10^{-16}$ g/g)
204 days of livetime

Whole 4-ton mass
Radial cut at 70cm for Reconstructed events
Radial cut at 60cm for Reconstructed events

1 MeV

238U decay chain
by courtesy of Dr. G. Heusser

- gamma active nuclides
- sub chains
- highly volatile
- also from atmospheric deposition

If Rn can escape (plate out active), otherwise Rn and Ra included

mass spectroscopy
Radioassay techniques for primordial U/Th decay chains and K

- Ge-spectroscopy
- Rn emanation assay
- Neutron activation
- Liquid scintillation counting
- Mass spectrometry (ICP-MS; A-MS)
- Graphite furnace Atom Adsorption Sp.
- Roentgen Exitation Analysis
- Alpha spectroscopy

Comparison of Radioassay techniques

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<thead>
<tr>
<th>Method</th>
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<th>primordial parents</th>
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<tbody>
<tr>
<td>Ge-spectroscopy</td>
<td>γ emitting nuclides</td>
<td>226Ra, 228Th</td>
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<tr>
<td>Rn emanation assay</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neutron activation</td>
<td>α emitting nuclides</td>
<td>210Po</td>
</tr>
<tr>
<td>Liquid scintillation</td>
<td></td>
<td></td>
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<tr>
<td>Mass spectrometry</td>
<td></td>
<td></td>
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<tr>
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Difficult to compare since each method has its special application.
Neutron activation analysis

\[ n + ^{41}K \rightarrow ^{42}K \rightarrow ^{42}Ca, \quad \sigma_{th} = 1.2 \, b \, (1.2 \, b) \]

\[ n + ^{232}Th \rightarrow ^{233}Th \rightarrow ^{233}Pa \rightarrow ^{233}U, \quad \sigma_{th} = 6.1 \, b \, (7.8 \, b) \]

\[ n + ^{238}U \rightarrow ^{239}U \rightarrow ^{239}Np \rightarrow ^{239}Pu, \quad \sigma_{th} = 2.3 \, b \, (7.9 \, b) \]

Sizable cross sections and long enough half lives for delayed counting

NAA (TU Munich)

\[ ^{239}Np \rightarrow ^{239}Pu, \quad \sigma = 2.3 \, b \, (7.9 \, b) \]

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M. Laubenstein, Y. Zakharov, W. Rau, B. Freudiger, H. Simgen, Ch. Buck, G. Zuzel

$sensitivity = f(procedure\; blank)$

$\alpha$

concentration of $\text{Rn}$

proportional counting

$\text{N}_2$

emanation

$\text{H}_2\text{O}$

$\text{Rn} (^{226}\text{Ra})$ assay with proportional counting

Ray Davis Jr. type miniature counter

efficiency for internal counting ($> 15$ keV):

background: $0.2 - 2$ counts per day

$\Rightarrow$ about $30 \mu\text{Bq}$ $^{222}\text{Rn}$ easily detectable (monitoring)

Extract $\text{Rn}$ from large quantities of water, nitrogen and as an emanation signal of subsystems of BOREXINO

$\text{H}_2\text{O}$: $1 \text{ mBq Ra/m}^3$

$0.1 \text{ mBq Rn/m}^3$

Reached sensitivities:

nitrogen: $0.5 \mu\text{Bq/m}^3$

surface emanation: $0.5 \mu\text{Bq/m}^2$

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Measuring procedure for Ar and Kr

Pipes baked out and flushed with nitrogen for some days

Gas

Liquid

Sample purification

Mass spectrometer

Metal-sealed valves

Sample volume: ~1 cm

N₂ 6.0

85Kr conc. in air, BMU Ann. Rep. 02

Dewar (200 L) with liquid nitrogen

Pipette

G. Zuzel

H. Simgen

Nitrogen plant of BOREXINO

activity in nitrogen [µBq/kg]

<table>
<thead>
<tr>
<th>nitrogen sample</th>
<th>12</th>
<th>41</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPN, Borexino</td>
<td>12</td>
<td>31</td>
<td>0.4</td>
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<tr>
<td>HPN, Borexino</td>
<td>0.017</td>
<td>0.07</td>
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<tr>
<td>Linde Worms (7.0)</td>
<td>0.006</td>
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<tr>
<td>SOL Mantua (7.0)</td>
<td>0.0006</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>E. Westfalen Hinszir (6.0)</td>
<td>0.4</td>
<td>0.14</td>
<td>6</td>
</tr>
<tr>
<td>required</td>
<td>&gt;1000 µBq/kg</td>
<td>&gt;1000 µBq/kg</td>
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</tr>
<tr>
<td>Measured</td>
<td>&lt;1000 µBq/kg</td>
<td>&lt;1000 µBq/kg</td>
<td></td>
</tr>
</tbody>
</table>

* measured by rare-gas MS; 1 ppm Ar = 1.19 µBq/kg; 1 ppt Kr = 1.0 µBq/kg

Ar and Kr conc. in air, BMU Ann. Rep. 02

11.5 l 2 kg Corba

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<td>primordial parents</td>
<td>10 mBq/kg</td>
</tr>
<tr>
<td>Alpha spectroscopy</td>
<td>$^{210}$Po, $\alpha$ emitting nuclides</td>
<td>1 mBq/kg</td>
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* Needs counting time of several weeks to several months


Published articles on CTF data (CTF2)


General remarks concerning data analysis

- **Energy reconstruction** is obtained by summing the collected photoelectrons in the event;
- **Position reconstruction** is obtained by a maximum likelihood fit to time of arrival of the photons to each PMT;
- **Particle identification** is obtained via pulse-shape discrimination methods;
- **Photon yield** is determined by a fit to the $^{14}\text{C}$ shape; it has been found to be around ~350 pe/MeV for 100 PMT;
- **Light quenching** at low energy causes a deviation from linearity between emitted light and deposited energy. This effect has been included in the interpretation of the energy spectrum (following Birks parametrization).

Background spectrum in CTF2

- The energy spectrum of the background counts in CTF is dominated by $^{14}\text{C}$ at low energy (<200 keV);
- $\text{Ar, Kr}$ (up to ~700 keV);
- $^{238}\text{U}$ and $^{232}\text{Th}$ daughters (up to ~3 MeV);
- external $^{40}\text{K}$ (peak at 1.4 MeV + continuum);
- Muons mainly affect the very high energy region of the spectrum and can be effectively removed with the muon-veto detector.
Search for electron decay mode $e \rightarrow \gamma + \nu$ with the CTF

- Non-conservation of electric charge would lead to electron decay via two processes: $e \rightarrow \gamma + \nu$, $e \rightarrow \nu + \nu + \nu$
- We look for the 256 keV $\gamma$ coming from the $e \rightarrow \gamma + \nu$ decay;
- A fit is performed to curve D between 138-300 kev including the contributions of:
  - $^{14}$C spectrum shape;
  - Residual linear background (U, Th, Ar, Kr)
  - Response function of the detector to a 256 keV $\gamma$ estimated with Montecarlo methods;
  - $\tau > 4.6 \times 10^{26}$ yr (90% C.L.)
- This result improves by a factor two the previous best bound on electron stability set on the same decay channel by DAMA

Study of neutrino electromagnetic properties with the CTF

- Neutrino-electron scattering is the most sensitive test for neutrino magnetic moment search.
- The differential cross-section is the sum of weak and electromagnetic terms

$$\frac{d\sigma_{\text{weak}}}{dT} (T_\nu, E_\nu) = 4 \sigma_0 \left( g^2 + g_V^2 \left( 1 - \frac{T_\nu}{E_\nu} \right)^2 - g^2 V 2 E_\nu \right) \frac{d\sigma_{\text{em}}}{dT} (T_\nu, E_\nu) = \pi r_\nu^2 \mu^2 \left( \frac{1}{T_\nu} - \frac{1}{E_\nu} \right)$$
- At low energy ($T_\nu \ll E_\nu$) their ratio is proportional to $1/T_\nu$ and the sensitivity to the $\mu$ increases;
- An energy region between (185-380)keV is selected to maximize the statistical significance of the effect and to minimize the systematic related to background;
- A fit is performed to the energy spectrum including contributions from $^{14}$C, other radioactive background (assumed to be linear) and solar (pp and $^7$Be) neutrino scattering on electrons with $\mu$ as free parameter.
32.1 days of data taking in the CTF2 campaign;

\[ \mu_\nu < 5.5 \times 10^{-10} \mu_B \quad (90\% \, C.L.) \]

1. e-\nu scattering  2. \(^{14}\)C spectrum  3. Linear background

New limits on nucleon decay into invisible channels with the CTF

- Many extensions of the Standard Model foresee B and L violation and predict the decay of protons and nucleons bounded in nuclei;
- Nucleon decays to strongly or electromagnetically interacting particles have been investigated by several experiments (IMB, Superk and so on). Limits on the lifetime of these processes are currently in the range of \(10^{33}\) years;
- Limits concerning nucleon decays to “invisible” particles (neutrinos, majorons and so on) are a few orders of magnitude lower;
- In CTF it is possible to investigate the decays of N or NN occurring inside \(^{12}\)C, \(^{13}\)C (scintillator) and \(^{16}\)O (water);
- These decays would produce daughter nuclei such as \(^{11}\)C, \(^{10}\)C, \(^{12}\)B, \(^{11}\)Be, \(^{14}\)O;
- Detecting in the scintillator volume the characteristic radioactive decays of these daughters would be a signature of N or NN decay;
New limits on nucleon decay into invisible channels (continued)

- The experimental data do not show evidence for decays of the daughter nuclei;
- Limits on the nucleon decay can be set conservatively assuming that all the events falling in appropriate energy window were due to the decay under study:

\[
\begin{align*}
\tau(n \rightarrow \text{invisible}) &> 1.8 \times 10^{25} \text{ yr (90\% C.L.)} \\
\tau(p \rightarrow \text{invisible}) &> 1.1 \times 10^{36} \text{ yr (90\% C.L.)} \\
\tau(nn \rightarrow \text{invisible}) &> 4.9 \times 10^{25} \text{ yr (90\% C.L.)} \\
\tau(pp \rightarrow \text{invisible}) &> 5.0 \times 10^{25} \text{ yr (90\% C.L.)}
\end{align*}
\]
New experimental limits on violation of the Pauli Exclusion Principle obtained with the CTF

- Pauli Exclusion Principle has been tested for \( n, p \) in \(^{12}\text{C} \) and \(^{16}\text{O} \) nuclei contained in the CTF scintillator and water buffer;
- The idea is to search for \( \gamma, n, p \) and/or \( \alpha \) emitted in a non-Paulian transition of 1P-shell nucleons to the filled 1S\(_{1/2} \) shell:

\[
\begin{align*}
\tau\left(^{12}\text{C} \rightarrow ^{12}\text{C} + \gamma\right) &> 2.2 \times 10^{27} \text{ y (90\% C.L.)} \\
\tau\left(^{16}\text{O} \rightarrow ^{16}\text{O} + \gamma\right) &> 2.1 \times 10^{27} \text{ y (90\% C.L.)} \\
\tau\left(^{12}\text{C} \rightarrow ^{11}\text{B} + p\right) &> 5.0 \times 10^{26} \text{ y (90\% C.L.)} \\
\tau\left(^{12}\text{C} \rightarrow ^{11}\text{C} + n\right) &> 3.7 \times 10^{26} \text{ y (90\% C.L.)} \\
\tau\left(^{12}\text{C} \rightarrow ^{7}\text{Be} + \alpha\right) &> 6.1 \times 10^{23} \text{ y (90\% C.L.)} \\
\tau\left(^{12}\text{C} \rightarrow ^{12}\text{B} + e^+ + \nu\right) &> 7.7 \times 10^{27} \text{ y (90\% C.L.)} \\
\tau\left(^{12}\text{C} \rightarrow ^{12}\text{B} + e^- + \bar{\nu}\right) &> 7.6 \times 10^{27} \text{ y (90\% C.L.)}
\end{align*}
\]

New experimental limits on heavy neutrino mixing in \(^{8}\text{B}-\) decay obtained with the CTF

- If heavy neutrinos \( \nu_H \) with \( m > 2 m_e \) are emitted in \(^{8}\text{B} \) reaction in the sun then decays like \( \nu_H \rightarrow \nu_L + e^+ + e^- \) should be observed;
- The rate of this decay depends on the heavy neutrino mass and on the mixing parameter \( U_{eH} \) between heavy neutrino and the positron;
- Exploiting the fact that after applying the \( \mu \)-veto cut the CTF data show no events for \( E > 4.5 \) Mev;
- Limits can be set in the \( m_{\nu_H} - |U_{eH}|^2 \) parameter space;
- For neutrino mass region between 4-10 MeV the obtained limits are stronger than those obtained in previous experiments using accelerators and reactors.
The BOREXINO experiment is designed for the real time detections of solar neutrinos via elastic scattering of the \( \nu_e \) on electrons. The threshold energy is 0.25 MeV and allows to study the monoenergetic neutrinos (0.86 MeV), so called \(^{7}\text{Be}-\text{neutrinos}.\)

- 300 t of liquid scintillator (PC (1,2,4)-trimethylbenzene + PPO (2,5) diphenyloxazole 1.5 g/l)
- 2200 photomultipliers
- 2500 t ultrapure water
- 40 evt/d according to the Standard Solar Model

The inner sphere (diametre 15.7 m) is supporting the PMTs. Contains purified PC. Outside of the sphere there is ultrapure water.

Collab.: Italy, France, USA, Germany, Hungary, Russia, Belgium, Poland, Canada

Water Tank (Stainless Steel)  
diametre 18 m, height 16.9 m

Nylon Vessel  
Diametre 8.5 m, thickness 100\( \mu \)m

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Borexino at Gran Sasso Laboratory

- 100 t target mass of C9H12 scintillator (pseudocumene) + 1.5g/l PPO
- ~10,000 photons/MeV (400phe/MeV)
- Energy resolution= 5%@1MeV
- Background studies carried out with a 4 t prototype, the Counting Test Facility
- Main background issues: 210Pb, 39Ar, 85Kr
  - Elastic scattering
  - 1/R^2 signature due to Earth's eccentricity: in 2 yr 3σ measurement
  - Compton like threshold signature for 7Be neutrinos
  - Spectroscopy
  - Expected ~30 events/day in [0.25, 0.8] keV
  - Expected sensitivity for pep neutrinos

Conclusions

- Borexino R&D and CTF showed the feasibility to measure sub-MeV solar neutrinos
- Sub-MeV neutrinos seems a BIG opportunity
- Borexino a unique opportunity for the near future