Solar neutrino: Experiments

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Joint Institute for Nuclear Research, Dubna
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...Puсть не поймаешь нейтрино за бороду
И не посадишь в пробирку,
— Было бы здорово, чтоб Понтекорво
Взял его крепче за шкирку…

Владимир Высоцкий 1964 г.

...Even if you don't catch a neutrino by the beard
And put it in a test tube,
It would be great if Pontecorvo
took it tighter by the scruff of the neck…

V.Vysotsky, 1964
Neutrino fluxes in nature
How the Sun shines

Core temperature $\sim 10^7$ K ($\sim 1$ keV).

Helium is lighter comparing to 4 protons (0.7%) - this energy is feeding the Sun.

pp-cycle is very slow reaction (time scale $7.9 \cdot 10^9$ y). Energy release = 26.7 MeV, 2 neutrinos are emitted.

Sun power is $L_{\text{Sun}} = 3.8 \cdot 10^{26}$ W (380 YW) $\Rightarrow 6.5 \cdot 10^{10}$ neutrino/s/cm$^2$.

Stellar Nuclear reactions occurs in the narrow energy range below 100 keV, the so called Gamow peak.

Reaction cross sections are very low: pico and femto barns.
pp-chain (99%)  

Neutrino fluxes brings snap-shot of the nuclear reactions in the Sun.
CNO-cycle (carbon-nitrogen-oxygen)

- a catalytic cycle.
- dominates in stars more massive than about 1.3 times the mass of the Sun.
- pp-chain reactions start occurring at temperatures around $4 \times 10^6 K$. A self-maintaining CNO chain starts at ~$15 \times 10^6 K$, but its energy output rises much more rapidly with increasing temperatures and at ~$17 \times 10^6 K$, the CNO cycle becomes dominant.
- The Sun has a core temperature of around $15.7 \times 10^6 K$ and only 1.7% of He-4 nuclei being produced in the Sun are born in the CNO cycle.
- The simplest CN-cycle (CNO-I, or Bethe cycle or carbon cycle) was proposed by Hans Bethe in 1938 and, independently, in 1939 by Carl Friedrich von Weizsäcker.

**Net result:**

$$4p \rightarrow ^4He + 2e^+ + 2\nu_e + 3\gamma + 26.8 \text{ MeV}$$

![Diagram of the CNO cycle](image)
Solar Neutrino: spectra

pp & pep: constrains from the Sun luminosity

Uncertainties in the theoretical predictions accumulates along the chain branches
Solar Neutrino spectra – a clue to the Solar physics

The study of neutrino spectra is the only available way to test ideas about the mechanisms of nuclear processes in the center of the Sun.

Nowhere is the connection between the microcosm and the cosmos more clearly manifested than in neutrino physics.

Bruno Pontecorvo
Solar Neutrino Experiments

- Homestake
- KamiokaNDE-II
- SAGE
- Gallex/GNO
- SuperK (I-V)
- SuperK-Gd
- SNO
- KamLAND
- Borexino
- SNO+
- JUNO
- HYPERK
- DUNE
Radiochemical detection of Solar neutrinos

Bruno Pontecorvo, 1946, proposed chlor-argon method for neutrino detection
"Inverse $\beta$-process", Chalk River Laboratory report PD-205 (1946):

\[ \nu_e + ^{37}\text{Cl} \rightarrow ^{37}\text{Ar} + e^- \]

37Ar – noble gas. 37Ar atoms are extracted from liquid with He flux. Efficiency of 37Ar of extraction is about 90%. Then 37Ar is absorbed by coal filters, cooled to the liquid nitrogen temperature, and is separated from He.

37Ar - radioactive, captures electron with half-life of 35 d converting back to Cl. Conversion is accompanied by gamma or Auger-electron.

At the beginning of 60s the problem of detecting of such a rare events was successfully solved in USSR and USA. Low background facilities on the base of proportional counters were developed for 37A detection.

"Confesso di essere piuttosto fiero del mio contributo personale alla nascita dell’astronomia solare neutrinica"
Note Autobiografiche (1988-1989)
A touch of history

- Pontecorvo’s inverse $\beta$-process $^{37}\text{Cl} - ^{37}\text{Ar}$ was described in 1946, in a lecture at a Nuclear Physics Conference organized for students by the National Research Council of Canada at McGill University.
- The lecture, issued as Report P.D.-205 of the National Research Council of Canada, Division of Atomic Energy, Chalk River, Ontario, 20 Nov. 1946, was immediately classified by the U.S. Atomic Energy Commission. It was declassified on Oct. 8, 1949. (in fact no Proceedings were published, only a few lectures).
- Pontecorvo’s first idea was a $^{35}\text{Cl} - ^{35}\text{S}$ process (Report P.D.-141 dated May 21, 1945, classified, apparently unknown to the physics community).
- The neutrino cross-section was extremely small, and neutrino was considered as undetectable at the time being. Purpose of P.D.-141 note was to show that the experimental observation of neutrino “is not out of question”, and to suggest a method which might make an experimental observation feasible.
- In P.D.-141 the neutrinos are Majorana neutrinos.
- The $^{37}\text{Cl} - ^{37}\text{Ar}$ method only acquired full shape in 1948, after Pontecorvo fully clarified the $^{37}\text{Ar}$ decay mode by recording the $\beta$-spectrum of $^{37}\text{Ar}$ gas introduced in a high-gain proportional counter, and measured the energy of the Auger electron.
Probably, the first radiochemical experiment

An Attempt to Observe the Absorption of Neutrinos

H. R. Crane

University of Michigan, Ann Arbor, Michigan
(Received January 10, 1939)

It has been quite conclusively demonstrated that the presence of neutrinos cannot be detected by an ionization effect, of the kind which example of this is $\text{Cl}^{35} + \mu \rightarrow \text{S}^{35} + e^+$. 

3 pounds of NaCl irradiated 90 days by 1 mCi source, study of extracted sulphur with ionization chamber with 10 decay/s sensitivity. No events found.

Small target, low intensity source, low sensitivity
Radiochemical detection of neutrinos

neutrino capture via Inverse Beta Decay (IBD) in a target chemical element with \((A, Z)\). The product element \((A, Z+1)\) is unstable with half-life \(T_{1/2}\).

\[
\nu_e + (A,Z) \rightarrow e^- + (A,Z+1)\]

Typical radiochemical experiment:
* operates in a batch mode, with exposure times on the order of \(2T_{1/2}\).
* typically \(\sim 10\) product atoms are separated from \(\sim 10^{30}\) target atoms with efficiency \(\geq 90\%\).
* counting technique: no neutrino direction or energy information is available
* the targets must be huge, containing many tons of material.
* requires sensitive radiochemical methods to separate few atoms of product element \((Z+1)\) from the target \(Z\).
* placed deep underground to minimize cosmic-ray interactions in the target that can produce protons, \((p,n)\) reactions mimic neutrino capture.
One should go deep underground to reduce the background.
# Radiochemical experiments: proposals

<table>
<thead>
<tr>
<th>Target</th>
<th>Reaction</th>
<th>$T_{1/2}$</th>
<th>Threshold MeV</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chlorine</td>
<td>$^{37}\text{Cl} \rightarrow ^{37}\text{Ar}$</td>
<td>35.0 d</td>
<td>0.814</td>
<td>closed</td>
</tr>
<tr>
<td>Gallium</td>
<td>$^{71}\text{Ga} \rightarrow ^{71}\text{Ge}$</td>
<td>11.4 d</td>
<td>0.233</td>
<td>Running (SAGE)</td>
</tr>
<tr>
<td>Iodine</td>
<td>$^{127}\text{I} \rightarrow ^{127}\text{Xe}$</td>
<td>36 d</td>
<td>0.789</td>
<td>Prototype (Lande at al.) at Homestake; abandoned</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>$^{98}\text{Mo} \rightarrow ^{98}\text{Tc}$</td>
<td>4 $\cdot$ 10$^6$ yr</td>
<td>&gt;1.74</td>
<td>(Wolfsberg et al.) failed, no funding to repeat</td>
</tr>
<tr>
<td>Lithium</td>
<td>$^{7}\text{Li} \rightarrow ^{7}\text{Be}$</td>
<td>53 d</td>
<td>0.862</td>
<td>[R&amp;D]</td>
</tr>
<tr>
<td>Bromine</td>
<td>$^{81}\text{Br} \rightarrow ^{81}\text{Xe}$</td>
<td>2 $\cdot$ 10$^5$ yr</td>
<td>0.470</td>
<td>[R&amp;D]</td>
</tr>
<tr>
<td>Tantalum</td>
<td>$^{205}\text{Tl} \rightarrow ^{205}\text{Pb}$</td>
<td>14 $\cdot$ 10$^6$ yr</td>
<td>0.054</td>
<td>[R&amp;D]</td>
</tr>
<tr>
<td>Ytterbium</td>
<td>$^{176}\text{Yb} \rightarrow ^{176}\text{Lu}^*$</td>
<td></td>
<td>0.301</td>
<td>[R&amp;D (exLENS)]</td>
</tr>
<tr>
<td>Indium</td>
<td>$^{115}\text{In} \rightarrow ^{115}\text{Sn}^*$</td>
<td></td>
<td>0.114</td>
<td>[R&amp;D (LENS)]</td>
</tr>
</tbody>
</table>
Radiochemical detection of Solar neutrinos.

Bruno Pontecorvo, 1946:

\[ \nu_e + ^{37}\text{Cl} \rightarrow ^{37}\text{Ar} + e^- \]

\[ Q_{\text{th}} = 813.5 \text{ keV} \]

V. Kuz'min, 1965

\[ \nu_e + ^{71}\text{Ga} \rightarrow ^{71}\text{Ge} + e^- \]

\[ Q_{\text{th}} = 229.4 \text{ keV} \]
Homestake

Raymond Davis Jr. (1914-2006). Nobel prize in 2002 "for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

Homestake Mine: mine in South Dakota.

Tank filled with 600 tones of perchloroethylene ($\text{C}_2\text{Cl}_4$) at the depth of 1.5 km underground.

Detector was taking data from 1970 to 1994

Pontecorvo met Davis at the first neutrino conference in Moscow in 1968 and expressed the opinion that measuring the form of the counter pulse, in addition to the amplitude, should result in a considerable decrease of the effective background in his solar experiment. The suggestion proved correct as Pontecorvo found out from Davis at the $\nu$-72 conference in Hungary.
In 1971 Raymond Davis Jr. takes a dip in the water surrounding the perchloroethylene tank deep within the Homestake Mine.

What was wrong? Was our understanding of how the sun shines incorrect? Had I made an error in calculating the rate at which solar neutrinos would be captured in Davis's tank? Was the experiment wrong? Or, did something happen to the neutrinos after they were created in the sun? Over the next twenty years, many different possibilities were examined by hundreds, and perhaps thousands, of physicists, chemists, and astronomers. Both the experiment and the theoretical calculation appeared to be correct.

John Norris Bahcall (1934 – 2005)
One of the first ideas to explain the SNP: neutrino oscillates!

Mesonium and anti-mesonium

B. Pontecorvo
1957

3 pages

Inverse beta processes and nonconservation of lepton charge

B. Pontecorvo (Dubna, JINR)
Oct. 1957

2 pages

Neutrino Experiments and the Problem of Conservation of Leptonic Charge

B. Pontecorvo (Dubna, JINR)
1967

9 pages

Neutrino astronomy and lepton charge

V.N. Gribov (Ioffe Phys. Tech. Inst.), B. Pontecorvo (Dubna, JINR)
Dec. 1966

4 pages
Published: 1969

**muonium** (μ⁺e⁻) to antimuonium (μ⁻e+) transitions considered. A possibility of the neutrino oscillations is mentioned.

Paper dedicated to neutrino oscillations

the second paper on neutrino oscillations. Flavor neutrino oscillations (νₑ ⇆ νₘ) and also oscillations between flavor and sterile neutrinos (νₑL ⇆ νₑL, etc.) were considered. Solar neutrino oscillations were considered before the first results of the Davis solar neutrino experiment appeared, B. Pontecorvo anticipated “the solar neutrino problem”.

Suggested that only active left-handed neutrinos νₑ and νₘ and and right-handed antineutrinos exist in nature (no sterile neutrinos). It was assumed that exist an interaction which does not conserve lepton numbers. The oscillations of solar neutrinos were discussed.
Gallium Experiments

A new experiment was needed to clarify the SNP. A feasible proposal was Ga-Ge experiment, also due to a lower threshold.

The main problem – the quantity of Gallium necessary to provide reasonable neutrino count was comparable with its yearly world production. In 1981 and 1985 the Gallium project was rejected in USA, NSF recommended to collaborate with Europe and USSR (SAGE = Soviet-American Gallium Experiment)

In 1984 group headed by Till Kirsten from Max Plank Institute presented a project of gallium experiment and started to form GALLEX collaboration.

In USSR works were started as early as in 1975, collaboration SAGE was formed in the end of 80s.

Till Kirsten

Vladimir Gavrin
**GALLEX (GNO) and SAGE**

**Gallex/GNO at LNGS**

GaCl$_4$ : 30 t

**SAGE at Baksan laboratory (BNO)**

GaCl (metal) : 50-57 t

(an unknown fraction of metallic Gallium was stolen in "saint 90s" – quoted as systematic error on the mass in later publications.)

Liquid metallic Ga in the window of chemical reactor of SAGE experiment

Experimental hall with (chemical) reactors
KamiokaNDE and SuperKamiokaNDE

Water Cherenkov detector.

Detection reaction $\nu + e^- \rightarrow \nu + e^-$

KamiokaNDE-II, 1988, Japan (1000 m depth in the Kamioka mine)

SuperKamiokande (or SuperK) — updated (scaled) version of Kamiokande-II, located 180 miles to the north from Tokyo. Japan-USA collaboration. Construction ended in 1996. 50 ktones of highly purified water. Equipped with 11146 PMTs

Neutrino detection: elastic scattering off electrons

Neutrino detection in SuperKamiokande. Points — PMTs, light ring — Cherenkov light from relativistic recoil electrons.

Neutrinogram of the Sun (angle coordinates), obtained during first 500 days of the data taking by SuperK. Intensity of color corresponds to the number of detected neutrinos in corresponding direction.
Large PMTs – the eyes of the detector

Masatoshi Koshiba (future Nobel prize winner, 2002) is happy to see new PMT with large area photocathode, specially designed by Hamamatsu photonics.
<table>
<thead>
<tr>
<th>Detector</th>
<th>Years, exposure</th>
<th>FV mass</th>
<th>Coverage</th>
<th>$E_{\text{Thr}}$</th>
<th>Result $[10^6 \text{ cm}^{-2}\text{s}^{-1}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>KamiokaNDE-II  +III</td>
<td>87-90 90-95 2079 d</td>
<td>H$_2$O 3 kt</td>
<td>20% 25%</td>
<td>7.0</td>
<td>$2.82^{+0.25}_{-0.24} \pm 0.27$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>96-01 1496 d</td>
<td>H$_2$O</td>
<td>40%</td>
<td>5.5</td>
<td>$2.380 \pm 0.024^{+0.064}_{-0.076}$</td>
</tr>
<tr>
<td>SuperK (50 kt)</td>
<td>02-05 791 d</td>
<td>H$_2$O 22.5 kt</td>
<td>19%</td>
<td>7.0</td>
<td>$2.41 \pm 0.05^{+0.16}_{-0.15}$</td>
</tr>
<tr>
<td></td>
<td>06-08 548 d</td>
<td>22.5 (&gt;5.5MeV) 13.3 (&lt;5.5MeV)</td>
<td>40%</td>
<td>4.5</td>
<td>$2.404 \pm 0.039 \pm 0.053$</td>
</tr>
<tr>
<td>III</td>
<td>08-18 1664 d (2014)</td>
<td>22.5 (&gt;5.5MeV) 13.3 (4.5&lt;E&lt;5.5) 8.8 (&lt;4.5MeV)</td>
<td>40%</td>
<td>3.5</td>
<td>$2.308 \pm 0.020 \pm 0.04$ (2016)</td>
</tr>
<tr>
<td></td>
<td>2970 d</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>I+II+III+IV</td>
<td>5805 d</td>
<td></td>
<td></td>
<td>$2.35 \pm 0.01 \pm 0.04$</td>
</tr>
<tr>
<td>IV (T2K phase)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2019</td>
<td></td>
<td>40%</td>
<td>3.5</td>
<td>$2.33 \pm 0.01 \pm 0.03$</td>
</tr>
<tr>
<td>HyperK (0.26 Mt)</td>
<td>2027</td>
<td>0.19 Mt</td>
<td>40%</td>
<td>4.5</td>
<td>Project</td>
</tr>
</tbody>
</table>

**Notes:**
- FV: Freon-12
- EThr: Threshold Energy
Was the SNP solved by Ga and Water Cherenkov experiments?

Gallex+GNO+SAGE: 66.1 ± 3.1 SNU

½ of the expected in SSM

WCh detectors confirmed the Homestake results:
~1/3 of the expected in SSM

The Solar neutrino flux is suppressed (SNP-1) and deformed (SNP-2)

Cl: pp(0%) + 7Be(13%) + pep(2.7%) + CNO(2.4%) + 8B(82%)
Ga: pp(55%) + 7Be(28%) + pep(2.3%) + CNO(3.4%) + 8B(11%)

8B neutrinos measured by WCh detectors
SNO (Sudbury Neutrino Observatory)

Heavy water Cherenkov detector

10 neutrino events/day

17.8m dia. PMT Support Structure
9456 20-cm PMTs
56% coverage

12.01m dia. acrylic vessel

1700 tonnes of inner shielding H$_2$O

5300 tonnes of outer shielding H$_2$O

2 km to surface
Physics of detection in heavy water

**CC**
\[ \nu_e + d \rightarrow p + p + e^- \]
- Measurement of \( \nu_e \) energy
- Weak directionality: \( 1 - 0.340 \cos \theta \)

**NC**
\[ \nu_x + d \rightarrow p + n + \nu_x \]
- Measurement of the total \(^8\text{B} \nu\) flux
- \( \sigma(\nu_e) = \sigma(\nu_\mu) = \sigma(\nu_\tau) \)

**ES**
\[ \nu_x + e^- \rightarrow \nu_x + e^- \]
- Low statistics.
- \( \sigma(\nu_e) \approx 6 \sigma(\nu_\mu) \approx 6 \sigma(\nu_\tau) \)
- Strong directionality: \( \theta_e \leq 18^\circ \) (\( \tau_e = 10 \text{ MeV} \))
## Neutrons detection in 3 phases of the SNO experiment

<table>
<thead>
<tr>
<th>Phase</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>n+d: $\gamma$(single;6.25 MeV)</td>
</tr>
<tr>
<td>II (NaCl)</td>
<td>n+$^{35}$Cl: $\gamma$(multiple;8.6 MeV)</td>
</tr>
<tr>
<td>III</td>
<td>800 meters of $^3$He counters</td>
</tr>
</tbody>
</table>
SNO: missing neutrinos found!

Y: Non-electron neutrino

X: Electron neutrino

ES

NC
### SNO: results

<table>
<thead>
<tr>
<th>Phase</th>
<th>Target, mass</th>
<th>Method</th>
<th>Threshold [MeV]</th>
<th>Result [x10^6 cm^-2 s^-1]</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>99-01 306.4 d, D_2O 1006 t</td>
<td>ν_e+d → p + p + e^- (CC)-1.4 MeV, ν_x+d → p + n + ν_x (NC)-2.22 MeV, ν_x + e^- → ν_x + e^- (ES)</td>
<td>5.0</td>
<td>1.76±0.05±0.09 (CC), 2.39±0.24±0.23 (ES), 5.09±0.44±0.43 (NC)</td>
</tr>
<tr>
<td>II</td>
<td>01-04 391d, +NaCl 2t</td>
<td>^{35}Cl+n → ^{36}Cl+8.6 MeV (2-4 γ)</td>
<td>5.5</td>
<td>1.72±0.05±0.11 (CC), 2.34±0.23±0.15 (ES), 4.81±0.19±0.28 (NC)</td>
</tr>
<tr>
<td>I+II</td>
<td>Low energy threshold analysis (LETA: 3.5 MeV)</td>
<td></td>
<td>3.5</td>
<td>5.046±0.159±0.152±0.107±0.123 (NC)</td>
</tr>
<tr>
<td>III</td>
<td>04-06, +^3He counters</td>
<td>^{3}He + n → p + ^3H + 0.76 MeV</td>
<td>6.0</td>
<td>1.67±0.05±0.04±0.07±0.08 (CC), 1.77±0.24±0.21±0.09±0.10 (ES), 5.54±0.33±0.31±0.36±0.34 (NC)</td>
</tr>
</tbody>
</table>

\[^{8}\text{B flux } (5.25\pm3.7\%)x10^{6} \text{ cm}^{-2}\text{s}^{-1}\]
Solar Neutrino Problem: solution

- a large discrepancy between the predicted and measured fluxes of solar neutrinos:
  - Cl & KamiokaNDE $\approx 1/3$ of predicted
  - Ga: $\approx 1/2$ of predicted

A lot of solutions have been proposed, now mainly of historical interest.

MSW/LMA has been established as the true solution of the SNP
Borexino

- 278 t of liquid organic scintillator PC + PPO (1.5 g/l)
- $(\nu, e)$-scattering with low threshold (~200 keV)
- Outer muon detector
Why the name?

The original BOREX proposal was based on B-loaded scintillator Boron Experiment
"Probing the nature of the neutrino: The boron solar-neutrino experiment"

With a welter of neutrino scenarios and uncertain solar models to be unraveled, can solar-neutrino experiments really break new ground in neutrino physics? A new solar-neutrino detector BOREX, based on the nuclide $^{11}B$, promises the tools for a definitive exploration of the nature of the neutrino and the structure of the Sun. Using double-mode detection by neutrino excitation of $^{11}B$ via the neutral-weak-current- and the charged-current-mediated inverse $\beta$ decay in the same target, independent measurements of the total neutrino flux regardless of flavor and the survival of electron neutrinos in solar matter and a vacuum can be made. Standard models of the Sun, and almost every proposed nonstandard model of the neutrino, can be subjected to sharp and direct tests. The development of BOREX, based on B-loaded liquid-scintillation techniques, is currently in progress.

\[
\begin{align*}
\nu_x + e & \rightarrow \nu_x + e \\
\nu_e + ^{11}B & \rightarrow e^- + ^{11}C (\rightarrow e^+ + ^{11}B) \\
n + ^{10}B & \rightarrow ^7Li + \alpha (2.3 \text{ MeV}) + \gamma (0.48 \text{ MeV}) \\
n + ^1H & \rightarrow ^2H + \gamma (2.2 \text{ MeV}) \\
\bar{\nu}_e + ^1H & \rightarrow e^+ + n
\end{align*}
\]

\[
\begin{array}{|c|c|}
\hline
E & >0.25 \text{ MeV} \\
\hline
E & >4 \text{ MeV} \\
\hline
E & >1.8 \text{ MeV} \\
\hline
94\% & 6\% \\
\hline
\end{array}
\]
The challenge

50 events/d/100t expected ($\nu_e + \nu_{\mu,\tau}$ elastic scattering on $e^-$) or $5 \cdot 10^{-9}$ Bq/kg

(typically: drinking water $\sim 1$ Bq/kg; human body in $^{40}$K: 5 kBq)

Low energy $\rightarrow$ no Cherenkov light $\rightarrow$ No directionality, no other tags $\rightarrow$ extremely pure scintillator is needed

$^{7}$Be $[\pm 6\%]$  
$^{13}$N $[\pm 15\%]$  
$^{15}$O $[\pm 17\%]$  
$^{17}$F $[\pm 20\%]$  
$^{8}$B $[\pm 12\%]$  
hep $[\pm 30\%]$  

$\sim 1$ Bq  

$5 \cdot 10^{-9}$ Bq/kg

banana (150 g): $19$ Bq in $^{40}$K

$^{40}$K in Borexino $< 2.4 \times 10^{-7}$ banana equivalent (95% C.L.)

(36 $\mu$g)
Concept of the graded shielding

Neutrons and external gammas
(ultrapure water layer, 2.15 m, 2400 tones)

γ-s from construction materials
(PC buffer, 700 tones, 2.5 m)

γ-s from construction materials
(outer layer of scintillator, 1.25 m or 200 tones)

Software-defined active volume of scintillator
(fiducial volume, 3m, 100 tones)

Position reconstruction needed. Possible source of systematics

Increasing radiopurity of materials
Borexino history since the start of the data taking

- **PHASE-I** (2007-2010)
  - Filling
  - **R(7Be) + D/N**
  - **R(p) - first observation**
  - **R(8B) - first with LS**
  - **R(CNO) - limit**
  - geo-ν - first robust observation
cosmic muons flux studies
rare processes

- **PHASE-II** (2010-2017)
  - LS repurification campaign
  - 6 cycles of water extraction
  - **R(7Be)**
  - Seasonal variations of **R(7Be)**
  - Simultaneous spectroscopy of pp, 7Be and pep ν
  - **R(8B) - improved**
  - geo-ν
  - ν magnetic moment
  - **NSI**
rare processes

- **PHASE III** (2016-2017)
  - CNO campaign
  - External Tank insulation

- **09/2021 stop of the data taking**
(Expected) contributions to the observed spectrum (MC)

- Solar neutrino $\rightarrow$ electron recoil spectra
- Irreducible $^{14}\text{C}$ and other internal radioactive contaminants: $\alpha$'s from $^{210}\text{Po}$, $^{210}\text{Bi}$ ($\beta$) both not in secular equilibrium, $^{85}\text{Kr}$ ($\beta$), $^{11}\text{C}$ ($\beta^+$)
- External $\gamma$ (high energy)

![Graph showing contributions to the observed spectrum](attachment:image.png)

MC input counting rates are quoted in cpd/100 t
$^{14}\text{C}$ and $^{85}\text{Kr}$

\begin{align*}
\text{Atmospheric } & ^{85}\text{Kr} \text{ content} \\
\text{Yearly } ^{85}\text{Kr} \text{ emission}
\end{align*}

$^{14}\text{C}$ in atmosphere

\begin{align*}
\text{SH: Wellington, New Zealand} \\
\text{NH: Vermontsee, Austria} \\
\text{natural level}
\end{align*}
Detection reactions

Both electron and non-electron flavours are detected, $\sigma(\nu_e) \approx 6 \sigma(\nu_{\mu,\tau})$. 

Neutrino detection: elastic scattering off electrons

Cross section / $10^{-45} \text{ cm}^2$

Neutrino energy [MeV]
Electron recoil spectra

- Detected signal contains a mixture of both contributions:
  \[
  R(E_\nu, T) = P_{ee}(E_\nu) \phi_\nu(E_\nu) \frac{d\sigma_e(E_\nu, T)}{dT} + (1 - P_{ee}(E_\nu)) \phi_\nu(E_\nu) \frac{d\sigma_{\mu,T}(E_\nu, T)}{dT}
  \]

- Elastic scattering cross section for monoenergetic $\nu$ has “step-like” form (quasi-Compton) with
  \[
  T_{max} = \frac{E_\nu}{1 + \frac{m_e}{2E_\nu}}
  \]

Example for $^7$Be neutrinos (0.862 MeV):
Data selection for spectral analysis

Events are collected in real time. Time stamp, muons are tagged. Vertex is reconstructed off-line.

Muon cuts: muon induced events are removed.

FV cut: Events in the outermost part of the scintillator volume are removed.
Three-fold Coincidence technique (TFC) for \(^{11}\text{C}\) tagging

\(^{11}\text{C}\) production in muon interactions is accompanied by neutron:

\[ \mu + ^{12}\text{C} \to \mu + ^{11}\text{C} + n \]

The likelihood for \(^{11}\text{C}\) tagging among selected events:

- distance in space and time from the \(\mu\)-track;
- distance from the neutron;
- neutron multiplicity;
- muon dE/dx and number of muon clusters in an event

The TFC algorithm has (92±4)% \(^{11}\text{C}\)-tagging efficiency, while preserving (64.28±0.01)% of the total exposure in the TFC-subtracted spectrum.
Multivariate fit

Using TFC two complementary spectra are obtained: depleted (left) and enriched (right) in $^{11}$C.

Radial distribution of events (left) and pulse-shape estimator ($e-/e+$) are fit simultaneously.
PP-chain (99%)

$pp \rightarrow ^2H + e^+ + \nu_e^{99.76\%}$

$2H + p \rightarrow ^3He + \gamma^{83.30\%}$

$^3He + ^3He \rightarrow ^4He + 2p^{16.70\%}$

$^3He + ^4He \rightarrow ^7Be + \gamma^{0.12\%}$

$^7Be + p \rightarrow ^8B + \gamma^{99.88\%}$

$^8B \rightarrow ^8Be + e^+ + \nu_e^{2010, 2018}$

$^7Li + p \rightarrow ^4He + ^4He^{2014, 2023 (seasonal)}$

$^8Be \rightarrow ^4He + ^4He^{2014+ \rightarrow \text{Phase II data used}}$

Neutrino fluxes bring a snapshot of the nuclear reactions in the Sun.
pp-chain solar $\nu$ : results

<table>
<thead>
<tr>
<th>flux</th>
<th>Borexino</th>
<th>B16(GS98) : HZ</th>
<th>B16(AGSS09) : LZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp</td>
<td>$6.1(1.00\pm0.116)\times10^{10}$</td>
<td>$5.98(1.0\pm0.006)\times10^{10}$</td>
<td>$6.03(1.0\pm0.005)\times10^{10}$</td>
</tr>
<tr>
<td>$^7\text{Be}$</td>
<td>$4.99(1.00\pm0.033)\times10^{9}$</td>
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</tr>
<tr>
<td>pep (HZ)</td>
<td>$1.27(1.00\pm0.177)\times10^{8}$</td>
<td>$1.44(1.00\pm0.009)\times10^{8}$</td>
<td>---</td>
</tr>
<tr>
<td>pep (LZ)</td>
<td>$1.39(1.00\pm0.166)\times10^{8}$</td>
<td>---</td>
<td>$1.46(1.00\pm0.009)\times10^{8}$</td>
</tr>
<tr>
<td>$^8\text{B}$</td>
<td>$5.68(1\pm0.08)\times10^{6}$</td>
<td>$5.46(1\pm0.12)\times10^{6}$</td>
<td>$4.50(1\pm0.12)\times10^{6}$</td>
</tr>
</tbody>
</table>

The results are quoted in units of $\text{cm}^{-2}\text{s}^{-1}$.

The results are obtained fixing the CNO flux at the SSM values (HM/LM accounted for as systematics).
The solar metallicity puzzle

- Solar metallicity = chemical composition of heavy elements. “Metals” in astrophysics are all elements with Z>2
- Metallicity:
  - 1) from spectroscopic measurement of the photosphere;
  - 2) from studies of meteorites;
- Metallicity is an input of the Standard Solar Models
- Metallicity influences the outputs of SSM (opacity -> Temperature)

In the early 2000s, the solar composition was revised downwards by about 30%, a result created a problem – solar models constructed with the older metallicities matched the structure of the Sun, the models with the newer metallicities are extremely discrepant.

The structure of the Sun can be determined in a model-independent manner by analyzing the frequencies with which the Sun oscillates (helioseismology). All such analyses have shown that the lower abundances produce models that are discrepant.
## HZ/LZ SSM predictions

<table>
<thead>
<tr>
<th>FLUX</th>
<th>Dependence on T: ( (T^x)_X )</th>
<th>SSM/HZ</th>
<th>SSM/LZ</th>
<th>((HZ-LZ)/HZ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp ((10^{10} \text{ cm}^{-2}\text{s}^{-1}))</td>
<td>-0.9</td>
<td>5.98(1±0.006)</td>
<td>6.03(1±0.005)</td>
<td>-0.8%</td>
</tr>
<tr>
<td>pep ((10^{8} \text{ cm}^{-2}\text{s}^{-1}))</td>
<td>-1.4</td>
<td>1.44(1±0.01)</td>
<td>1.46(1±0.009)</td>
<td>-1.4%</td>
</tr>
<tr>
<td>(^7\text{Be} ((10^{9} \text{ cm}^{-2}\text{s}^{-1}))</td>
<td>11</td>
<td>4.94(1±0.06)</td>
<td>4.50(1±0.06)</td>
<td>8.9%</td>
</tr>
<tr>
<td>(^8\text{B} ((10^{6} \text{ cm}^{-2}\text{s}^{-1}))</td>
<td>24</td>
<td>5.46(1±0.12)</td>
<td>4.50(1±0.12)</td>
<td>17.6%</td>
</tr>
<tr>
<td>(^{13}\text{N} ((10^{8} \text{ cm}^{-2}\text{s}^{-1}))</td>
<td>18</td>
<td>2.78(1±0.15)</td>
<td>2.04(1±0.14)</td>
<td>26.6%</td>
</tr>
<tr>
<td>(^{15}\text{O} ((10^{8} \text{ cm}^{-2}\text{s}^{-1}))</td>
<td>20</td>
<td>2.05(1±0.17)</td>
<td>1.44(1±0.16)</td>
<td>29.7%</td>
</tr>
</tbody>
</table>
Solar metallicity puzzle

Global fit to all solar + Kamland data (including the new $^7$Be result from BX)

\[
f_{\text{Be}} = \frac{\Phi(\text{Be})}{\Phi(\text{Be})_{\text{HZ}}} = 1.01 \pm 0.03
\]

\[
f_{\text{B}} = \frac{\Phi(B)}{\Phi(B)_{\text{HZ}}} = 0.93 \pm 0.02
\]


- **a hint towards the HZ:**
  - Assuming HZ to be true, BX data disfavour LZ at 96.6% C.L. (1.8$\sigma$) (slightly stronger than the median sensitivity of 94.2% C.L.).
  - $p$-value (HZ) = 0.87
  - $p$-value (LZ) = 0.11
  - Theoretical errors of the SSM are dominating
pp-chain termination relative intensity

Assuming local equilibrium of $^2$H and $^3$He

$$R \equiv \frac{\langle ^3 \text{He} + ^4 \text{He} \rangle}{\langle ^3 \text{He} + ^3 \text{He} \rangle} = \frac{2\phi(\,^7\text{Be})}{\phi(\,^8\text{pp}) - \phi(\,^7\text{Be})}$$

$R(\text{HZ}) = 0.180 \pm 0.011$
$R(\text{LZ}) = 0.161 \pm 0.010$

From the pp and $^7\text{Be}$ fluxes measurement

$R(\text{BRX}) = 0.178^{+0.027}_{-0.023}$
Key to the Solar metallicity: CNO flux

Main background from $^{210}$Bi:

- ~20 cpd/100 t

If we will be able to extract $^{210}$Bi with few counts precision, we will be able to constraint it in the spectral fit and extract the CNO flux.

Another background in the region of sensitivity is pep-neutrino flux. Can be constrained through pp/pep ratio, using theoretical prediction for pp (luminosity constraint) or pp measured value.

Expected spectrum assuming $\nu$(CNO) HZ flux and other rates from last solar analysis

Predictions:

- HZ $\sim$5 cpd/100 t
- LZ $\sim$3 cpd/100 t
CNO neutrinos

$^{210}\text{Bi}$ and CNO: similar spectral shapes close rates
Strategy towards CNO measurement

- Main route: using $^{210}\text{Bi}-^{210}\text{Po}$ evolution in time to measure “support term” for $^{210}\text{Po}$ (secular equilibrium in $^{210}\text{Pb}$ sub-chain)
- Option: further purification of the LS by water extraction to reduce $^{210}\text{Bi}$

Instabilities observed in the evolution in time of the $^{210}\text{Po}$ (making impossible precision evaluation of the $^{210}\text{Bi}$) were found to be the result of the temperature instabilities of the surrounding
Hardware solution for thermal stabilization: thermal insulation
The low Po field was identified and the CNO measurements was performed at 5\( \sigma \) level. 

*Nature 587 (2020)578 ; PRL 129 (2022)252701*

**Correlation with the Sun Direction (CID):**

Final Borexino measurement of CNO neutrinos (>7\( \sigma \)):

*Accepted for pub on PRD-arXiv 2307.14636*
Solar $\nu$: all results by Borexino

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<td>CNO</td>
<td>$6.7(1.00^{+0.19}_{-0.12})x10^{8}$</td>
<td>$4.88(1.00\pm0.11)x10^{8}$</td>
<td>$3.51(1.00\pm0.10)x10^{8}$</td>
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CNO cycle is here! (C.L. > 7$\sigma$)
- CNO is the most important process of energy burning in the universe;
- Its experimental confirmation is a milestone for experimental astrophysics;

results are quoted in units of cm$^{-2}$s$^{-1}$
Solar metallicity puzzle after the CNO measurement

Assuming SSM-HZ, Borexino results on $^7$Be, $^8$B and CNO neutrinos disfavors SSM-LZ with a p-value of $9.1 \times 10^{-4}$ (~3.1σ)
Implications: Solar Luminosity

Borexino data

\[ L = (3.89^{+0.35}_{-0.42}) \times 10^{33} \text{ erg s}^{-1} \]

Photon luminosity

\[ L = (3.846 \pm 0.015) \times 10^{33} \text{ erg s}^{-1} \]

This confirms the nuclear origin of the solar power;

• It proves that the Sun has been in thermodynamic equilibrium at least over last $10^5$ years (the time required for radiation to diffuse from the center to the surface of the Sun)
Assuming HZ-SSM fluxes we get:

$$P_{ee}(pp) = 0.57 \pm 0.09$$
$$P_{ee}(7\text{Be}) = 0.53 \pm 0.05$$
$$P_{ee}(\text{pep}) = 0.43 \pm 0.11$$
$$P_{ee}(8\text{B}) = 0.37 \pm 0.08$$

Data disfavour vacuum-LMA hypothesis at 98.2% C.L.

(i.e., neutrino do not oscillate but undergo MSW transition)
MSW/LMA: electron neutrino survival probabilities

High metallicity SSM

Low metallicity SSM

*p-values:
Bx only: 0.998
All exp: 0.956

*p-values:
Bx only: 0.362
All exp: 0.465
Seasonal modulations of $^7$Be neutrino flux: confirmation of the Solar origin

"Independent determination of the Earth’s orbital parameters with solar neutrinos in Borexino"

Astroparticle Physics 145 (2023) 102788

$T=363.1\pm3.6$ the duration of the astronomical year is measured from underground using neutrino!
Day/Night neutrino signal asymmetry

Borexino: no diurnal variations of $^7$Be neutrino flux

"negative" result on day/night asymmetry with 3 years statistics (380.63 "nights" + 360.25 "days") is in agreement with MSW/LMA predictions:

$$ADN = \frac{N - D}{N + D} = 0.001 \pm 0.012(stat) \pm 0.007(syst)$$

Absence of a day–night asymmetry in the $^7$Be solar neutrino rate in Borexino

$$A_{dn} = 0.001 \pm 0.012 \text{ (stat)} \pm 0.007 \text{ (syst)}$$

Diurnal variations of $^8$B signal in SK

$\Delta m^2_{21}$ (10$^{-5}$ eV$^2$) vs. Day/Night Asymmetry (%)

**2014:**
$A_{DN} = -3.2 \pm 1.1 \pm 0.5 \%$ (2.8$\sigma$)

**2016:**
$A_{DN} = -3.2 \pm 1.0 \pm 0.5 \%$ (2.9$\sigma$)

Note: The graph shows the MSW prediction and the best fit for SK I, II, III, IV. The data points for 2014 and 2016 are compared with the theoretical predictions.
Upturn in $^8$B spectrum

SNO

$P_{\nu_e \to \nu_e}$ 1σ band
- SNO
- Borexino $^7$Be
- pp - All solar $\nu$ experiments

SK

SK I-IV 5610 Days
- Data (Stat. + Syst. errors)
- SK+SNO best-fit MSW oscillations

Recoil energy (MeV)
Beyond the Solar neutrinos with Solar neutrino detectors

Modern detectors are thought of as multipurpose detectors: a vast physical program is envisaged beyond the primary goal.

Measurements of geo-neutrino fluxes with the Solar neutrino detector (Borexino) and/or with the reactor antineutrino detector (KamLAND) is a good example. Another example: using GaGe method for the search of the sterile neutrinos (BEST at BNO).

Real-time Solar neutrino experiments are also an important component of Multimessenger Astronomy.
The weighted average for the four experiments $R = 0.87 \pm 0.05$

$\chi^2/DOF = 1.9/3$

Overestimated cross sections?

Sterile neutrino?

BEST
BEST (Baksan Experiment on Sterile Transitions)
Geo-neutrino (Borexino)

52.6 $^{+9.4/-8.6}_{\text{stat}}$ $^{+2.7/-2.1}_{\text{syst}}$ events (Th/U=3.9)

+17/-15 % $^{+18.3/-17.2}_{\%}$

Mantle cooling (18 TW)

Crust R (7 ± 1 TW)

Mantle R (~9 TW) (4-15 TW)

Core (~9 TW) (~4-15 TW)
Effective magnetic moment of Solar neutrino

XENON1T (2020) observes excess of events that can be explained by anomalous neutrino MM:
$1.4 < \mu_\nu < 2.9 \times 10^{-11} \mu_B$ (90% CL)

*Borexino* is spectroscopical detector.

Solar neutrino analysis (spectral fit) is performed assuming SM cross sections. The shapes can be adjusted to take into account any non-standard interactions (NSI), including neutrino EM interactions.

Radiochemical (Ga) constraints

$$\sum_i \frac{R_i^{Brx}}{R_i^{Expected}} \frac{\langle \sigma_i^{\odot} \rangle_{new}}{\langle \sigma_i^{\odot} \rangle_{old}} = 66.1 \pm 3.1 \pm \delta_R \pm \delta_{FV}$$

Without Ga constraint: $\mu_\nu < 4.0 \cdot 10^{-11} \mu_B$, 90% C.L.

With Ga constraint: $\mu_\nu < 2.6 \cdot 10^{-11} \mu_B$, 90% C.L.

+ systematics: $\mu_\nu < 2.8 \cdot 10^{-11} \mu_B$, 90% C.L.
Non-standard neutrino interactions

The absence of the visible upturn in the SuperK spectrum triggered speculations on NSI

Survival probabilities from all solar v results

"Upturn" predicted by standard MSW is not seen yet.

NSIs modifies Pee...

... and cross sections
Constrains on NSI

JHEP02(2020)038
Searches for rare physics

- NN, NNN disappearance (decays into invisible channels)
- Search for Pauli forbidden transitions in nuclei
- $e^{-}\rightarrow\nu+\gamma$ decay (charge conservation; life-time of electron
- Dark Matter
- Sterile neutrino
- Search for axions
- Heavy sterile neutrino mixing in $^{8}\text{B}$ decay
- Antineutrinos from the Sun
- DSNB (Diffuse SN Neutrino Background)
- etc....
Multimessenger Astronomy

- SNEWS

- Search for low-energy neutrinos in coincidence with:
  - GRB
  - GW
  - Fast radiobursts
  - Solar flares
  - ....
Future

- It looks like Borexino was the last detector with a primary goal of detecting Solar neutrino.

- All future detectors with sensitivity to Solar neutrino have another priority and this complicates the Solar neutrino studies (mainly not deep enough, radiopurity).

- But, in general, larger volumes and better energy resolution offer a good possibility for further studies of the Solar neutrino.
JUNO

JUNO: Fiducial M=10kt

8B solar neutrinos
- 60k ES events in 10y
- Also possible to see
  CC: $\nu_e^+ + ^{13}\text{C} \rightarrow e^- + ^{13}\text{N}$
  NC: $\nu_x^+ + ^{13}\text{C} \rightarrow \nu_x^+ + ^{13}\text{N}^*$

7Be, pep, CNO solar neutrinos
- Radiopurity?

Planned data taking start: 2024
HyperK – the third generation of Kamioka WCh detectors

Tochibora Mine ~8 Km far from SuperK (overburden= 650 m, less than SuperK!);
• better energy and angular resolution;
• **Main goal**: far detector for the JPARC beam : study the $\delta_{CP}$, NMO ...
• Data taking start ~2027

$^8$B solar neutrinos
In ~ 10 years

• Upturn at 5\(\sigma\);
• D/N at 4\(\sigma\)-8\(\sigma\) (depending on background)
• hep neutrinos at ~3\(\sigma\);
**THEIA**

**Multi-purpose detector:** far detector for LBNF beam: \( \delta_{CP}, \) NMO ...

- Theia will be located at SURF (Sanford Underground Research Facility, South Dakota)
- Mass: \((25 - 100) \) kt;
- water based Liquid scintillator (WbLS)

Uncertainty on CNO \(~ 4\%

\(-5 \) years;

\(-60 \) kt Fiducial M;

\(-\sigma(\theta) \sim 25^0\)

\(^7\)Li for CC (8B neutrinos)
Instead of conclusions

“\textbf{It is now well realized that the Sun and the Earth were created for neutrino oscillation experiments. The Earth–Sun distance was chosen as the oscillation length, solar matter density was selected specially to include the Mikheev–Smirnov–Wolfenstein effect, and the Sun was prepared in the form of an ideal electron neutrino source.}

\textbf{When all was done, Bruno Pontecorvo was created to invent the idea of neutrino oscillations, John Bahcall was created to calculate the solar neutrino fluxes, Ray Davis was created to accomplish the first neutrino experiment, and all other individuals in solar neutrino physics were created to finalize this hard job…}”

M. Goodman, cited by V. Berezinsky.