Contribution of radiochemical experiments in the solar neutrino and neutrino oscillations research

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International Session-Conference of SNP PSD RAS Physics of Fundamental Interactions"
dedicated to 50th anniversary of Baksan Neutrino Observatory.
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Outlines

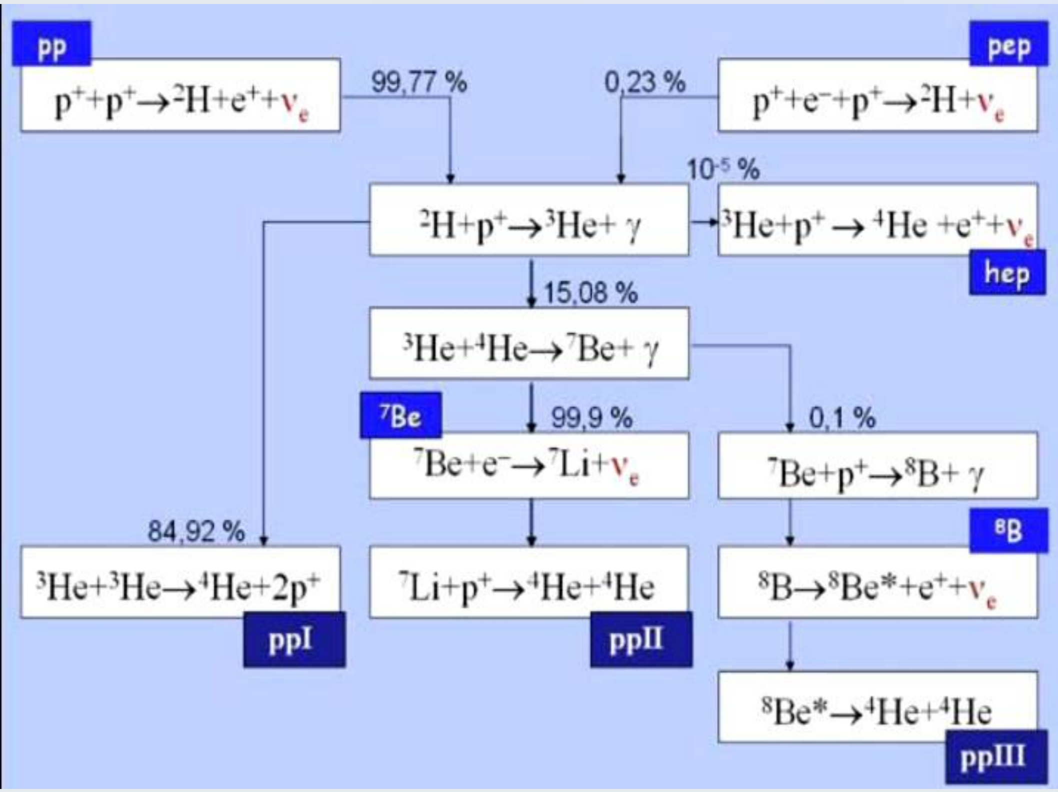
1. A little of history, Cl- Ar experiment
2. Ga solar neutrino experiments
3. Ga neutrino sources experiments
4. "Ga anomaly" & sterile neutrino
5. New neutrino source experiment on Ga

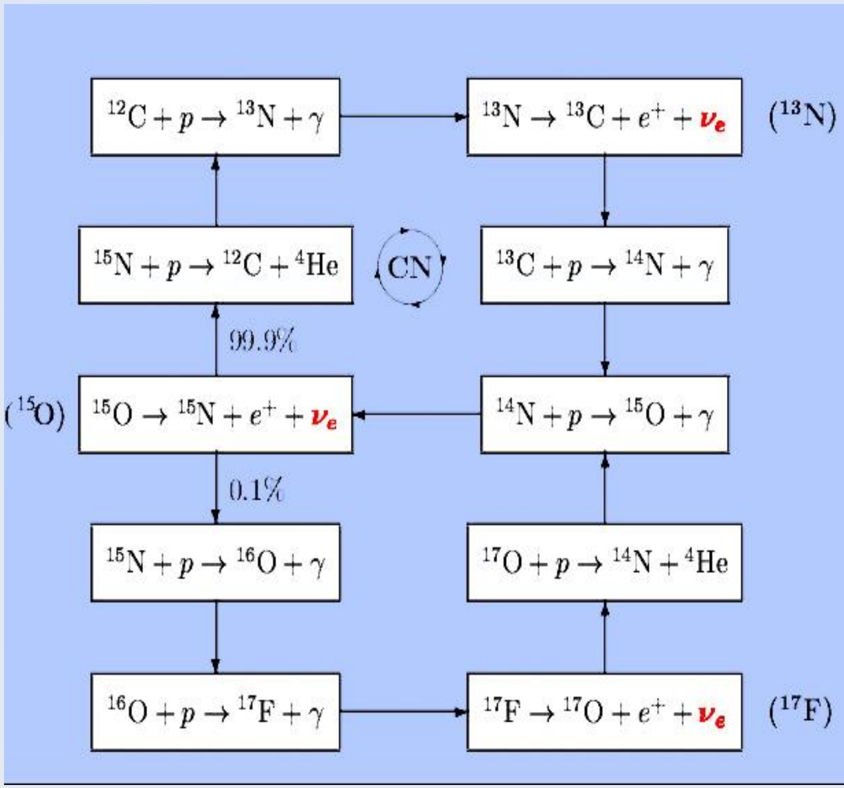
The Sun's sources of Energy & Neutrino

$$4p \rightarrow \alpha + 2e^{+} + 2\nu_e$$

pp-chain

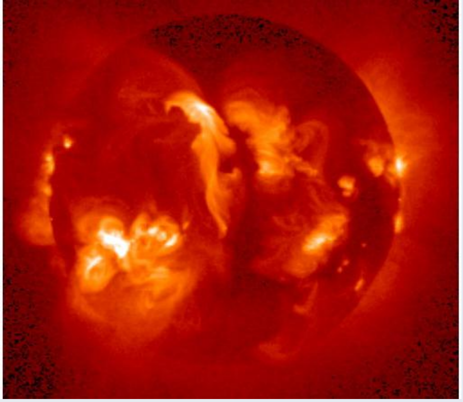
CNO cycle



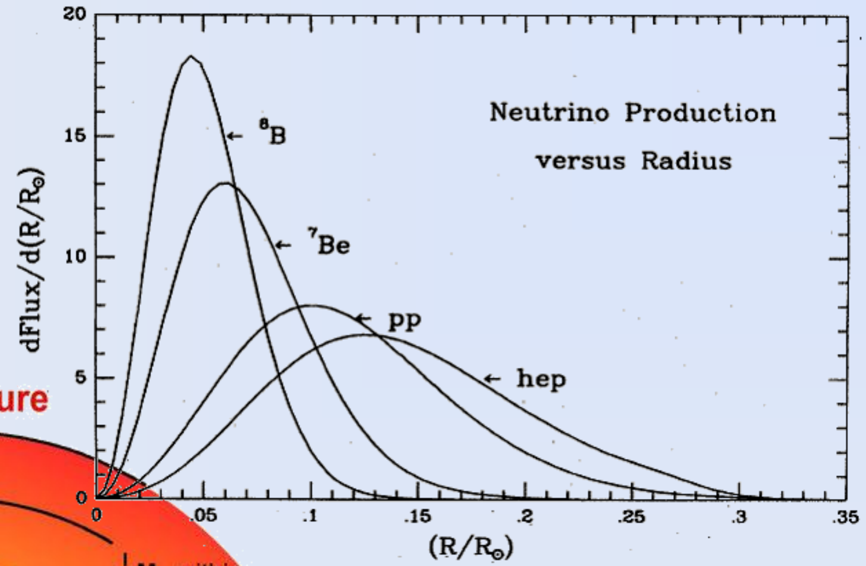


>99% of the energy is released in the *pp*-chain reactions **<1% in the CNO cycle**

von Weizacker, H. Bethe, C. L. Crichtfield, 1938.



Neutrino production as a function of radius

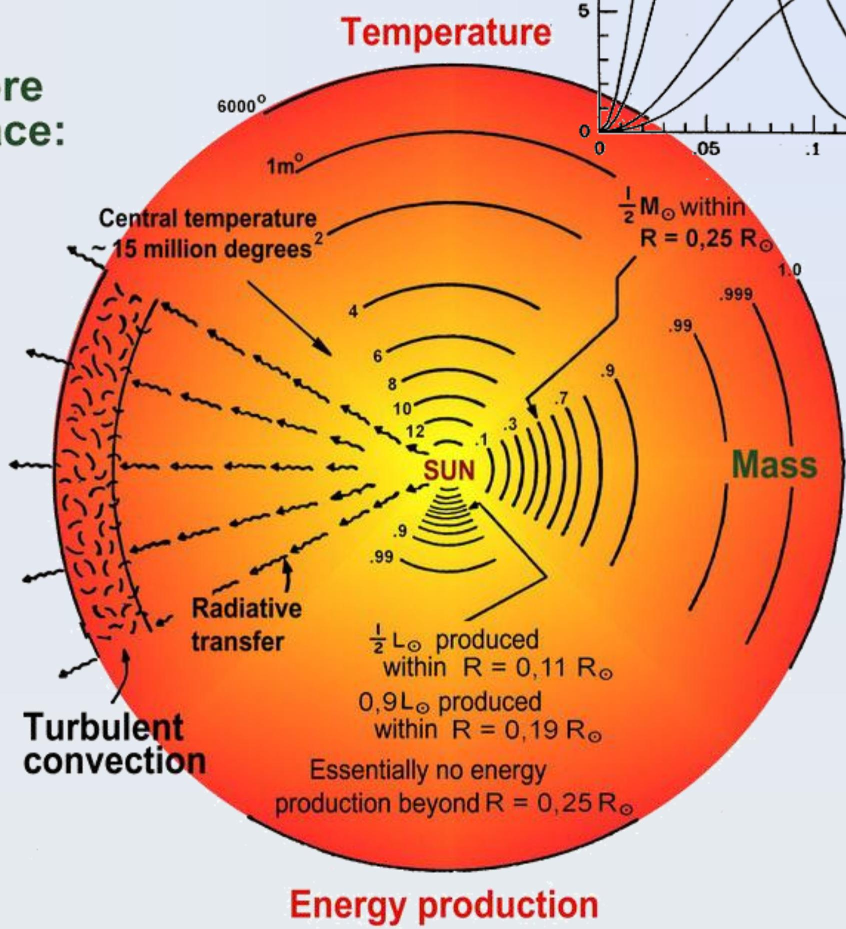


Transport time from the Solar core to the Solar surface:

Thermal energy
~ 10 million years

Photons
~ 10's 000 years

Neutrino
to the Earth
- 8 minutes



$L_\odot = \Sigma \Phi_i \cdot \alpha_i$, where

$L_\odot = L\odot = 3.846\times10^{26}$ W,
or 3.846×10^{33} erg/s

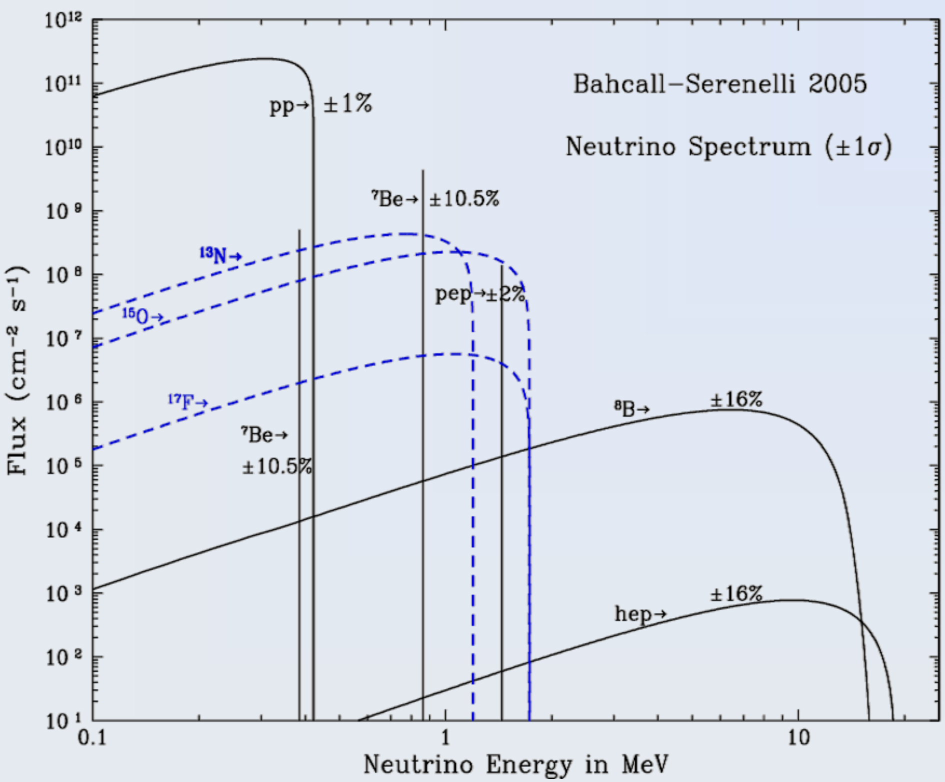
the solar luminosity,

i = *pp*, *pep*, ^{7}Be, . . .

(6×10^{10} neutrino $cm^{-2}s^{-1}$ on the Earth)

Neutrino production in the Sun

Neutrino energy spectrum as predicted by the Standard Solar Model (SSM)



John Norris Bahcall
(Dec. 30,1934 – Aug. 17, 2005)

John Bahcall creates SSM and on the basis of the model calculates ν fluxes “…to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars...”

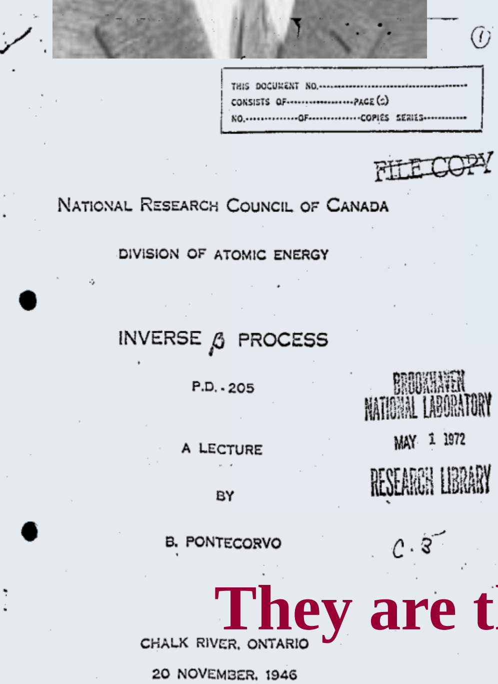
Conception of neutrino astrophysics

1930 Pauli invents the neutrino as *"a desperate way out"*
Bethe + Peierls calculate cross-section → 10^{-43} cm^2 @ MeV
Pauli: *"I have invented something that cannot be detected"*

1946 Pontecorvo [Chalk River, Report P.D. -205, 1946]

- Shows that "observation of neutrinos is not out of question" and suggest "inverse beta process" as a process:
  $\nu + (A,Z) \rightarrow e^- + (A, Z+1)$.
- Suggested ν sources: reactor or material from it, or the Sun.
- Among multiple targets, considers ^{37}Cl as the most promising.
- Suggests to use the new high-gain, miniature, low background proportional counter.

Exactly those two ideas were used by Davis in Cr-Ar experiment.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INVERSE β PROCESS

P.D. - 205

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MAY 1 1972
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A LECTURE

BY

B. PONTECORVO

C. 3

CHALK RIVER, ONTARIO

20 NOVEMBER, 1946

They are the basis of all neutrino radiochemical experiments

THE NEUTRINO SPECTROSCOPY OF THE SUN

Radiochemical methods of the solar neutrinos detection similar to that of Pontecorvo proposed began to be actively discussed at the second half of the last century (1964-1965) by a wide range of scientists, including Davis, Reines, Zatsepin, Domogatsky, Kropp, Bahcall, Kuzmin.

The possibilities of a detailed investigation of a solar neutrino spectrum were considered, having in mind that it is a rather effective approach to the study of the solar internal structure. It was necessary to obtain several independent measurements by means of detectors having well known and essentially different dependences of neutrino absorption cross section on neutrino energy. (Proc. of the 9th Inter. Cosmic Rays Conf, 1023. London, Sept., 1965.)

The following arrangements of detectors are suitable for a program of solar neutrino spectroscopy:

^{37}Cl, ^{71}Ga and ^{7}Li

The difficult problem is to determine the role of the CNO cycle, while the ^{13}N, ^{15}O neutrinos have not high energy and their flux is not intense. But, information about the CNO cycle is rather important as we may find in this way the distribution of heavy elements in the Sun.

Principles of Radiochemical Solar ν Detection

Nu Capture, $\nu_e + (A, Z) \rightarrow e^- + (A, Z+1)$

- Huge multi-ton detectors
- Locate deep underground; (p,n) as well as spallation reactions mimic ν capture
- Sensitive radiochemical separations of product (Z+1) from target Z:

  isolate ~10 product atoms from ~10^{30} target atoms
- Purifecation product, convertateion to suitable chemical form for high- efficiency, low-background counting of (Z+1) nucleas
- Measured energy spectrum and half-life identify **(A, Z+1)**

The BNO program of the neutrino spectroscopy of the Sun

Reaction	ν energy (MeV)	ν flux ($cm^{-2}s^{-1}$)	ν capture rate (SNU) Cl	Ga	Li
$p+p \rightarrow d+e^{+}+\nu$	0-0.42	$(5.95\pm0.06)\times10^{10}$	0.00	69.7	0.0
$p+e^{-}+p \rightarrow d+\nu$	1.44	$(1.40\pm0.02)\times10^{8}$	0.22	2.8	9.2
$^{3}He+p \rightarrow {}^{4}He+e^{+}+\nu$	18.8	9.30×10^{3}	0.04	0.1	0.1
$^{7}Be+e^{-} \rightarrow {}^{8}B+\nu$	0.38, 0.86	$(4.77\pm0.48)\times10^{9}$	1.15	34.2	9.1
$^{8}B \rightarrow {}^{8}Be^{*}+e^{+}+\nu$	0-14.1	$(5.05^{+1.01}_{-0.81})\times10^{6}$	5.76	12.1	19.7
$^{13}N \rightarrow {}^{13}C+e^{+}+\nu$	1.2	$(5.48^{+1.15}_{-0.93})\times10^{8}$	0.09	3.4	2.3
$^{15}O \rightarrow {}^{15}N+e^{+}+\nu$	1.7	$(4.80^{+1.20}_{-0.91})\times10^{8}$	0.33	5.5	11.8
$^{17}F \rightarrow {}^{17}O+e^{+}+\nu$	1.7	$(5.63\pm1.41)\times10^{6}$	0.00	0.1	0.1
Total			$7.6^{+1.3}_{-1.1}$	128^{+9}_{-7}	$52.3^{+6.5}_{-6.0}$

Prediction of SSM (BP2000)

In radiochemical experiments the capture rate has been conventionally expressed in '**SNU units**', defined as one neutrino capture per second in a target that contains 10^{36} atoms of the neutrino-absorbing isotope, in our case ^{37}Cl ,^{71}Ga ^{7}Li.

BNO INR RAS
V.N. Gavrin

Radiochemical Solar Neutrino Detectors

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

✓* ^{37}Cl - ^{37}Ar ($T_{1/2}$= 35.0 d, E-threshold = 0.814 MeV)

✓* ^{71}Ga - ^{71}Ge ($T_{1/2}$= 11.4 d, E-threshold = 0.233 MeV)

x ^{127}I - ^{127}Xe ($T_{1/2}$= 36 d, E-threshold = 0.789 MeV)

? * ^{7}Li - ^{7}Be ($T_{1/2}$= 53 d, E-threshold = 0.862 MeV)

✓ = "Successful", X = "Not successful", ? = Did not get beyond R&D stage

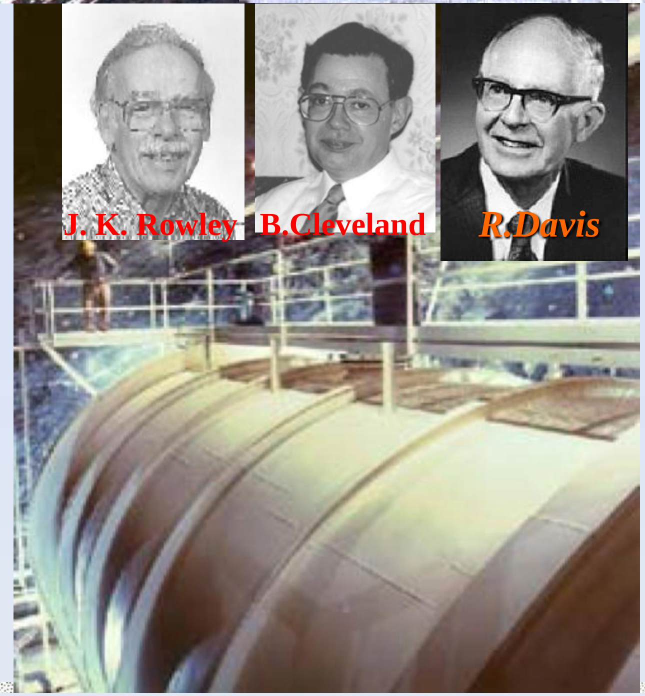
*** - included to the BNO program of the neutrino spectroscopy of the Sun**

1960-1970 - excellent decade

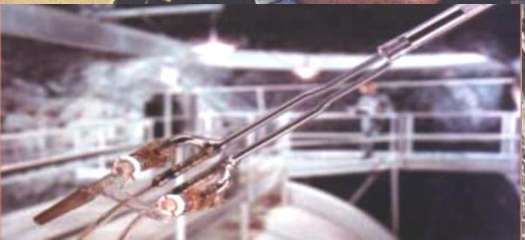
1960 – 1970 (this decade was the beginning of the rapid development of neutrino astrophysics)

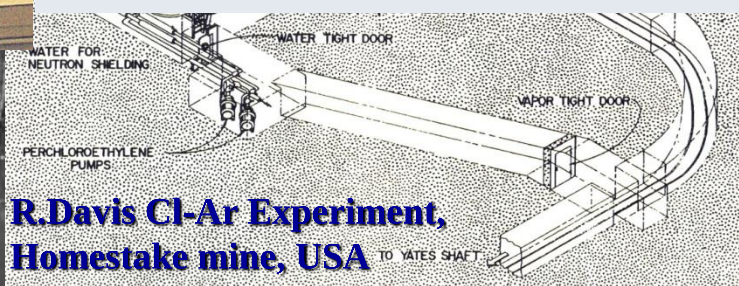
- **Ray Davis** constructs Chlorine detector for measurements of production rate in reaction $^{37}Cl\ (\nu, e^-)\ ^{37}Ar$ (1946 Pontecorvo, 1949 Alvarez)
- **John Bahcall** creates SSM and on the basis of the model calculates ν fluxes
- **SU** starts the construction of the **Baksan Neutrino Observatory** INR RAS
- **V. Kuzmin** suggests the reaction $^{71}Ga(\nu, e^-)^{71}Ge$ for detection of *pp* ν as well as artificial ^{51}Cr neutrino source for calibration of Ga detector
- **Bruno Pontecorvo** – "possibly neutrino oscillate"
- The idea of oscillations doesn't get common recognition. Large mixing angle for neutrino is required that contradicts the existing conception
- **Davis' first result**– significant difference with SSM.
  Solar neutrino problem was born.
- **Start of a 40-year solar neutrino mystery**

Homestake Radiochemical experiment



The **Nobel Prize in Physics 2002** "for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"



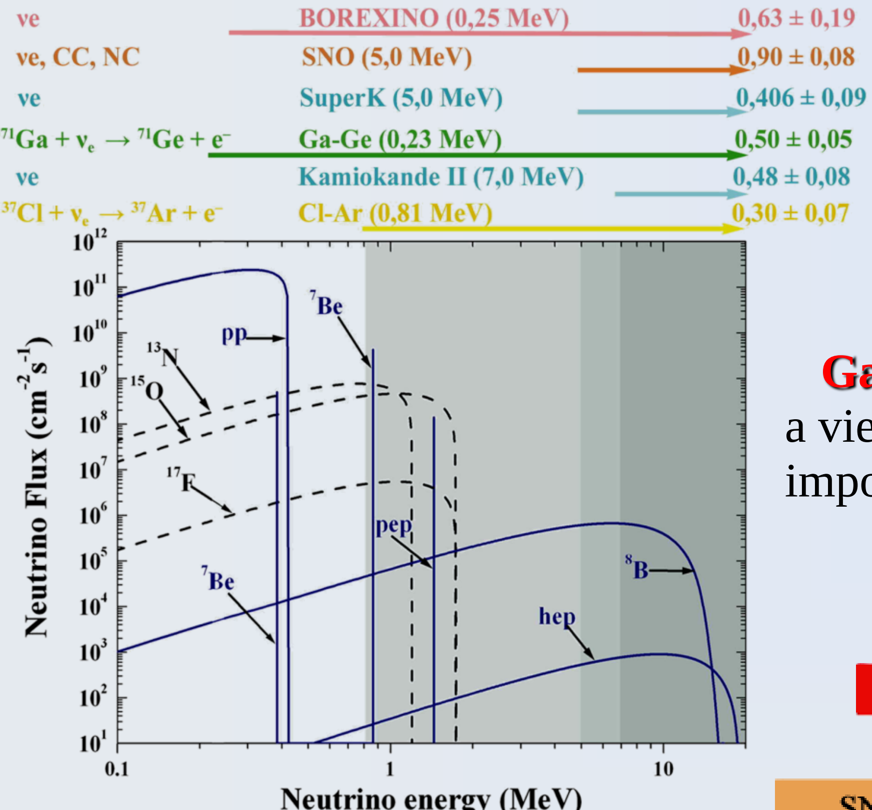


R.Davis Cl-Ar Experiment, Homestake mine, USA

Ga solar neutrino experiments

Ga experiment is keenly claimed

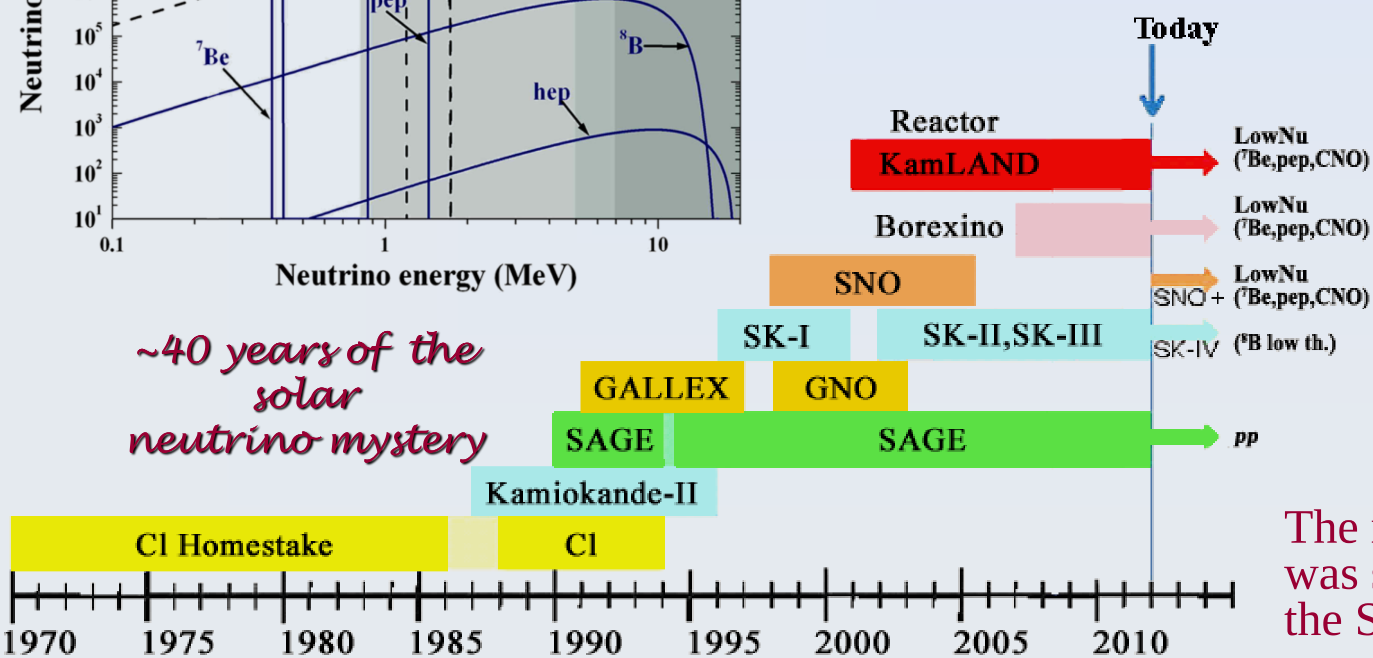
The **Ga** experiments were built to measure the capture rate of solar neutrinos by the reaction $^{71}\mathrm{Ga} + \nu_e \rightarrow {}^{71}\mathrm{Ge} + e^-$ and thus to provide information to aid in understanding the deficit of neutrinos observed in the $^{37}\mathrm{Cl}$ experiment, in which only about one-third of the solar neutrino capture rate predicted by the standard solar model was detected.

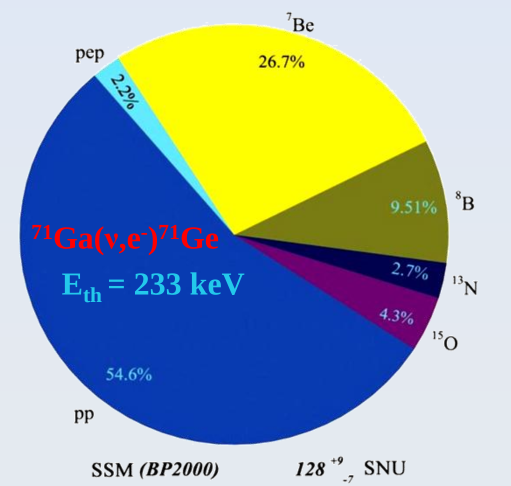


The feature that distinguishes the **Ga** experiment from all other past or present solar neutrino detectors is its sensitivity to the proton-proton fusion reaction, $p + p \rightarrow d + e^+ + \nu_e$, which generates most of the Sun's energy.

Ga experiments have given a great impact upon a view of neutrino oscillation and have supplied most important motivation for creation of **SNO** (*J. Bahcall, 2004*)

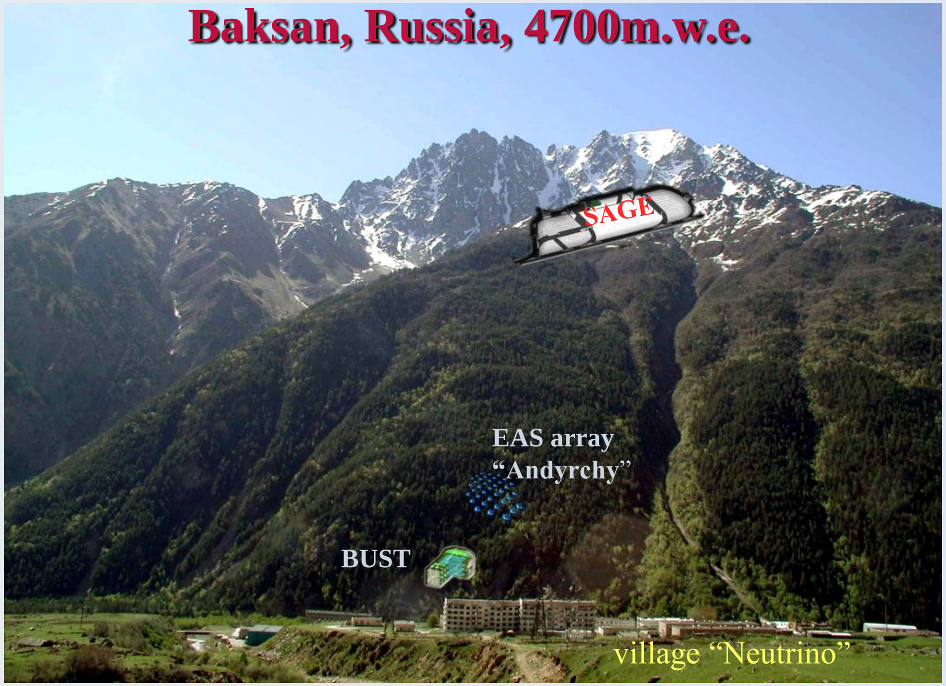
~40 years of the solar neutrino mystery



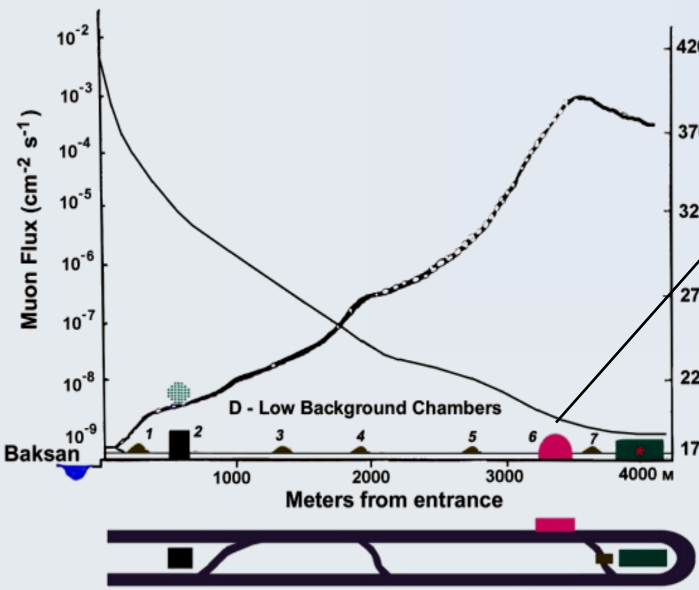


The measured neutrino signal was smaller than predicted by the SSM (~ 53%)

SAGE – 50t Ga metall
Baksan, Russia, 4700m.w.e.



GALLEX/GNO - 30.3t of Ga
Gran Sasso, Italy, 3500m.w.e.



SAGE

50 tons of metallic natural Ga

1990 - 2016, running

259 runs (01.1990 – 10.2016)

Result: **$64.7^{+2.4}_{-2.3}$SNU**

GALLEX/GNO

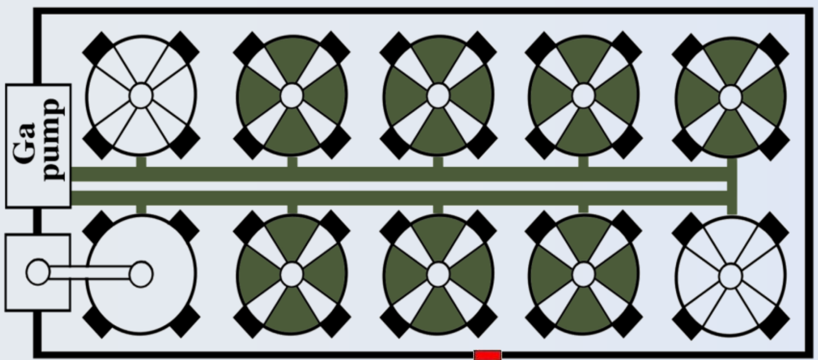
30 tons of natural Ga **(103 tons of $GaCl_3$ acidic solution)**

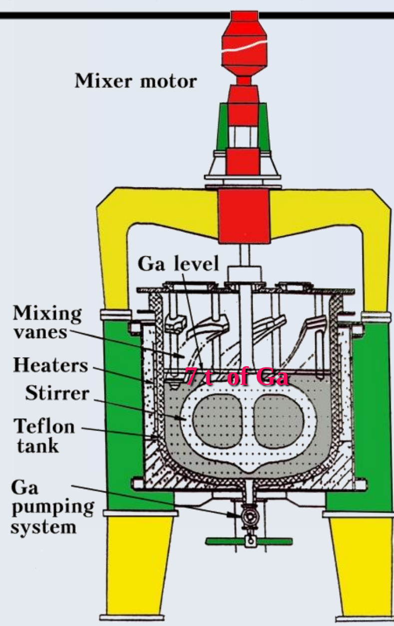
1991 – 2003 finished

123 runs (05.1991 – 04.2003)

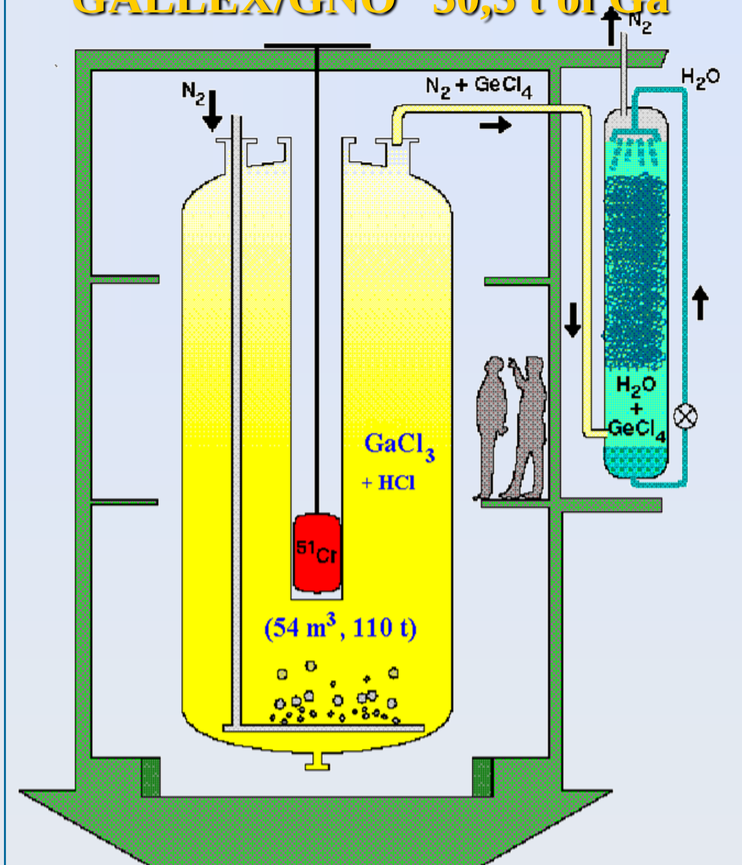
Result: **67.5 ± 5.1 SNU**

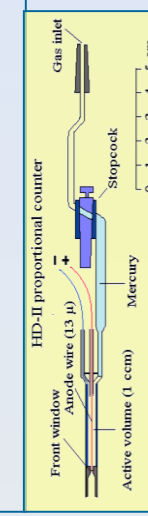
SAGE 50 t of Ga





GALLEX/GNO 30,3 t of Ga

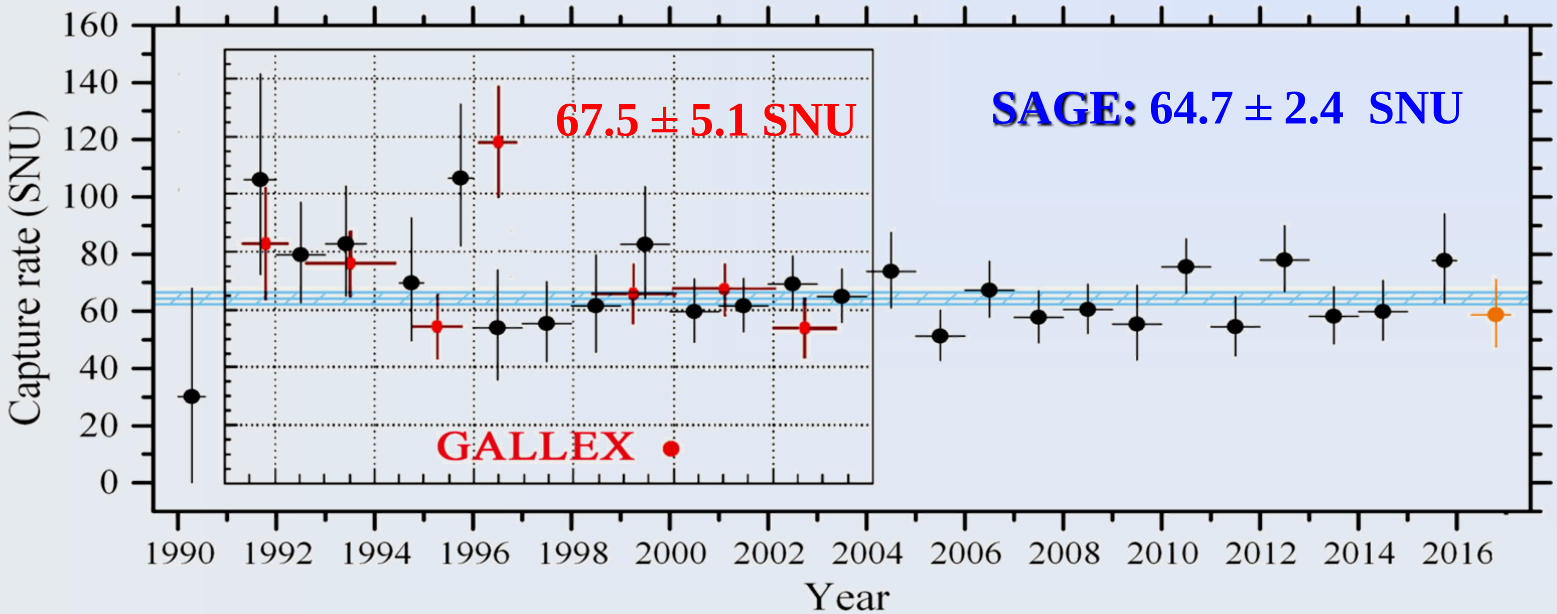




Both experiments are based on chemical technology of extraction a few ^{71}Ge atoms from large amount (tens ton) of Ga target and on technology of counting of ^{71}Ge decay in small proportional counters (less than 1 cm^3)

GALLEX+GNO (1991-2004) & SAGE (1990-2016)

$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$



- a <u>very good agreement between their results</u>. The good agreement between results of the **Ga** experiments has led to increase of their confidence. It was very good that for many years there were two **Ga** experiments, **SAGE** and **GALLEX/GNO**

The weighted average of the results of all Ga experiments is
66.1±3.1 SNU

1 SNU = 1 interaction/s in a target that contains 10^{36} atoms of the neutrino-absorbing isotope

Ga experiments

[*PRC80, 015807 (2009)*]

- **Have shown deficit of solar neutrino in the entire energy range:**

Ga experiments: 66.1 ± 3.1 SNU

SSM (**Ga**): BPS08(GS) (high metallicity) **127.9 ± 8.2 SNU**,
BPS08(AGS) (low metallicity) **120.5 ± 7.0 SNU.**

- **Presented direct experimental evidence of proton-proton chain in reactions of thermonuclear synthesis in the Sun:**

the value of electron ***pp*** *ν flux on the Earth*:

(39.9±5.2)/cross. sec. = (3.40$^{+0.44}_{-0.46}$) × 10^{10} ν_e/(cm^2 s)

- **Have shown the correctness of SSM and LMA solution for neutrino oscillations:**

the value of ***pp*** *ν flux on the Earth* (3.40$^{+0.44}_{-0.46}$) × 10^{10}/(⟨ P^{ee}_i ⟩ = 0.560(1$^{+0.030}_{-0.045}$)) =

(6.1 ± 0.84) × 10^{10} ν_e/(cm^2 s)

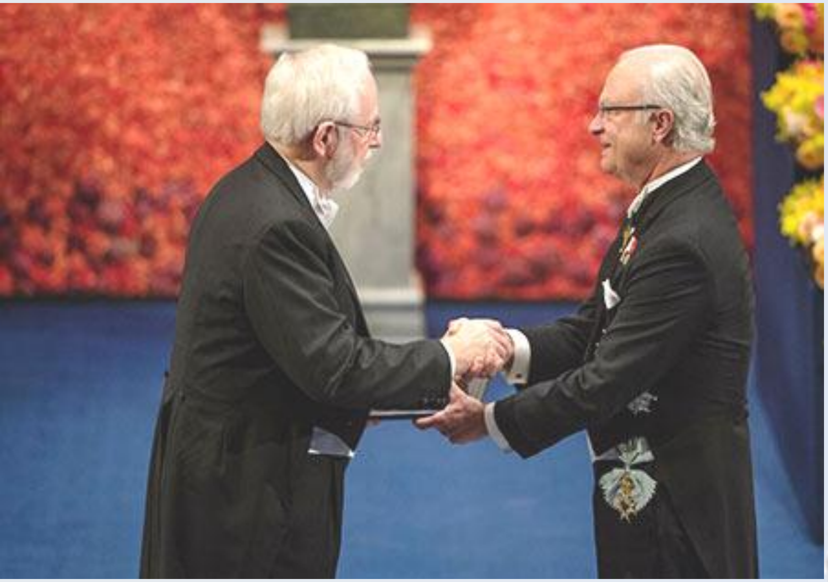
The expected value of ***pp*** *ν flux* predicted by two modern SSMs :
(5.97 ± 0.05) × 10^{10} ν_e/(cm^2 s) (BPS08(GS)), **(6.04 ± 0.05) × 10^{10}** ν_e/(cm^2 s) (BPS08(AGS05))

BOREXINO have measured solar ***pp*** neutrino flux [Nature 512 383 (2014)] :
(6.6 ± 0.7)×10^{10} cm^{-2} s^{-1} – excellent agreement with calculated flux presented above.

Contribution of Ga solar neutrino experiments

Ga solar neutrino experiments have given direct indication on existing of neutrino oscillation and therefore that neutrinos have mass.

The famous SNO experiment have given excellent direct evidence of that.



SNO successfully solved ~40 years of the solar neutrino mystery

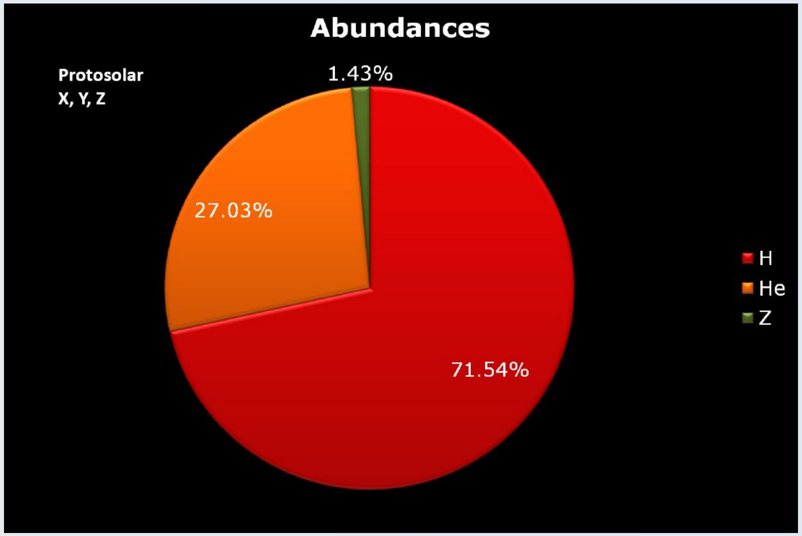
that began from Cl experiment

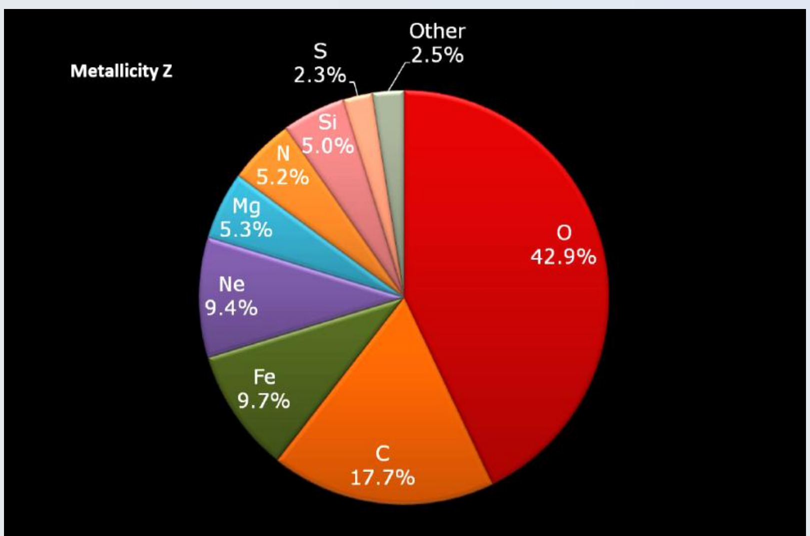
The Nobel Prize in Physics 2015 was awarded to Arthur B. McDonald
"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

New solar neutrino problem

Neutrinos and Solar metallicity

One of the fundamental inputs of the Standard Solar Model is the opportunity to study the metallicity of the Sun – abundance of all elements above helium





The Standard Solar Model based on old (high) metallicity (*Grevesse and Sauval, Space Sci. Rev. 85, 161, 1998*) is in good agreement within 0.5% with the solar speed measured by helioseismology.

Latest work by Asplund, Grevesse and Sauval, (*Nucl. Phys. A 777, 2006*) indicates a metallicity lower by a factor ~2. This result destroys the agreement with helioseismology.

A direct measurement of the CNO neutrinos rate could help to solve the latest controversy surrounding the Standard Solar Model.

Neutrinos and Solar Metallicity

- A direct measurement of the CNO neutrinos rate could help solve the latest controversy surrounding the Standard Solar Model
- One fundamental input of the Standard Solar Model is the metallicity of the Sun - abundance of all elements above Helium
- The Standard Solar Model, based on the old metallicity derived by Grevesse and Sauval (Space Sci. Rev. **85**, 161 (1998)), is in agreement within 0.5% with the solar sound speed measured by helioseismology.
- Latest work by Asplund, Grevesse and Sauval (Nucl. Phys. A **777**, 1 (2006)) indicates a metallicity lower by a factor ~2. This result destroys the agreement with helioseismology
  maybe it was fortuitous agreement before with high metallicity?
- use solar neutrino measurements to help resolve!
  ^{7}Be (12% difference) and CNO (50-60% difference)

Prediction of SSM (BP2000)

Reaction	ν energy (MeV)	ν flux ($cm^{-2}s^{-1}$)	ν capture rate (SNU) Cl	Ga	Li
$p+p \to d+e^{+}+\nu$	0-0.42	$(5.95\pm0.06)\times10^{10}$	0.00	69.7	0.0
$p+e^{-}+p \to d+\nu$	1.44	$(1.40\pm0.02)\times10^{8}$	0.22	2.8	9.2
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Total			$7.6^{+1.3}_{-1.1}$	128^{+9}_{-7}	$52.3^{+6.5}_{-6.0}$

In radiochemical experiments the capture rate has been conventionally expressed in 'SNU units', defined as one neutrino capture per second in a target that contains 10^{36} atoms of the neutrino-absorbing isotope, in our case ^{37}Cl or ^{71}Ga.

Predicted solar neutrino fluxes from solar models.

Source	BPS08(GS)	BPS08(AGS)	Difference
pp	$5.97(1 \pm 0.006)$	$6.04(1 \pm 0.005)$	1.2%
pep	$1.41(1 \pm 0.011)$	$1.45(1 \pm 0.010)$	2.8%
hep	$7.90(1 \pm 0.15)$	$8.22(1 \pm 0.15)$	4.1%
^{7}Be	$5.07(1 \pm 0.06)$	$4.55(1 \pm 0.06)$	10%
^{8}B	$5.94((1 \pm 0.11)$	$4.72(1 \pm 0.11)$	21%
^{13}N	$2.88(1 \pm 0.15)$	$1.89(1\ ^{+0.14}_{-0.13})$	34%
^{15}O	$2.15(1\ ^{+0.17}_{-0.16})$	$1.34(1\ ^{+0.16}_{-0.15})$	31%
^{17}F	$5.82(1\ ^{+0.19}_{-0.17})$	$3.25(1\ ^{+0.16}_{-0.15})$	44%
Cl	$8.46^{+0.87}_{-0.88}$	$6.86^{+0.69}_{-0.70}$	
Ga	$127.9^{+8.1}_{-8.2}$	$120.5^{+6.9}_{-7.1}$	

The table presents the predicted fluxes, in units of 10^{10}(*pp*), 10^{9}(^{7}Be), 10^{8}(*pep*, ^{13}N,^{15}O), 10^{6}(^{8}B,^{17}F), and 10^{3}(*hep*) $cm^{-2}s^{-1}$. Columns 2 and 3 show BPS08 for high and low metalicities; and column 4 the flux differences between the models. [*Carlos Pena-Garay, Aldo Serenelli, arXiv:0811.2424 [astro-ph*]

Lithium Experiment on Solar Neutrinos

In INR the group of A.V. Kopylov develop the project of the lithium-beryllium experiment based on metallic lithium.

[Veretenkin E. et al., Russian J. Atomic Energy. 1985. V. 88. N 1. P. 65],
[A. Kopylov et al., Russian Zhurnal Technicheskoi Fiziki 54 (2009) 1058, (nucl-ex/0910.3889)]

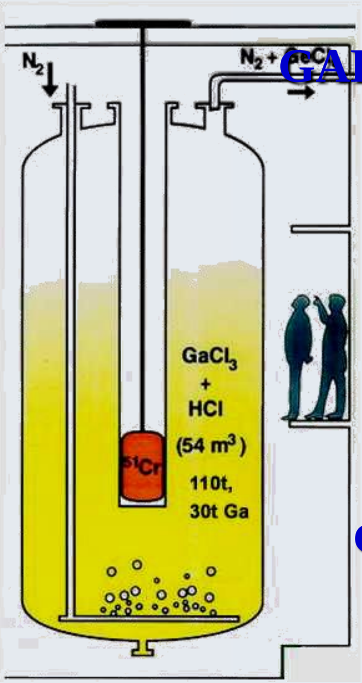
The realization of which in the BNO would solve this new problem.

This could be one more outstanding contribution of radiochemical experiments in our understanding of the physics of the Sun.

Ga sources neutrino experiments

Gallium anomaly

Radioactive sources in gallium solar neutrino exps.: $\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$



GALLEX: $A(Cr_1) = 1.714 \pm 0.036$ MCi; $A(Cr_2) = 1.868 \pm 0.073$ MCi

SAGE: $A(Cr) = 0.517 \pm 0.006$ MCi; $A(Ar) = 0.409 \pm 0.002$ MCi

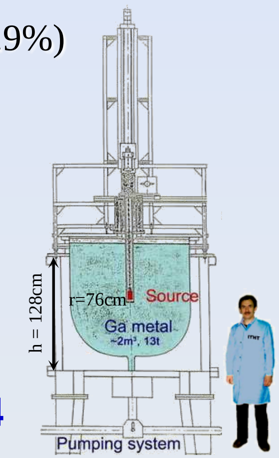
^{51}Cr: 747 keV (81.6%), 427 keV (9.0%), 752 keV (8.5%), 432 keV (0.9%)

^{37}Ar: 811 keV (90.2%), 813 keV (9.8%)

Ratio of measured to predicted [Bahcall 97] rate (R):
(no uncertainty on cross sectection included)

GALLEX: $R_1(Cr) = 0.953 \pm 0.11$; $R_2(Cr) = 0.812 \pm 0.10$

SAGE: $R_3(Cr) = 0.95 \pm 0.12$; $R_4(Ar) = 0.791 \pm 0.084$



Gallex has twice used ^{51}Cr

SAGE has used ^{51}Cr and ^{37}Ar

$$R_{Bahcall} = 0.87 \pm 0.05\ (2.6\sigma)$$

The reason of low result in the source experiments can be :

(1) the capture rate, predicted by Bahcall, can be overestimated (W. Haxton),
(2) statistical fluctuation (probability~5%),
(3) electron neutrinos disappear due to a real physical effect. For example, neutrino oscillations with a transition from active to sterile neutrinos with $\Delta m^2 \sim 1 eV^2$.

РОССИЙСКАЯ АКАДЕМИЯ НАУК
ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ

ИЯИ / INR

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Professor Tadafumi Kishimoto
Director
Research Center for Nuclear Physics
10-1 Mihogaoka, Ibaraki, Osaka
567-0047 JAPAN

July 23, 2008

Dear Professor Kishimoto,

We write to you in an attempt to spark your interest to solve the problem of the discrepancy between experiments and predictions found in neutrino source experiments with Ga.

In the attached file you can find some details about this problem. We would very much appreciate it if you could let us know your opinion regarding this problem and whether or not you believe there may be researchers at your institution who could be interested in experimental work aimed at its resolution.

Sincerely,

Victor Matveev

Academician, Director
Institute for Nuclear Research RAS
Moscow 117312 Russia

for SAGE Collaboration:

Vladimir Gavrin

Professor, Head of Gallium Laboratory
Institute for Nuclear Research RAS
Moscow, 117312 RUSSIA

Bruce Cleveland

Professor
University of Washington
Seattle, WA 98195 USA

江尻宏泰

Research Proposal to the

Research Center for Nuclear Physics,
Osaka University (B-PAC Jan. 2009)
High resolution study of the $^{71\,69}$Ga(^{3}He,t) reactions at 0.42 GeV and GT neutrino responses for $^{71\,69}$Ga

SPOKESPERSONS:

Hidetoshi Akimune (Asociate Professor)
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Remco Zegers (Assistant Professor)
National Superconducting Cyclotron Laboratory,
Michigan State University,
East Lansing, MI 48823, USA.

Consequences of ^{71}Ga(^{3}He, t) ^{71}Ge and Q_{EC} -value measurements:

1. contribution from excited states: 7.2% ± 2.0% (5.1% by Bahcall)(1)

Recent measurement of ^{71}Ga(^{3}He, t)^{71}Ge (At RCNP, Japan)

2. Q_{EC} is close to the value employed by Bahcall(2) :

233.7 ± 1.2 keV (232.7 ± 0.15 keV used by Bahcall)

Penning trap Q-value determination of the ^{71}Ga(ν,e$^-$)^{71}Ge reaction using threshold charge breeding of on-line produced isotopes (at ISAC/TRIUMF Canada)

3. the observed discrepancy is NOT due to any unknowns in Nuclear Physics.

↓

The deficit of neutrinos in the Ga source experiments can be a real physical effect of unknown origin, such as a transition to sterile neutrinos

$$R^{Ga}_{ave\text{-}Frefers} = 0.84 \pm 0.05\ (2.9\sigma)$$

[S Gariazzo, C Giunti, M Laveder, Y F Li, E M Zavanin, arXiv:1507.08204v1 [hep-ph]]

(1) D. Frekers, H. Ejiri, H. Akimune et al., Phys. Lett. B 706, 134 (2011)

(2) D. Frekers, M. C. Simon, C. Andreoiu,et al., Phys. Lett. B 722, 4–5 (2013)

GALLEX:

$R_1(\mathrm{Cr}) = 0.953 \pm 0.11$

$R_2(\mathrm{Cr}) = 0.812 \pm 0.10$

SAGE:

$R_3(\mathrm{Cr}) = 0.95 \pm 0.12$

$R_4(\mathrm{Ar}) = 0.791 \pm 0.084$

R – ratio of the measured production rate to that expected [Bahcall 97] (no uncertainty on cross section included)

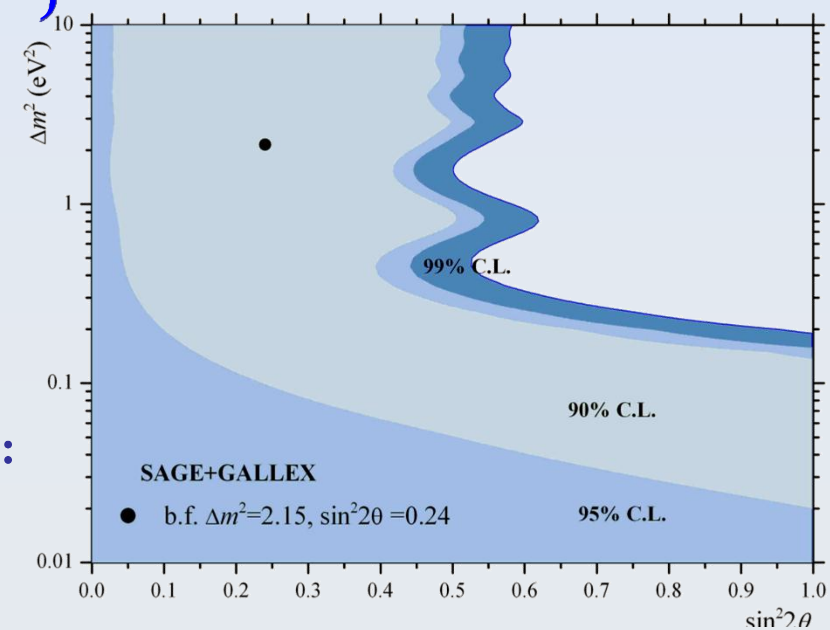
Gallium anomaly - $R_{ave\text{-Bahcall}} = 0.87 \pm 0.05\ (2.6\sigma)$; $R^{Ga}_{ave\text{-Frekers}} = 0.84 \pm 0.05\ (2.9\sigma)$

Region of allowed mixing parameters inferred from 4 gallium source experiments assuming oscillations to a sterile neutrino

$$P_{ee} = 1 - \sin^2 2\theta \cdot \sin^2\left(1.27 \frac{\Delta m^2(eV^2)\cdot L(m)}{E_\nu(MeV)}\right)$$

In Ga experiments: $E_\nu \sim 1$ MeV, $L \sim 1$ m

Oscillations affect the capture rate with $\Delta m^2 \sim 1\ \mathrm{eV}^2$



Limits for oscillation parameters obtained in the four artificial neutrino source experiments: the best-fit point (•) at

$\Delta m^2 = 2.15\ \mathrm{eV}^2$, $\sin^2(2\theta) = 0.24$

$\chi^2/\mathrm{dof} = 1.77/2$, GOF=41%

New neutrino source experiment - BEST

Statistics & systematic of the BEST

Expected ν capture rates from the source in each zone in the absence of oscillation for 10 exposures of 9 days each :

> Total number of the captures in one zone ~ 1650
> Total number of ^{71}Ge pulses in one zone ~ 873

Production rate from solar ν :

[~0.0197 atoms ^{71}Ge/(day – 1 tonne Ga)]

1.18 at. ^{71}Ge in 8 t of Ga, 6.20 at. ^{71}Ge in 42 t of Ga

> Statistical uncertainty: 3.7% in one zone
2.6% in the entire target

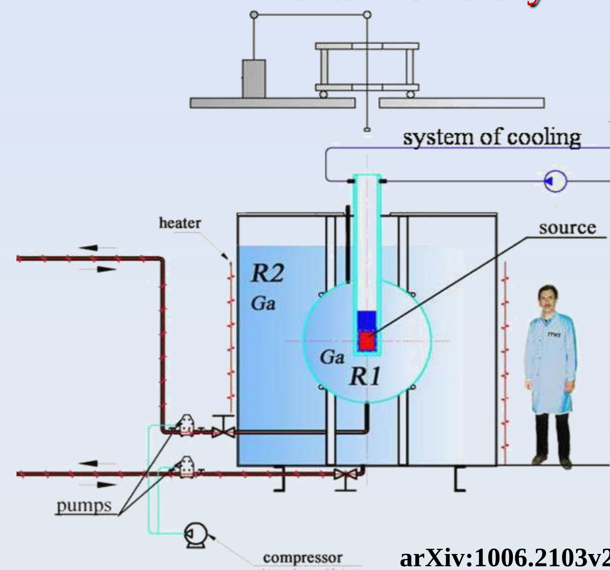
Known systematic effects and their uncertainties:

chemical extraction (±2.3%) & counting of the ^{71}Ge decays (±0.9%) & backgrounds (±0.16%) & source activity (±0.5% - optimistic)

> Total systematic uncertainty : ± 2.6% (close to statistical uncertainty for entire target)

Target: 50 t Ga metall
Masses of the zones: 8 t and 42 t
Path length in each zone: <L> = 55 cm
σ – cross sect.{5.8×10^{-45} cm^2 *[Bahcall]*}

The rate at SOE: 64.5 atoms/day



arXiv:1006.2103v2 [nucl-ex]

> Statistical and systematic uncertainties combined in quadrature :

4.5% in 1 zone
3.7% in the entire target

> With the Bahcall cross section uncertainty:

5.5% and 4.8%

The main advantages of the project BEST

- **A Search for Electron Neutrino disappearance via charged-current (CC) reaction only:**

$$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$$

- **Monochromatic spectrum of compact source – observation of the pure sinusoid of oscillation transitions:**

$$P_{ee} = 1 - \sin^2 2\theta \cdot \sin^2(1.27 \frac{\Delta m^2(eV^2) \cdot L(m)}{E_\nu(MeV)})$$

- **Precisely known intensity of the source.**
- **Independent measurements on two different baselines.**
- **Very Short Baseline.**
- **Almost zero background. Mainly from the Sun.**
  The source, 3 MCi, provides a capture rate in the Ga that will exceed the rate from the Sun by several factors of ten.
- **Very well known experimental procedures developed in SAGE solar measurements .**
- **Simple interpretation of results.**

Realization of the radiochemical experiment BEST could be one more outstanding contribution to our understanding of the neutrino physics.

Back up

THE *pp* NEUTRINO FLUX from Ga

$[pp+^7Be+CNO+pep+^8B|Ga] = 66.1 \pm 3.1$ SNU (from the SAGE and GALLEX/GNO)

$[^7Be|Borexino] = (5.18\pm0.51)\times10^9\ \nu_e/(cm^2\ s) \rightarrow [^7Be|Ga] = 19.1^{+2.3}_{-2.1}$ SNU

$[^8B|SNO] = (1.67\pm0.08)\times10^6\ \nu_e/(cm^2\ s) \rightarrow [^8B|Ga] = 3.6^{+1.2}_{-0.6}$ SNU

$\rightarrow [pp+CNO+pep|Ga]=43.3^{+3.8}_{-4.1}$ SNU [1]

$[^7Be+CNO+pep+^8B|Cl] = 2.56\pm 0.23$ SNU $\rightarrow [^7Be|Cl] = 0.67 \pm 0.07$ SNU

$[^8B|Cl] = 1.73 \pm 0.12$ SNU

$\rightarrow [CNO+pep|Cl] = 0.16^{+0.26}_{-0.16}$ SNU

half of the upper limit of the (CNO|Ga + *pep*|Ga) rates with uncertainty 100% $\rightarrow [CNO+pep|Ga] = 3.44 \pm 3.4$ SNU [2]

measured *pp* capture rate in the Ga experiments: $[pp|Ga] = [1] - [2] =$ **39.9±5.2 SNU**

LMA-MSW included:

pp ν flux on the Earth $(3.40^{+0.44}_{-0.46})\times10^{10}/(\langle P^{ee}_i\rangle = 0.560(1^{+0.030}_{-0.045})) =$ $\mathbf{(6.1\pm0.84)\times10^{10}\ \nu_e/(cm^2\ s)}$ **(14%)**

[*PRC80, 015807 (2009)*]

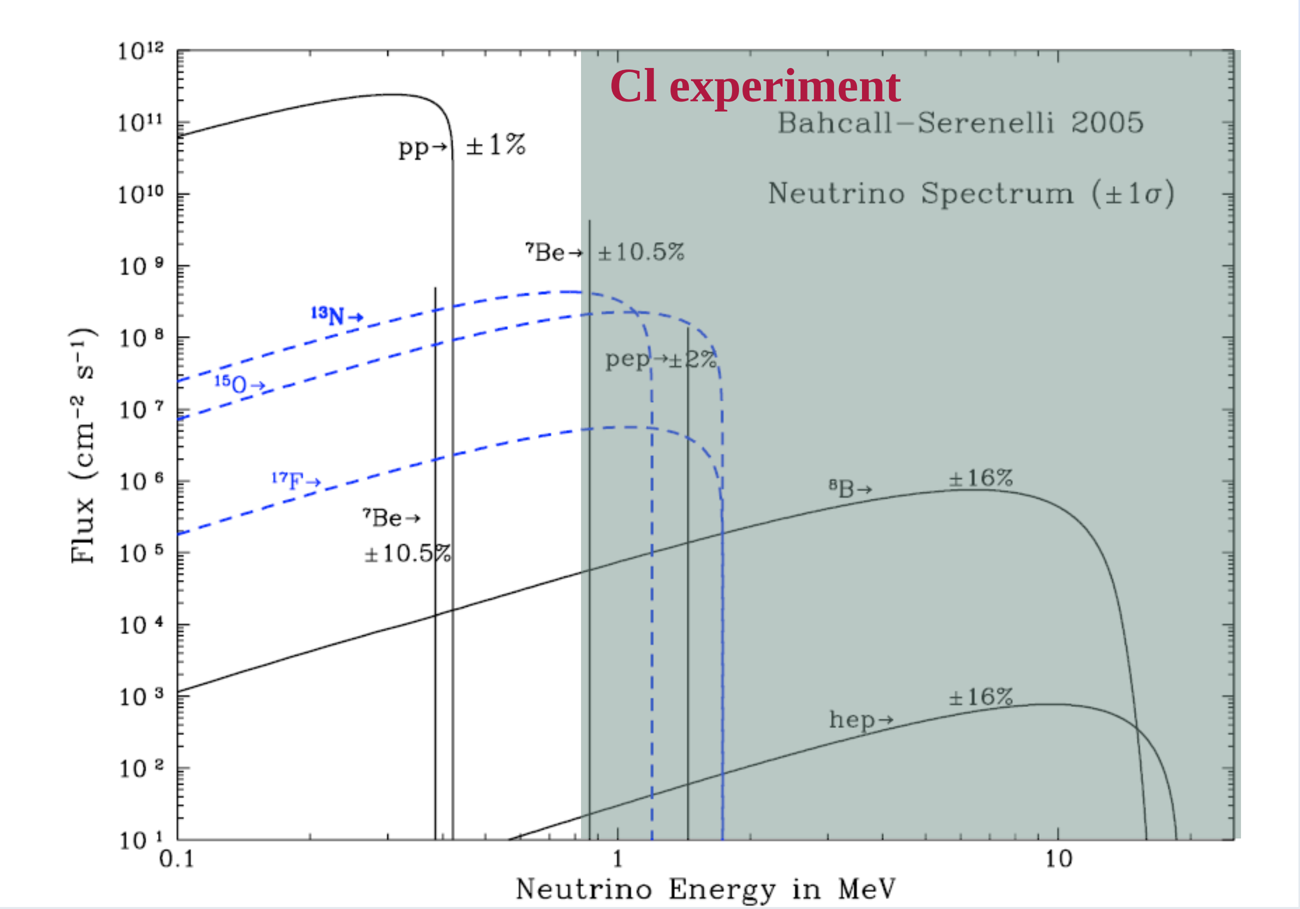
THE *pp* NEUTRINO FLUX from BOREXINO

pp: $(\mathbf{6.6\pm0.7})\times10^{10}\ cm^{-2}\ s^{-1}$ (10.6%)

LMA-MSW included

[*Nature 512 383 (2014)*]

Solar Neutrinos Spectrum



Chemical controversy at the solar surface

2006-2007 improvement

Improved measurements of elemental abundances suggest that something might be wrong with our model of the Sun :

the solar surface contains 30-40% less carbon, nitrogen, oxygen, neon and argon than previously believed.

Asplund et al, astro-ph/0410214

Radiochemical Solar ν Experiments

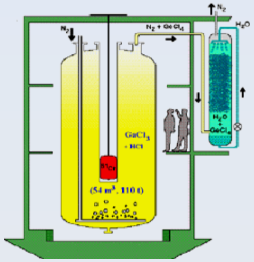
- In the early 1990's, the radiochemical Cl and Ga experiments and Kamiokande were the only operating
- Ga experiments have sensitivity to the low energy Solar *pp*-neutrino
- Ga experiments have shown deficit of solar neutrino in the entire energy range
- Ga experiments firstly presented direct experimental evidence of proton-proton chain in reactions of thermonuclear synthesis in the Sun
- The radiochemical Cl and Ga experiments have been important contributors to the advances in our understanding of ν properties, and in solving the SNP

Homestake 0.34 ± 0.03

The birth of the solar neutrino puzzle

Kamiokande 0.36 ± 0.02

SAGE 0.59 ± 0.06



GALLEX&GNO 0.58 ± 0.05

Not All ν Experiments have worked:

"Unsuccessful" Experiments -

$^{127}I \rightarrow {}^{127}Xe$ ($T_{1/2}$= 36 d, E-threshold = 0.789 MeV)

- **Developed by K. Lande et al. at U Penn to check the well-known Cl deficit**
- **Chemistry used was analogous to the Cl experiment**
- **Novel automated chemistry developed to segregate the product Xe into day and night fractions**
- **Prototype testing was ended when Homestake Mine was shut down after the Barrick Co. purchased the mine and the water pumps were shut down**

PHYSICAL REVIEW C VOLUME 51, NUMBER 5 MAY 1995

What can be learned with an iodine solar-neutrino detector?

J. Engel
…ment of Physics and Astronomy, CB3255, University of North Carolina, Chapel Hill, North Carolina 27599

P. I. Krastev*
Institute for Advanced Study, Princeton, New Jersey 08540

K. Lande
…artment of Astronomy and Astrophysics, University of Pennsylvania, Philadelphia, Pennsylvania 19104
(Received 3 January 1995)

We study the potential benefits of an iodine-based solar-neutrino detector for testing hypotheses that involve neutrino oscillations. We argue that such a detector will have a good chance of distinguishing the two allowed regions of Δm^2-$\sin^2 2\theta$ parameter space if neutrino conversion is occurring in the Sun. It should also be able to detect seasonal variations in the signal due to vacuum oscillations and might be sensitive enough to detect day/night variations due to MSW transitions in the earth. Although it would need to be calibrated, a working iodine detector could be completed long before more ambitious projects that seek to accomplish the same things.

VOLUME 60, NUMBER 9 PHYSICAL REVIEW LETTERS 29 FEBRUARY 1988

Radiochemical Neutrino Detection via $^{127}I(\nu_e, e^-)\,^{127}Xe$

W. C. Haxton
Institute for Nuclear Theory, Department of Physics, University of Washington, Seattle, Washington 98195
(Received 6 October 1987)

Solar or supernova neutrinos incident on an iodine-bearing liquid will produce the noble gas ^{127}Xe ($\tau_{1/2}$ = 36.4 d), which can be recovered and counted as in the present ^{37}Cl experiment. The rate of neutrino reactions per unit volume of detector could be more than an order of magnitude greater than in perchloroethylene. I discuss the new physics that might be learned from such an experiment.

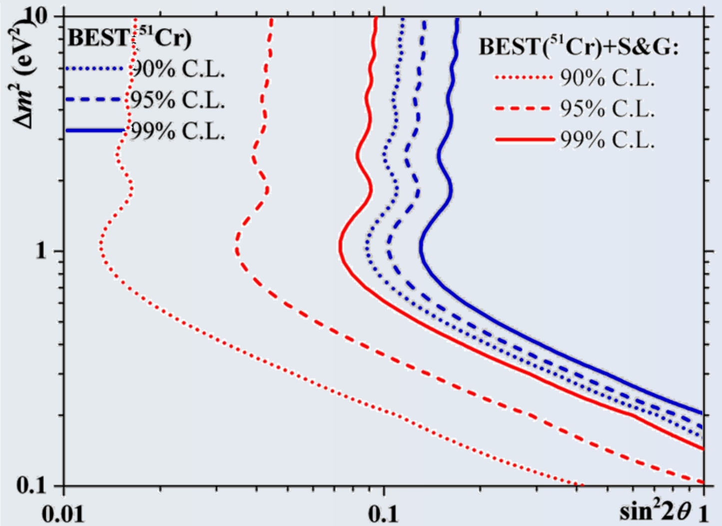
"It seems that the following arrangements of detectors are suitable for a program of solar neutrino spectroscopy; (i) ^{71}Ga, ^{7}Li and ^{37}C1 (^{87}Rb) used in a radiochemical method similar to that of Pontecorvo-Davis (Davis 1964) It seems to us that the most difficult problem is to determine the role of the CNO cycle, while the ^{13}N, ^{15}O neutrinos have not high energy and their flux is probably not intense enough. On the other hand, information about the CNO cycle is rather important as we may find in this way a ^{14}N concentration in the solar centre and probably come to a conclusion about the distribution of heavy elements in the Sun. We should also have more evidence for the existence or absence of a convective core in the solar centre, etc."

SAGE

Ga_{met} ~ 50 tons

Global intensity of muon
$(3.03 \pm 0.19) \times 10^{-9}$ $(cm^2 s)^{-1}$
Fast neutron flux (>3MeV)
$(6.28 \pm 2.20) \times 10^{-8}$ $(cm^2 s)^{-1}$

BEST (^{51}Cr) 3MCi source



The region in Δm^2 - $\sin^2(2\theta)$ space to which BEST(^{51}Cr) will be sensitive

The region in Δm^2 - $\sin^2(2\theta)$ space to which BEST(^{51}Cr) experiment combined with 4 Ga source experiments will be sensitive

Statistics of the experiment

Expected ν capture rates from the source in each zone in the absence of oscillation for 10 exposures of 9 days each :

> Total number of the captures in 1 zone ~ 1650
> Total number of ^{71}Ge pulses in 1 zone ~ 873

Production rate from solar ν : [~0.0197 atoms ^{71}Ge/(day – 1 tonne Ga)]
1.18 at. ^{71}Ge in 8 tonne of Ga,
6.20 at. ^{71}Ge in 42 tonne of Ga

> Statistical uncertainty: 3.7% in 1 zone
2.6% in the entire target

> Total systematic uncertainty : ±2.6%

> Statistical and systematic uncertainties combined in quadrature :

4.5% in 1 zone
3.7% in the entire target

> With the Bahcall cross section uncertainty:

5.5% and 4.8%

Gallium data and sterile neutrinos

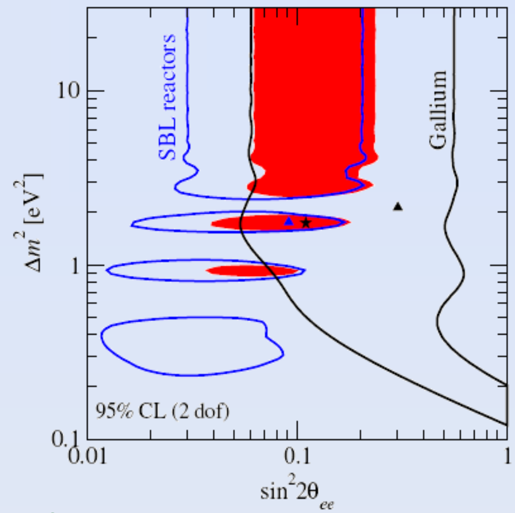
» Gallium + SBL reactor data

$\sin^2 2\theta = 0.11,\ \Delta m^2 = 1.8\ \text{eV}^2$

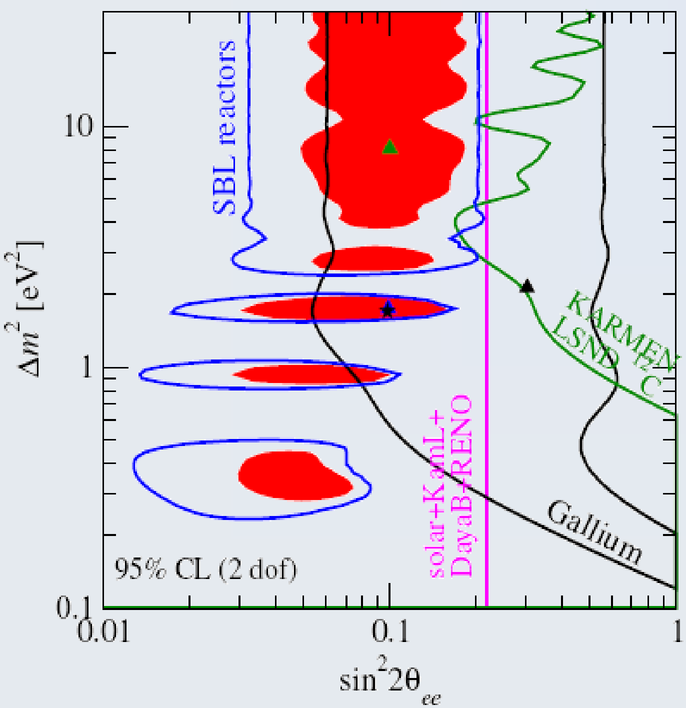
$\chi^2_{min} = 64.0/78\ (P = 87\%)$

$\chi^2_{no\text{-}osc} = 78.0/80\ (P = 54\%)$

$\Delta\chi^2_{no\text{-}osc} = 14.0/2\ (99.9\%\text{CL},\ 3.3\sigma)$



Global ν_e disappearance data



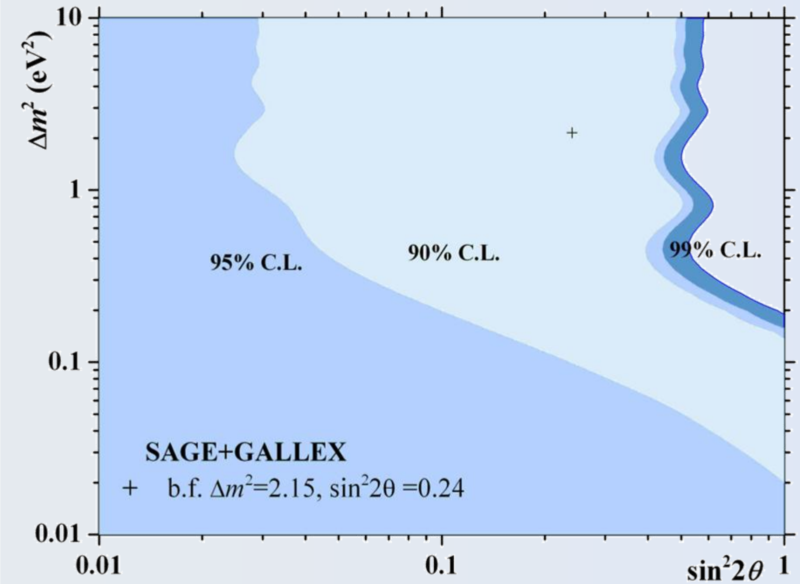
» ν_e disappearance constraints from LSND & KARMEN. LSND and KARMEN measure the cross section for $\nu_e + {}^{12}C \rightarrow {}^{12}N + e^-$ consistent with expectations → limit on ν_e disappearance

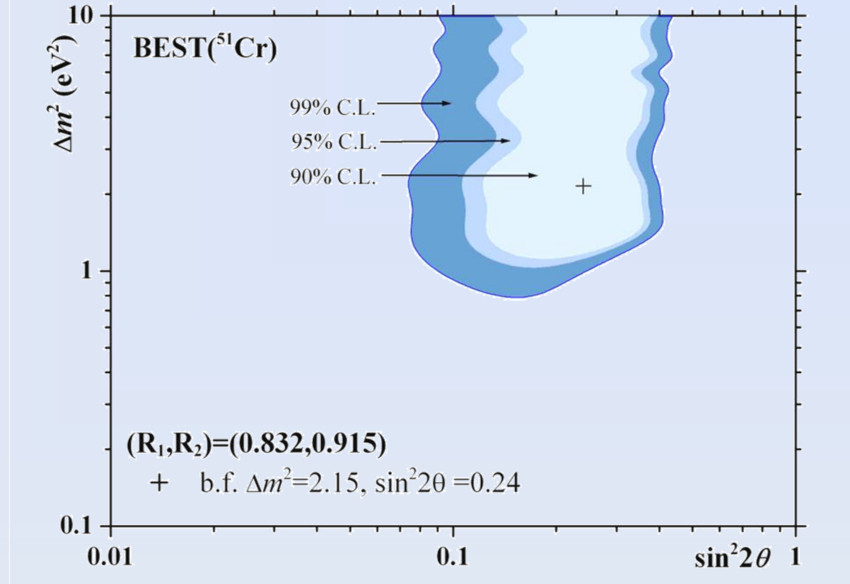
» solar neutrinos.
determination of θ_{13} by reactors leads to a bound on ν_e mixing with eV-scale states from solar + KamLAND

$\sin^2 2\theta = 0.099,\ \Delta m^2 = 1.71\ \text{eV}^2$

$\chi^2_{min} = 306.0/(332\text{-}3),\ \Delta\chi^2_{no\text{-}osc} = 12.4/2\ (99.8\%\text{CL},\ 3.1\sigma)$

[*T. Schwetz, Neutrino2012, Kyoto 6 June 2012*]





Regions of allowed oscillation parameters for possible result of the BEST(^{51}Cr) experiment, and BEST(^{51}Cr) combined with results of 4 previous experiments with sources SAGE and GALLEX (SG) .
"+" sign indicates the best fit point, which is corresponded b.f. SG.
R_1 and R_2 are the ratios of the measured rate to the predicted rate in the inner and outer zones, respectively.