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

V. N. Gavrin
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

*pp*-chain

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

CNO cycle

\[ 12C + p \rightarrow ^{13}N + \gamma \]
\[ ^{13}N \rightarrow ^{13}C + e^+ + \nu_e \]
\[ ^{15}O \rightarrow ^{15}N + e^+ + \nu_e \]
\[ ^{17}F \rightarrow ^{17}O + e^+ + \nu_e \]

>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

\[ L_{\odot} = \sum \Phi_i \cdot \alpha_i, \text{ where} \]
\[ L_{\odot} = L_{\odot} = 3.846 \times 10^{26} \text{ W}, \]
\[ \text{or } 3.846 \times 10^{33} \text{ erg/s} \]

the solar luminosity,

\[ i = pp, pep, ^7\text{Be}, \ldots \]

\[ (6 \times 10^{10} \text{ neutrino cm}^{-2}\text{s}^{-1} \text{ on the Earth}) \]

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 $\nu$ 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.

They are the basis of all neutrino radiochemical experiments
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:

\[ ^{37}\text{Cl}, ^{71}\text{Ga} \text{ and } ^{7}\text{Li} \]

The difficult problem is to determine the role of the CNO cycle, while the \(^{13}\text{N}, ^{15}\text{O}\) 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 \( \nu \) Detection

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

- Huge multi-ton detectors
- Locate deep underground; (p,n) as well as spallation reactions mimic \( \nu \) capture
- Sensitive radiochemical separations of product \((Z+1)\) from target \(Z\):
  - isolate \( \sim 10 \) product atoms from \( \sim 10^{30} \) target atoms
- Purification product, convert to suitable chemical form for high-efficiency, low-background counting of \((Z+1)\) nuclei
- Measured energy spectrum and half-life identify \((A, Z+1)\)
The BNO program of the neutrino spectroscopy of the Sun

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

| 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 $^{37}\text{Cl}$, $^{71}\text{Ga}$, $^7\text{Li}$. 
Radiochemical Solar Neutrino Detectors
\[ \nu_e + (A, Z) \rightarrow e^- + (A, Z+1) \]

\[ \checkmark \ast \quad ^{37}\text{Cl} \rightarrow ^{37}\text{Ar} \quad (T_{1/2} = 35.0 \text{ d}, \ E\text{-threshold} = 0.814 \text{ MeV}) \]

\[ \checkmark \ast \quad ^{71}\text{Ga} \rightarrow ^{71}\text{Ge} \quad (T_{1/2} = 11.4 \text{ d}, \ E\text{-threshold} = 0.233 \text{ MeV}) \]

\[ x \quad ^{127}\text{I} \rightarrow ^{127}\text{Xe} \quad (T_{1/2} = 36 \text{ d}, \ E\text{-threshold} = 0.789 \text{ MeV}) \]

\[ ? \ast \quad ^{7}\text{Li} \rightarrow ^{7}\text{Be} \quad (T_{1/2} = 53 \text{ d}, \ E\text{-threshold} = 0.862 \text{ MeV}) \]

\[ \checkmark = \text{“Successful”}, \ X = \text{“Not successful”}, \ ? = \text{Did not get beyond R&D stage} \]

\[ \ast \ - \text{included to the BNO program of the neutrino spectroscopy of the Sun} \]
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 $^{37}\text{Cl}(\nu,\text{e}^-)^{37}\text{Ar}$ (1946 Pontecorvo, 1949 Alvarez)
- John Bahcall creates SSM and on the basis of the model calculates $\nu$ fluxes
- SU starts the construction of the Baksan Neutrino Observatory INR RAS
- V. Kuzmin suggests the reaction $^{71}\text{Ga}(\nu,\text{e}^-)^{71}\text{Ge}$ for detection of $pp\nu$ as well as artificial $^{51}\text{Cr}$ 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

Homestake Gold Mine (Lead, South Dakota, USA), 1478 m deep, 4200 m.w.e. $\Phi \sim 4\text{m}-2\text{day}$, steel tank, 6.1 m diameter, 14.6 m long ($6\times10^5$ liters), 615 tons of tetrachlorethylene ($\text{C}_2\text{Cl}_4$), $2.16\times10^{30}$ atoms of $^{37}\text{Cl}$ (133 tons).

$^{\nu_e + ^{37}\text{Cl} } \rightarrow ^{37}\text{Ar} + e_-$

$E_{\text{Cl th}} = 0.814\text{ MeV} \rightarrow ^8\text{B}, ^7\text{Be}, \text{pep, hep}$

$R_{\text{exp Cl}} = 2.56 \pm 0.23\text{ SNU} \sim 34\%$ of SSM

$R_{\text{SSM Cl}} = 7.6 \pm 1.3/1.1\text{ SNU}$

The Nobel Prize in Physics 2002 "for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"
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 $^{71}\text{Ga} + \nu_e \rightarrow ^{71}\text{Ge} + e^-$ and thus to provide information to aid in understanding the deficit of neutrinos observed in the $^{37}\text{Cl}$ experiment, in which only about one-third of the solar neutrino capture rate predicted by the standard solar model was detected.
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).

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.

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
Result: $67.5 \pm 5.1$ SNU
Both experiments are based on chemical technology of extraction a few $^{71}\text{Ge}$ atoms from large amount (tens ton) of Ga target and on technology of counting of $^{71}\text{Ge}$ decay in small proportional counters (less than 1 cm$^3$).
a very good agreement between their results. 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 $66.1 \pm 3.1$ SNU

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

- 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 $pp$ flux on the Earth:
  
  $(39.9 ± 5.2) / \text{cross. sec.} = (3.40^{+0.44}_{-0.46}) \times 10^{10} \nu_e / (\text{cm}^2 \text{ s})$

- Have shown the correctness of SSM and LMA solution for neutrino oscillations:
  
  the value of $pp$ flux on the Earth $(3.40^{+0.44}_{-0.46}) \times 10^{10} / \langle P_{\nu e} \rangle = 0.560(1^{+0.030}_{-0.045}) = (6.1 ± 0.84) \times 10^{10} \nu_e / (\text{cm}^2 \text{ s})$

  The expected value of $pp$ flux predicted by two modern SSMs:
  
  $(5.97 ± 0.05) \times 10^{10} \nu_e / (\text{cm}^2 \text{ s})$ (BPS08(GS)), $(6.04 ± 0.05) \times 10^{10} \nu_e / (\text{cm}^2 \text{ s})$ (BPS08(AGS05))

**BOREXINO** have measured solar $pp$ neutrino flux [Nature 512 383 (2014)]:

$(6.6 ± 0.7) \times 10^{10} \text{ cm}^{-2} \text{ s}^{-1}$ – 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.
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
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! $^7\text{Be}$ (12% difference) and CNO (50-60% difference).
Prediction of SSM (BP2000)

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

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

<table>
<thead>
<tr>
<th>Source</th>
<th>BPS08(GS)</th>
<th>BPS08(AGS)</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>(pp)</td>
<td>5.97(1 ± 0.006)</td>
<td>6.04(1 ± 0.005)</td>
<td>1.2%</td>
</tr>
<tr>
<td>(pep)</td>
<td>1.41(1 ± 0.011)</td>
<td>1.45(1 ± 0.010)</td>
<td>2.8%</td>
</tr>
<tr>
<td>(hep)</td>
<td>7.90(1 ± 0.15)</td>
<td>8.22(1 ± 0.15)</td>
<td>4.1%</td>
</tr>
<tr>
<td>(\text{\textsuperscript{7}Be})</td>
<td>5.07(1 ± 0.06)</td>
<td>4.55(1 ± 0.06)</td>
<td>10%</td>
</tr>
<tr>
<td>(\text{\textsuperscript{8}B})</td>
<td>5.94((1 ± 0.11)</td>
<td>4.72(1 ± 0.11)</td>
<td>21%</td>
</tr>
<tr>
<td>(\text{\textsuperscript{13}N})</td>
<td>2.88(1 ± 0.15)</td>
<td>1.89(1</td>
<td>34%</td>
</tr>
<tr>
<td>(\text{\textsuperscript{15}O})</td>
<td>2.15(1)</td>
<td>1.34(1)</td>
<td>31%</td>
</tr>
<tr>
<td>(\text{\textsuperscript{17}F})</td>
<td>5.82(1)</td>
<td>3.25(1)</td>
<td>44%</td>
</tr>
<tr>
<td>Cl</td>
<td>8.46(^{+0.87}_{-0.88})</td>
<td>6.86(^{+0.69}_{-0.70})</td>
<td></td>
</tr>
<tr>
<td>Ga</td>
<td>127.9(^{+8.1}_{-8.2})</td>
<td>120.5(^{+6.9}_{-7.1})</td>
<td></td>
</tr>
</tbody>
</table>
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.


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.:

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

\[
A(\text{Cr}_1) = 1.714 \pm 0.036 \text{ MCl} \\
A(\text{Cr}_2) = 1.868 \pm 0.073 \text{ MCl} \\
A(\text{Cr}) = 0.517 \pm 0.006 \text{ MCl} \\
A(\text{Ar}) = 0.409 \pm 0.002 \text{ MCl}
\]

\[
^{51}\text{Cr}: \quad 747 \text{ keV (81.6%)}, \quad 427 \text{ keV (9.0%)}, \quad 752 \text{ keV (8.5%)}, \quad 432 \text{ keV (0.9%)}
\]

\[
^{37}\text{Ar}: \quad 811 \text{ keV (90.2%)}, \quad 813 \text{ keV (9.8%)}
\]

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

\[
R_1(\text{Cr}) = 0.953 \pm 0.11 \\
R_2(\text{Cr}) = 0.812 \pm 0.10 \\
R_3(\text{Cr}) = 0.95 \pm 0.12 \\
R_4(\text{Ar}) = 0.791 \pm 0.084
\]

Galex has twice used \(^{51}\text{Cr}\)

\[ R_{\text{Bahcall}} = 0.87 \pm 0.05 \ (2.6\sigma) \]

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 \(\Delta m^2 \sim 1\text{eV}^2\).
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

July 23, 2008

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

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 (Associate Professor)
Dept. Physics, Konan University

Hiroyasu Ejiri (Professor EM Visiting Professor)
Research Center for Nuclear Physics, Osaka Univ.
Ibaraki, Osaka 567-0047
Czech Technical University, Praque

Dieter Frekers (Professor)
IKP Univ. Munster Germany

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: $7.2\% \pm 2.0\%$ (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$^{(2)}$: $233.7 \pm 1.2$ keV ($232.7 \pm 0.15$ keV used by Bahcall)
   Penning trap Q-value determination of the $^{71}$Ga($\nu$,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.

\[
R_{ave-Frekers}^{Ga} = 0.84 \pm 0.05 \ (2.9\sigma) \\
\]


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

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

In Ga experiments: \( E_{\nu} \sim 1 \text{ MeV} \)

Oscillations affect the capture rate with \( \Delta m^2 \sim 1 \text{ eV}^2 \)

Limits for oscillation parameters obtained in the four artificial neutrino source experiments: the best-fit point (●) at \( \Delta m^2 = 2.15 \text{ eV}^2 \), \( \sin^2(2\theta) = 0.24 \)

\( \chi^2/\text{dof} = 1.77/2 \), GOF = 41%
New neutrino source experiment - BEST
Statistics & systematic of the BEST

Expected $\nu$ 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 $\sim 1650$
- Total number of $^{71}\text{Ge}$ pulses in one zone $\sim 873$

Production rate from solar $\nu$:

- $1.18$ at. $^{71}\text{Ge}$ in $8$ t of Ga, $6.20$ at. $^{71}\text{Ge}$ 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 ($\pm 2.3\%$) & counting of the $^{71}\text{Ge}$ decays ($\pm 0.9\%$) & backgrounds ($\pm 0.16\%$) & source activity ($\pm 0.5\%$ - optimistic)

- Total systematic uncertainty: $\pm 2.6\%$ (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
$\sigma$ – cross sect. $\{5.8 \times 10^{-45}$ cm$^2$ [$\text{Bahcall}$]\}

The rate at SOE: $64.5$ atoms/day

Statistics & systematic of the BEST

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

- 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 \textit{pp} NEUTRINO FLUX from Ga

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

\[ [^7\text{Be}] | \text{Borexino} ] = (5.18 \pm 0.51) \times 10^9 \nu_e / (\text{cm}^2 \text{ s}) \quad \rightarrow \quad [^7\text{Be}] | \text{Ga} ] = 19.1 \pm 2.3 \text{ SNU} \]

\[ [^8\text{B}] | \text{SNO} ] = (1.67 \pm 0.08) \times 10^6 \nu_e / (\text{cm}^2 \text{ s}) \quad \rightarrow \quad [^8\text{B}] | \text{Ga} ] = 3.6 \pm 1.2 \text{ SNU} \]

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

\[ [\text{CNO} + \text{pep}] | \text{Cl} ] = 0.16 \pm 0.26 \text{ SNU} \]

\[ [^8\text{B}] | \text{Cl} ] = 1.73 \pm 0.12 \text{ SNU} \quad \rightarrow \quad [\text{CNO} + \text{pep}] | \text{Ga} ] = 3.44 \pm 3.4 \text{ SNU} \quad [2] \]

half of the upper limit of the \( \text{CNO} | \text{Ga} + \text{pep} | \text{Ga} \) rates with uncertainty 100%

measured \textit{pp} capture rate in the Ga experiments: \( [\text{pp}] | \text{Ga} ] = [1] - [2] = 39.9 \pm 5.2 \text{ SNU} \)

LMA-MSW included:

\[ \text{\textit{pp} neutrino flux on the Earth} \ (3.40^{+0.44}_{-0.46}) \times 10^{10} / (\langle P_{\nu e} \rangle = 0.560(1^{+0.030}_{-0.045})) = (6.1 \pm 0.84) \times 10^{10} \nu_e / (\text{cm}^2 \text{ s}) \quad (14\%) \]

\[ [\text{PRC80, 015807 (2009)}] \]

THE \textit{pp} NEUTRINO FLUX from BOREXINO

\textit{pp}: \( (6.6 \pm 0.7) \times 10^{10} \text{ cm}^{-2} \text{ s}^{-1} \) (10.6%)

LMA-MSW included

\[ [\text{Nature 512 383 (2014)}] \]
Solar Neutrinos Spectrum

Cl experiment
Bahcall–Serenelli 2005

Neutrino Spectrum (±1σ)

Neutrino Energy in MeV
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.
Not All $\nu$ Experiments have worked:

“Unsuccessful” Experiments -

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

- 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
“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

\( \text{Ga}_{\text{met}} \approx 50 \text{ tons} \)

Global intensity of muon

\( (3.03 \pm 0.19) \times 10^{-9} \text{ (cm}^2\text{s})^{-1} \)

Fast neutron flux (>3MeV)

\( (6.28 \pm 2.20) \times 10^{-8} \text{ (cm}^2\text{s})^{-1} \)
The region in $\Delta m^2 - \sin^2(2\theta)$ space to which BEST($^{51}$Cr) will be sensitive

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

**BEST ($^{51}$Cr) 3M Ci source**

**Statistics of the experiment**

Expected $\nu$ 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 $\sim 1650$
- Total number of $^{71}$Ge pulses in 1 zone $\sim 873$

Production rate from solar $\nu$:

$\nu$ production rate from solar $\nu$: [~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: $\pm 2.6$
- 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

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

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

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

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

Global \( \nu_e \) disappearance data

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

solar neutrinos.
determination of \( \theta_{13} \) by reactors leads to a bound on \( \nu_e \) mixing with eV-scale states from solar + KamLAND

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

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

[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.