The neutrino reaction on $^{71}$Ga:

a) new measurement of the neutrino response of $^{71}$Ge from terrestrial $\nu$'s
b) $^{71}$Ge EC Q-value

PI's: D. Frekers, H. Ejiri, V.N. Gavrin, M.N. Harakeh, J. Dilling

Annika Lennarz

DPG Tagung, Mainz
22. März 2012
Reviewing the issue

**Neutrino flux measured via the $^71\text{Ga}(\nu_e,e^-)^{71}\text{Ge}$ CC-reaction**
- Expected rate after the SSM: $\approx 132$ SNU
- Detected rate (GALLEX/GNO): $67.6\pm4.0$ (stat.) SNU
- Detected rate (SAGE): $65.4+3.1$ SNU
- Confirmed missing flux!

**Calibration with $^{51}\text{Cr}$ ($^{37}\text{Ar}$) terrestrial $\nu$-sources (EC-decay)**

<table>
<thead>
<tr>
<th>$E_\nu$</th>
<th>transition</th>
<th>BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>747.3 keV</td>
<td>K-EC $\rightarrow$ $^{51}\text{V}$ g.s.</td>
<td>81.6 %</td>
</tr>
<tr>
<td>752.1 keV</td>
<td>L-EC $\rightarrow$ $^{51}\text{V}$ g.s.</td>
<td>8.5 %</td>
</tr>
<tr>
<td>427.1 keV</td>
<td>K-EC $\rightarrow$ $^{51}\text{V}^*$ (320)</td>
<td>8.95 %</td>
</tr>
<tr>
<td>432.0 keV</td>
<td>L-EC $\rightarrow$ $^{51}\text{V}^*$ (320)</td>
<td>0.9 %</td>
</tr>
</tbody>
</table>

Low reaction threshold! → Sensitive to pp $\nu$'s
<table>
<thead>
<tr>
<th>Exp.</th>
<th>source</th>
<th>ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>GALLEX</td>
<td>$^{51}\text{Cr-1}$</td>
<td>0.95 ± 0.11</td>
</tr>
<tr>
<td>GALLEX</td>
<td>$^{51}\text{Cr-2}$</td>
<td>0.81 ± 0.11</td>
</tr>
<tr>
<td>SAGE</td>
<td>$^{51}\text{Cr}$</td>
<td>0.95 ± 0.12</td>
</tr>
<tr>
<td>SAGE</td>
<td>$^{37}\text{Ar}$</td>
<td>0.79 ± 0.10</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>$^{51}\text{Cr}, ^{37}\text{Ar}$</td>
<td>0.87 ± 0.05</td>
</tr>
</tbody>
</table>

**Ratio:** # of measured $^{71}\text{Ge}$ atoms
Normalized to # of calculated atoms

**Average** value $\approx 2.5 \sigma$ away from unity

---

**Origin of the discrepancy?**
- Lower detector efficiencies?
- Neutrino cross section?
- Unknown properties of neutrinos?

---

**J. Bahcall:**

**Contribution from excited states:** 5.1 %

$$\sigma\left(^{51}\text{Cr}\right) = \sigma_0\left(^{51}\text{Cr}\right) \left[ 1 + 0.67 \frac{B_1\text{(GT)}}{B_0\text{(GT)}} + 0.22 \frac{B_2\text{(GT)}}{B_0\text{(GT)}} \right]$$

B(GT) values taken from $^{71}\text{Ga(p,n)}^{71}\text{Ge}$ exp. (Krofcheck, Sugarbaker, Rapaport)

**Poor energy resolution!** ($\approx 200$ keV)
Gallium experiments with artificial neutrino sources as a tool for investigation of transition to sterile states

V. N. Gavrin, * V. V. Gorbachev, * E. P. Veretenkin, * and B. T. Cleveland†

20 July 2010

We propose to place a very intense source of $^{51}$Cr at the center of a 50–tonne target of gallium metal that is divided into two concentric spherical zones and to measure the neutrino capture rate in each zone. This experiment can set limits on transitions from active to sterile neutrinos with $\Delta m^2 \approx 1 \text{ eV}^2$ with a sensitivity to disappearance of electron neutrinos of a few percent.

ratio: $\frac{\text{# event outer circle}}{\text{# event inner circle}}$

For $\sin^2 \theta = 0.3$
Extracting the $B(\text{GT})$-strength via the $^{71}\text{Ga}(^{3}\text{He},t)^{71}\text{Ge}$-reaction @ RCNP

$$\frac{d\sigma(q_{tr}=0)}{d\Omega_{\text{GT}}} = \left( \frac{\mu}{\pi \hbar^2} \right)^2 \frac{k_f}{k_i} N_{D_{\sigma T}} |J_{\sigma T}|^2 B(\text{GT})$$

CER sensitive to $B(\text{GT})$ strength

<table>
<thead>
<tr>
<th>$E_x$ [keV]</th>
<th>$J^\pi$</th>
<th>GT</th>
<th>$B(\text{GT})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>g.s.</td>
<td>$1/2^-$</td>
<td>92%</td>
<td>0.0852(40)</td>
</tr>
<tr>
<td>175</td>
<td>$5/2^-$</td>
<td>40%</td>
<td>0.0034(26)</td>
</tr>
<tr>
<td>500</td>
<td>$3/2^-$</td>
<td>87%</td>
<td>0.0176(14)</td>
</tr>
</tbody>
</table>

$^{71}\text{Ga}(^{3}\text{He},t)^{71}\text{Ge}$

E = 420 MeV
$\Delta E = 45$ keV
$\Theta_{\text{c.m.}} = 0.26^\circ$

RCNP
$^{71}$Ga($^3$He, $t$)$^{71}$Ge

$E = 420$ MeV

$\Delta E = 45$ keV

$\Theta_{\text{c.m.}} = 0.26^\circ$
Results

Contribution from the excited states: \(7.2 \pm 2.0\%\)

- 175 keV: \(2.7 \pm 2.0\%\)
- 500 keV: \(4.5 \pm 0.35\%\)

as opposed to 5.1% taken by J. Bahcall

Discrepancy confirmed/slightly increased
Contributions from the excited states do **NOT resolve** the discrepancy

What else could contribute?

What about the \(Q_{EC}\)-value of \(^{71}\text{Ge}\)?

\[
\sigma_0 (^{51}\text{Cr}) = F(\text{atom}) \cdot \frac{1}{ft} \quad ft \propto Q_{EC}^2 \cdot t_{1/2}
\]
How was the $Q_{EC}$-value measured before?

All measurements in context of 17 keV ν!

$EC$ is accompanied by Internal bremsstrahlungs-photon ($1/10^4$)

1. End-point spectrum is sensitive to neutrino mass
2. $Q$-value is determined by end-point energy

$Q_{EC}$-value only side effect!!

PROBLEMS!

1. Lack of precise knowledge about the end-point spectrum near $Q_{EC}$-(E$(K_\alpha)$) $\approx$ 8-10 keV
2. Extremely strong sources needed ($\approx 10^{10} - 10^{11}$ Bq) (thru (n,$\gamma$) activation)
3. Use of external source atomic excitations on the end-point energy!
4. Pile-up issues
5. Background issues after activation?
6. Detector efficiencies need to be know precisely!
$^{71}$Ge $Q_{EC}$-value by Lee at al. (1995)

None of the internal bremsstrahlungs (IB)-EC expmts. were aimed at a precise determination of the $Q_{EC}$-value!!

$Q_{EC}$-value: $232.65 \pm 0.15$ keV

70 mg Ge target irradiated with n’s

$^{71}$Ge activity: 6.5 GBq

external source $\rightarrow$ effect of atomic X-ray de-excitation on the final spectrum??
$^{71}\text{Ge } Q_{EC}$-value by DiGrigorio et al. (1993)

$Q_{EC}$-value: 232.1 ± 0.1 keV
$^{71}\text{Ge } Q_{EC}$-value by Zlimen et al. (1991)

Also in context of the 17 keV neutrino; positive report!!

$Q_{EC}$-value: $229.0 \pm 0.5$ keV
$^{71}\text{Ge} \ Q_{EC}$-value measurement at TRIUMF’s TITAN experiment – **NEW** approach: mass measurement via cyclotron frequencies

- Trap experiment
- Radioactive beam of $^{71}\text{Ge}$
- Mass measurement of $^{71}\text{Ge}$ and $^{71}\text{Ga}$ via cyclotron frequencies
TITAN – TRIUMF’s Ion Traps for Atomic and Nuclear science

1. Radioactive beam provided by ISAC
2. Transfer to EBIT (Charge breeding – creating highly charged ions)
3. Transfer to Penning trap (frequency determination via TOF measurement)
Principle of mass measurement with Penning Traps

1. Single ion injection
2. Confinement by B-field + electrostatic quadrupole field
3. Lorentz force ⇒ oscillation with cyclotron frequency perpendicular to B-field
4. Excitation With $\nu_{RF} = \nu_C$
5. Trap opening & transfer of energy to $E_{kin}$ ⇒ TOF-measurement

Ions oscillate with cyclotron frequency

$$\nu_C = \frac{1}{2\pi} \frac{q}{m} \cdot B$$

**Precision** increases with charge state and number of measurements

**CAVEAT:** HCI ⇒ increase of systematic effects:
1. HCI’s interact with residual gas; i.e. increased damping
2. ion-ion interaction (when more than 1 ion in trap)
EBIT — Electron-Beam Ion Trap

produces and traps highly charged ions (HCl’s) using a high-current (up to 500 mA) e-beam

- Consists of e- gun, trap center, e- collector
- Injected ions are accelerated towards trap center & compressed by B-field
- Radial confinement by e− beam space charge
- Longitudinally by external field
- Ionisation by intense e− beam (500 mA)
- Ions are captured deeper in trap potential with every loss of e−

The electron beam is compressed by a magnetic (Helmholtz) field up to 6T

Creation of highly charged ions (HCl’s) by multiple electron impact
Novel approach: Production of $^{71}$Ga and radioactive $^{71}$Ge

- Ta-target + 50μA, 500MeV p-beam ⇒ produce $^{71}$Ga/$^{71}$Ge ($\approx 10^7 - 10^8$ p/s)
- **Beam-1:** surf. ion. $^{71}$Ga ($\approx 10^7$ p/s)
- **Beam-2:** surf. ion. $^{71}$Ga + laser ionized $^{71}$Ge ($\approx 10^6$ p/s)
- Beam transport to EBIT
- Charge breeding to Ne-like charge states
  - ⇒ **Beam-1:** Ga$^{21+}$
  - ⇒ **Beam-2:** two species: Ga$^{21+}$ and Ge$^{22+}$
- High purity and high isobaric mass separation due to HCI’s
- Assurance of single ion injection (minimize ion-ion interaction) into MPET

3 step photoionization @ TRILIS

Autoionization

- ionization potential: 63,713.24 cm$^{-1}$
- $\lambda = 780.82$ nm
- 51,011.4392 cm$^{-1}$; 4s$^2$4p5p ($^1S_0$)
- $\lambda = 909.85$ nm
- 40,020.5604 cm$^{-1}$; 4s$^2$4p5s ($^1P_1$)
- $\lambda = 253.4$ nm
- 557.1341 cm$^{-1}$; 4s$^2$4p$^2$ ($^3P_1$)
**Typical TOF-resonances for $^{71}$Ga and $^{71}$Ge**

**Excitation frequency versus the TOF**

Minimum of the resonance corresponds to the cyclotron frequency

- **Calculation of atomic mass excess**
- **Stable nucleus ($^{71}$Ga) as reference ($m_2$)**

$$m_1 = \frac{q_1}{q_2} \cdot \frac{\nu_2}{\nu_1} \cdot m_2$$

$Q_{EC}$-value
Double resonance

$Q_{EC}$-value with two species trapped at the same time

$Q_{EC}$-value: $234 \pm 1$ keV

(Preliminary!)

Independent measurement; direct measurement of mass difference

Mass difference close to literature value!

$\Rightarrow Q_{EC}$-value: $234 \pm 1$ keV (Preliminary!)

TRIUMF
Consequences of $Q_{EC}$-value measurement

- $ft \propto Q_{EC}^2 \cdot T_{1/2}$
  $\Rightarrow$ phase space factor for $B_2(GT) \approx 14\%$ lower
- $\Rightarrow \sigma_0(^{51}\text{Cr} - \nu)$ slightly reduced $\Rightarrow$ Only slightly reduced discrepancy

\[
\sigma(^{51}\text{Cr}) = \sigma_0(^{51}\text{Cr}) \left[ 1 + 0.67 \frac{B_1(GT)}{B_0(GT)} + 0.22 \frac{B_2(GT)}{B_0(GT)} \right]
\]

0.66    0.18

Contribution from excited states: 6.3\%
**Conclusion:**

Nuclear physics aspect of the $\nu$ x-section investigated

Contribution from excited states: $7.2\% \pm 2.0\%$ (5.1\% by Bahcall)

⇒ slightly amplifies the discrepancy

2. $Q_{EC}$ is close to J. Bahcall value & reduces @ most contrib.
   from exct. states from 7.2\% to 6.3\%

3. New calculations of phase space factors

---

the observed discrepancy is NOT due to any unknowns in Nuclear Physics!!
Acknowledgements

MANY THANKS TO:

- RCNP facility and members
- D.Frekers
- H.Ejiri
- H.Akimune
- T.Adachi
- B.Bilgier
- B.A.Brown
- B.T.Cleveland
- H.Fujita
- Y.Fujita
- M.Fujiwara
- E.Ganioglu
- V.N.Gavrin
- E.-W.Grewe
- C.J.Guess
- M.N.Harakeh
- K.Hatanaka
- R.Hodak
- C.Iwamoto
- N.T.Khai
- H.C.Kozer
- A.Okamoto
- H.Okamura
- P.P.Povinec
- P.Puppe
- F.Simkovic
- G.Ssoy
- T.Suzuki
- A.Tamii
- J.H.Thies
- J.Van de Walle
- R.G.T.Zegers
- Supported by DFG
Many thanks to the TITAN group at TRIUMF!
THANK YOU FOR YOUR ATTENTION!