

Short-BaseLine Electron Neutrino Disappearance

Carlo Giunti

INFN, Sezione di Torino

NOW 2010, 4-11 September 2010

Collaboration with Marco Laveder (Padova University)

Statistical Significance of the Gallium Anomaly

[arXiv:1006.3244](https://arxiv.org/abs/1006.3244)

Hint of CPT Violation in Short-Baseline Electron Neutrino Disappearance

[arXiv:1008.4750](https://arxiv.org/abs/1008.4750)

Standard Model: Massless Neutrinos

- ▶ Standard Model: $\nu_L, \nu_R^c \implies$ no Dirac mass term

$$\mathcal{L}^D = m^D (\overline{\nu}_L \nu_R + \overline{\nu}_R \nu_L)$$

- ▶ Majorana Neutrino: $\nu^c = \nu$

- ▶ $\nu_R^c = \nu_R \implies$ Majorana mass term

$$\mathcal{L}^M = \frac{1}{2} m^M (\overline{\nu}_L \nu_R^c + \overline{\nu}_R^c \nu_L)$$

- ▶ Standard Model: Majorana mass term **not** allowed by $SU(2)_L \times U(1)_Y$

(no Higgs triplet)

- ▶ Neutrinos are special in the Standard Model: the only **neutral fermions**
- ▶ In extensions of SM neutrinos can mix with non-SM fermions

$$L_{\alpha L} = \begin{pmatrix} \nu_{\alpha L} \\ \alpha_L \end{pmatrix} \quad \tilde{\Phi} = i\sigma_2 \Phi^* = \begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix} \xrightarrow[\text{Breaking}]{\text{Symmetry}} \begin{pmatrix} v/\sqrt{2} \\ 0 \end{pmatrix}$$

$(\alpha = e, \mu, \tau)$

$\overline{L_{\alpha L}} \tilde{\Phi}$ can be coupled to new non-SM chiral fermion fields $f_{\beta R}$

Dirac mass terms $\sim \overline{L_{\alpha L}} \tilde{\Phi} f_{\beta R}$ + Majorana mass terms $\sim \overline{f_{\beta R}^C} f_{\beta R}$

$f_{\beta R}$ are often called **Right-Handed Neutrinos**: $f_{\beta R} \rightarrow \nu_{\beta R}$

- ▶ If $f_{\beta R}$ are light, they are called **Sterile Neutrinos**:

$$\nu_{s\beta L} = f_{\beta R}^C$$

Sterile Neutrinos

- ▶ Sterile means No Standard Model Interactions
- ▶ Obviously no electromagnetic interactions as normal active neutrinos
- ▶ Thus Sterile means No Standard Weak Interactions
- ▶ But Sterile Neutrinos are not absolutely sterile:
 - ▶ Gravitational Interactions
 - ▶ New Non-Standard Interactions of the Physics Beyond the Standard Model which generates the masses of sterile neutrinos
- ▶ Extremely interesting and powerful window on Physics Beyond the SM
- ▶ Active Neutrinos (ν_e, ν_μ, ν_τ) can oscillate into Sterile Neutrinos (ν_s)
- ▶ Observables:
 - ▶ disappearance of Active Neutrinos
 - ▶ indirect evidence through combined fit of data

Solar and Atmospheric Neutrino Oscillations

Solar
 $\nu_e \rightarrow \nu_\mu, \nu_\tau$

Reactor
 $\bar{\nu}_e$ disappearance

(Homestake
 Kamiokande
 GALLEX/GNO & SAGE
 Super-Kamiokande
 SNO
 BOREXino
 (KamLAND))

$\rightarrow \left\{ \begin{array}{l} \Delta m_{\text{SOL}}^2 \simeq 7.6 \times 10^{-5} \text{ eV}^2 \\ \sin^2 \vartheta_{\text{SOL}} \simeq 0.32 \end{array} \right.$

Atmospheric
 $\nu_\mu \rightarrow \nu_\tau$

Accelerator
 ν_μ disappearance

(Kamiokande
 IMB
 Super-Kamiokande
 MACRO
 Soudan-2
 (K2K & MINOS))

$\rightarrow \left\{ \begin{array}{l} \Delta m_{\text{ATM}}^2 \simeq 2.4 \times 10^{-3} \text{ eV}^2 \\ \sin^2 \vartheta_{\text{ATM}} \simeq 0.50 \end{array} \right.$

Two scales of $\Delta m^2 \iff$ Three-Neutrino Mixing

$$\Delta m_{\text{SOL}}^2 = \Delta m_{21}^2 \simeq 7.6 \times 10^{-5} \text{ eV}^2$$

$$\Delta m_{\text{ATM}}^2 \simeq |\Delta m_{31}^2| \simeq |\Delta m_{32}^2| \simeq 2.4 \times 10^{-3} \text{ eV}^2$$

- ▶ New Short-BaseLine Oscillations: $\frac{L}{E} \lesssim 1 \frac{\text{m}}{\text{MeV}} \implies \Delta m_{\text{SBL}}^2 \gtrsim 1 \text{ eV}^2$
- ▶ Necessary introduction of at least one new massive neutrino: 4ν Mixing

$$\Delta m_{\text{SBL}}^2 = \Delta m_{41}^2$$

Mass Basis: $\nu_1 \quad \nu_2 \quad \nu_3 \quad \nu_4$

Flavor Basis: $\nu_e \quad \nu_\mu \quad \nu_\tau \quad \nu_s$

- ▶ Effective SBL Oscillation Probabilities:

$$\text{▶ } P_{\nu_\alpha \rightarrow \nu_\beta}^{\text{SBL}} = \sin^2 2\vartheta_{\alpha\beta} \sin^2 \left(\frac{\Delta m_{\text{SBL}}^2 L}{4E} \right) \quad (\alpha \neq \beta)$$

$$\text{▶ } P_{\nu_\alpha \rightarrow \nu_\alpha}^{\text{SBL}} = 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2 \left(\frac{\Delta m_{\text{SBL}}^2 L}{4E} \right)$$

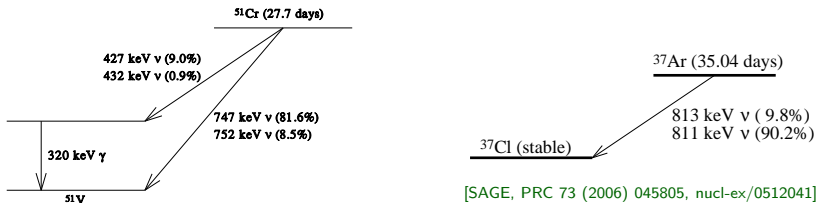
Gallium Anomaly

Gallium Radioactive Source Experiments

Tests of the solar neutrino detectors GALLEX (Cr1, Cr2) and SAGE (Cr, Ar)

Detection Process: $\nu_e + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^-$

ν_e Sources: $e^- + {}^{51}\text{Cr} \rightarrow {}^{51}\text{V} + \nu_e$ $e^- + {}^{37}\text{Ar} \rightarrow {}^{37}\text{Cl} + \nu_e$



[SAGE, PRC 59 (1999) 2246, hep-ph/9803418]

[Giunti, Laveder, arXiv:1006.3244]

$$R_{\text{Ga}} = 0.76_{-0.08}^{+0.09}$$

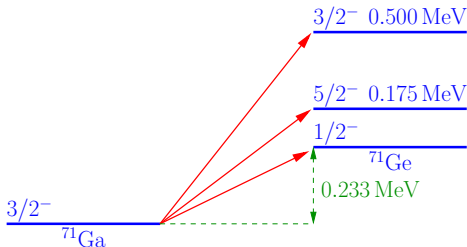
Haxton cross section and uncertainty

[Haxton, PLB 431 (1998) 110, nucl-th/9804011]

- ▶ Deficit could be due to overestimate of

$$\sigma(\nu_e + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^-)$$

- ▶ Calculation: Bahcall, PRC 56 (1997) 3391, hep-ph/9710491



- ▶ $\sigma_{\text{G.S.}}$ related to measured $\sigma(e^- + {}^{71}\text{Ge} \rightarrow {}^{71}\text{Ga} + \nu_e)$:

$$\sigma_{\text{G.S.}}({}^{51}\text{Cr}) = 55.3 \times 10^{-46} \text{ cm}^2 (1 \pm 0.004)_{3\sigma}$$

- ▶ $\sigma({}^{51}\text{Cr}) = \sigma_{\text{G.S.}}({}^{51}\text{Cr}) \left(1 + 0.669 \frac{\text{BGT}_{175 \text{ keV}}}{\text{BGT}_{\text{G.S.}}} + 0.220 \frac{\text{BGT}_{500 \text{ keV}}}{\text{BGT}_{\text{G.S.}}} \right)$

- ▶ Contribution of Excited States only 5%!

► Bahcall:

[Bahcall, PRC 56 (1997) 3391, hep-ph/9710491]

from $p + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + n$ measurements [Krofccheck et al., PRL 55 (1985) 1051]

$$\frac{\text{BGT}_{175 \text{ keV}}}{\text{BGT}_{\text{G.S.}}} < 0.056 \Rightarrow \frac{\text{BGT}_{175 \text{ keV}}}{\text{BGT}_{\text{G.S.}}} = \frac{0.056}{2} \quad \frac{\text{BGT}_{500 \text{ keV}}}{\text{BGT}_{\text{G.S.}}} = 0.146$$

$$3\sigma \text{ lower limit: } \frac{\text{BGT}_{175 \text{ keV}}}{\text{BGT}_{\text{G.S.}}} = \frac{\text{BGT}_{500 \text{ keV}}}{\text{BGT}_{\text{G.S.}}} = 0$$

$$3\sigma \text{ upper limit: } \frac{\text{BGT}_{175 \text{ keV}}}{\text{BGT}_{\text{G.S.}}} < 0.056 \times 2 \quad \frac{\text{BGT}_{500 \text{ keV}}}{\text{BGT}_{\text{G.S.}}} = 0.146 \times 2$$

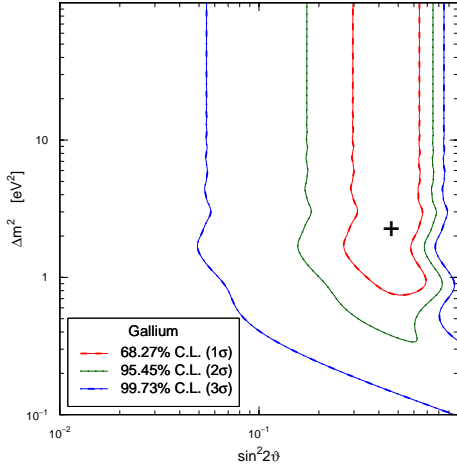
$$\sigma({}^{51}\text{Cr}) = 58.1 \times 10^{-46} \text{ cm}^2 \left(1_{-0.028}^{+0.036} \right)_{1\sigma}$$

► Haxton:

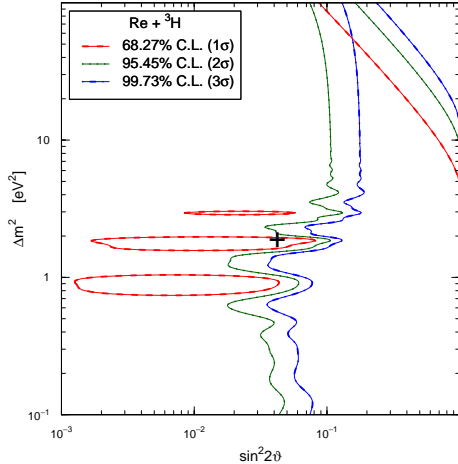
[Hata, Haxton, PLB 353 (1995) 422, nucl-th/9503017; Haxton, PLB 431 (1998) 110, nucl-th/9804011]

“a sophisticated shell model calculation is performed ... for the transition to the first excited state in ${}^{71}\text{Ge}$. The calculation predicts destructive interference between the (p, n) spin and spin-tensor matrix elements.”

$$\sigma({}^{51}\text{Cr}) = 63.9 \times 10^{-46} \text{ cm}^2 (1 \pm 0.106)_{1\sigma}$$



[Giunti, Laveder, arXiv:1006.3244]

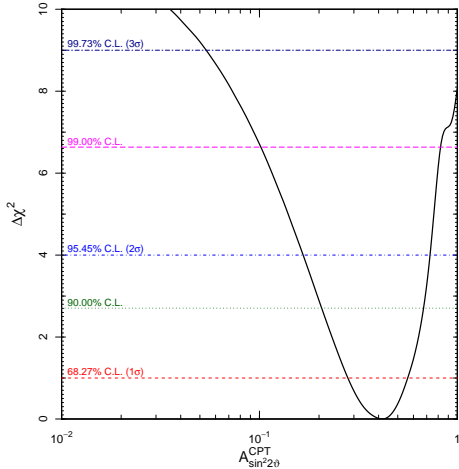
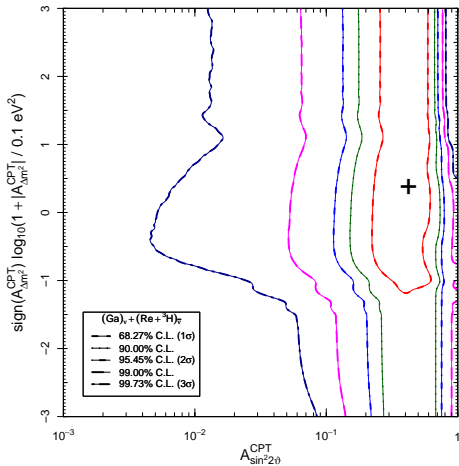


[Giunti, Laveder, arXiv:1005.4599]

$$\Delta m_{\text{SBL}}^2 \gtrsim 1 \text{ eV}^2 \quad \text{is OK}$$

$$\sin^2 2\vartheta_\nu > \sin^2 2\vartheta_{\bar{\nu}} \quad \text{CPT violation?}$$

Parameter Goodness-Of-Fit: $\Delta\chi_{\text{min}}^2 = 12.1$, $\text{NDF} = 2$, $\text{GoF} = 0.2\%$



[Giunti, Laveder, arXiv:1008.4750]

$$A_{\sin^2 2\theta}^{\text{CPT}} = \sin^2 2\vartheta_{\nu} - \sin^2 2\vartheta_{\bar{\nu}}$$

$$(A_{\sin^2 2\theta}^{\text{CPT}})_{\text{bf}} = 0.42$$

$$A_{\Delta m^2}^{\text{CPT}} = \Delta m_{\nu}^2 - \Delta m_{\bar{\nu}}^2$$

$$(A_{\Delta m^2}^{\text{CPT}})_{\text{bf}} = 0.37 \text{ eV}^2$$

$$A_{\sin^2 2\theta}^{\text{CPT}} > 0.055 \text{ at } 3\sigma$$

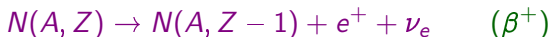
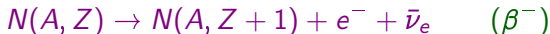
$$A_{\sin^2 2\theta}^{\text{CPT}} > 0 \text{ at } 3.5\sigma.$$

Future

- ▶ New Gallium source experiments: ν_e disappearance [Gavrin et al, arXiv:1006.2103]

- ▶ CPT test: ν_e and $\bar{\nu}_e$ disappearance

- ▶ Beta-Beam experiments:



- ▶ Neutrino Factory experiments:



- ▶ New ν_e and $\bar{\nu}_e$ radioactive source experiments with low-threshold neutrino elastic scattering detectors? (as Borexino or liquid Argon TPC)

Conclusions

- ▶ Gallium Anomaly may be a signal of Short-Baseline ν_e disappearance with $\Delta m^2 \gtrsim 1 \text{ eV}^2$ and $\sin^2 2\vartheta \gtrsim 0.1$
- ▶ Tension with reactor $\bar{\nu}_e$ disappearance limit $\sin^2 2\vartheta \lesssim 0.1$
- ▶ Hint of CPT violation: $A_{\sin^2 2\vartheta}^{\text{CPT}} > 0$ at 3.5σ .
- ▶ Needed high-precision ν_e and $\bar{\nu}_e$ disappearance experiments
- ▶ Short-Baseline ν_e disappearance maybe connected with LSND and MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ signal (work in progress)