Short-BaseLine Electron Neutrino Disappearance

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Statistical Significance of the Gallium Anomaly
arXiv:1006.3244

Hint of CPT Violation in Short-Baseline Electron Neutrino Disappearance
arXiv:1008.4750

Standard Model: Massless Neutrinos

- Standard Model: $\nu_L, \nu_R^c \quad \Longrightarrow \quad$ no Dirac mass term

$$\mathcal{L}^{\text{D}} = m^{\text{D}} \left(\overline{\nu_L} \nu_R + \overline{\nu_R} \nu_L \right)$$

- Majorana Neutrino: $\nu^c = \nu$

- $\nu_R^c = \nu_R \quad \Longrightarrow \quad$ Majorana mass term

$$\mathcal{L}^{\text{M}} = \frac{1}{2} m^{\text{M}} \left(\overline{\nu_L} \nu_R^c + \overline{\nu_R^c} \nu_L \right)$$

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

(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

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

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

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

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

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

- 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 $(\nu_e, \nu_\mu, \nu_\tau)$ 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 $\nu_e \to \nu_\mu, \nu_\tau$	Homestake Kamiokande GALLEX/GNO & SAGE Super-Kamiokande SNO BOREXino	$\to$	$\Delta m^2_{\text{SOL}} \simeq 7.6 \times 10^{-5}\,\text{eV}^2$ $\sin^2\vartheta_{\text{SOL}} \simeq 0.32$
Reactor $\bar{\nu}_e$ disappearance	(KamLAND)		
Atmospheric $\nu_\mu \to \nu_\tau$	Kamiokande IMB Super-Kamiokande MACRO Soudan-2	$\to$	$\Delta m^2_{\text{ATM}} \simeq 2.4 \times 10^{-3}\,\text{eV}^2$ $\sin^2\vartheta_{\text{ATM}} \simeq 0.50$
Accelerator ν_μ disappearance	(K2K & MINOS)		

Two scales of Δm^2 $\Longleftrightarrow$ Three-Neutrino Mixing

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

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

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

$$\Delta m^2_{\text{SBL}} = \Delta m^2_{41}$$

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:
  - $P^{\text{SBL}}_{\nu_\alpha \to \nu_\beta} = \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{\text{SBL}} L}{4E}\right) \qquad (\alpha \neq \beta)$
  - $P^{\text{SBL}}_{\nu_\alpha \to \nu_\alpha} = 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{\text{SBL}} L}{4E}\right)$

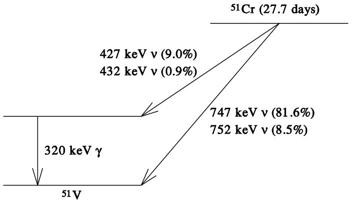
Gallium Anomaly

Gallium Radioactive Source Experiments

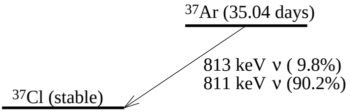
Tests of the solar neutrino detectors GALLEX (Cr1, Cr2) and SAGE (Cr, Ar)

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

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



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



[SAGE, PRC 73 (2006) 045805, nucl-ex/0512041]

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

[Giunti, Laveder, arXiv:1006.3244]

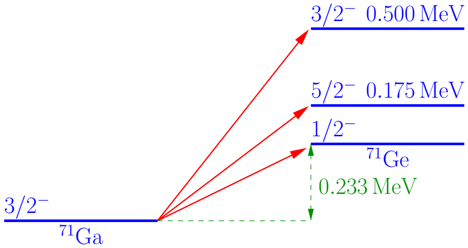
Haxton cross section and uncertainty

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

- Deficit could be due to overestimate of

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

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



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

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

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

- Contribution of Excited States only 5%!

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

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

$$\frac{\mathrm{BGT}_{175\,\mathrm{keV}}}{\mathrm{BGT}_{\mathrm{G.S.}}} < 0.056 \Rightarrow \frac{\mathrm{BGT}_{175\,\mathrm{keV}}}{\mathrm{BGT}_{\mathrm{G.S.}}} = \frac{0.056}{2} \qquad \frac{\mathrm{BGT}_{500\,\mathrm{keV}}}{\mathrm{BGT}_{\mathrm{G.S.}}} = 0.146$$

  3σ lower limit: $\frac{\mathrm{BGT}_{175\,\mathrm{keV}}}{\mathrm{BGT}_{\mathrm{G.S.}}} = \frac{\mathrm{BGT}_{500\,\mathrm{keV}}}{\mathrm{BGT}_{\mathrm{G.S.}}} = 0$

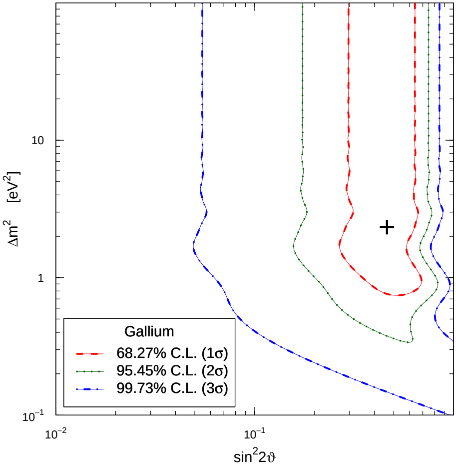
  3σ upper limit: $\frac{\mathrm{BGT}_{175\,\mathrm{keV}}}{\mathrm{BGT}_{\mathrm{G.S.}}} < 0.056 \times 2 \qquad \frac{\mathrm{BGT}_{500\,\mathrm{keV}}}{\mathrm{BGT}_{\mathrm{G.S.}}} = 0.146 \times 2$

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

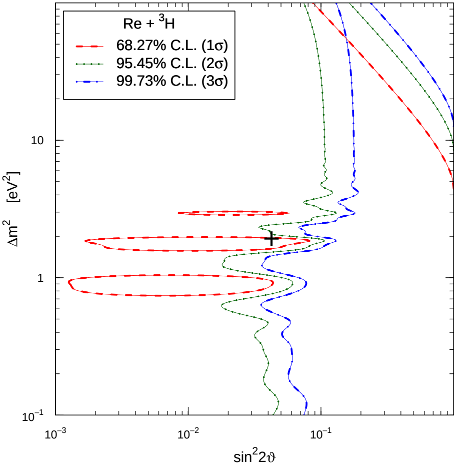
- Haxton: [Hata, Haxton, PLB 353 (1995) 422, nucl-th/9503017; Haxton, PLB 431 (1998) 110, nucl-th/9804011]

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

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



[Giunti, Laveder, arXiv:1006.3244]

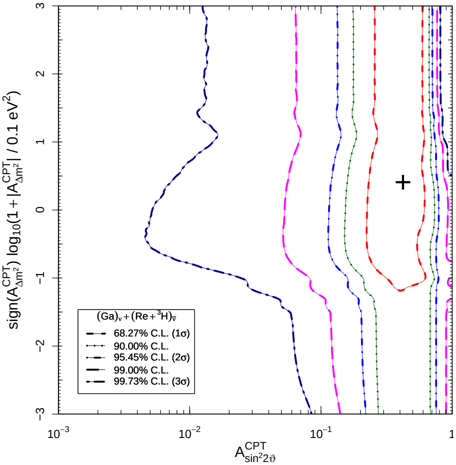


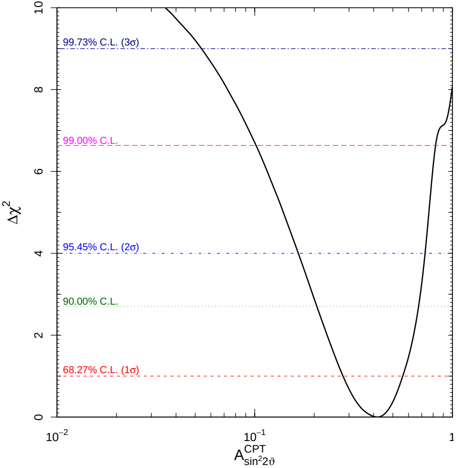
[Giunti, Laveder, arXiv:1005.4599]

$\Delta m^2_{\text{SBL}} \gtrsim 1\,\text{eV}^2$ is OK

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

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





[Giunti, Laveder, arXiv:1008.4750]

$$A^{CPT}_{\sin^2 2\vartheta} = \sin^2 2\vartheta_\nu - \sin^2 2\vartheta_{\bar\nu} \qquad (A^{CPT}_{\sin^2 2\vartheta})_{bf} = 0.42$$

$$A^{CPT}_{\Delta m^2} = \Delta m^2_\nu - \Delta m^2_{\bar\nu} \qquad (A^{CPT}_{\Delta m^2})_{bf} = 0.37\,\mathrm{eV}^2$$

$$A^{CPT}_{\sin^2 2\vartheta} > 0.055 \text{ at } 3\sigma \qquad A^{CPT}_{\sin^2 2\vartheta} > 0 \text{ at } 3.5\sigma.$$

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:

$$N(A,Z) \to N(A,Z+1) + e^- + \bar{\nu}_e \qquad (\beta^-)$$

$$N(A,Z) \to N(A,Z-1) + e^+ + \nu_e \qquad (\beta^+)$$

- Neutrino Factory experiments:

$$\mu^+ \to \bar{\nu}_\mu + e^+ + \nu_e$$

$$\mu^- \to \nu_\mu + e^- + \bar{\nu}_e$$

- 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: $A^{\text{CPT}}_{\sin^2 2\vartheta} > 0$ 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 $\bar{\nu}_\mu \to \bar{\nu}_e$ signal (work in progress)