Hint of CPT Violation in Short-Baseline Electron Neutrino Disappearance

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Standard Model

- Neutrinos are the only massless fermions
- Neutrinos are the only fermions with only left-handed component ν_L

Extension of the SM: Massive Neutrinos

- Simplest extension: introduce right-handed component ν_R
- Neutrinos become massive
- Dirac mass $m_{\text{D}}\overline{\nu_R}\nu_L$ + Majorana mass $m_{\text{M}}\overline{\nu_R^c}\nu_R$
- It is likely that right-handed neutrinos are connected with new physics beyond the Standard Model

Sterile Neutrinos

- Light anti-ν_R are called sterile neutrinos

$$\nu_R^c \to \nu_s \qquad \text{(left-handed)}$$

- Sterile means no standard model interactions
- 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
- Extremely interesting and powerful window on new physics beyond the Standard Model

How many Sterile Neutrinos?

$e^+e^- \to Z \to \nu\bar{\nu} \quad \Rightarrow \quad \nu_e \;\; \nu_\mu \;\; \nu_\tau$ 3 light active flavor neutrinos

mixing $\Rightarrow \quad \nu_{\alpha L} = \sum_{k=1}^{N} U_{\alpha k} \nu_{kL} \qquad \alpha = e, \mu, \tau$

$N \geq 3$
no upper limit!

Mass Basis:	ν_1	ν_2	ν_3	ν_4	ν_5	$\cdots$
Flavor Basis:	ν_e	ν_μ	ν_τ	ν_{s_1}	ν_{s_2}	$\cdots$
		ACTIVE			STERILE	

Solar and Atmospheric Neutrino Oscillations

Solar $\nu_e \to \nu_\mu, \nu_\tau$: Homestake, Kamiokande, GALLEX/GNO & SAGE, Super-Kamiokande, SNO, BOREXino

Reactor $\bar{\nu}_e$ disappearance: (KamLAND)

$\to$ $\Delta m^2_{\text{SOL}} \simeq 7.6 \times 10^{-5}\,\text{eV}^2$, $\sin^2\vartheta_{\text{SOL}} \simeq 0.32$

Atmospheric $\nu_\mu \to \nu_\tau$: Kamiokande, IMB, Super-Kamiokande, MACRO, Soudan-2

Accelerator ν_μ disappearance: (K2K & MINOS)

$\to$ $\Delta m^2_{\text{ATM}} \simeq 2.4 \times 10^{-3}\,\text{eV}^2$, $\sin^2\vartheta_{\text{ATM}} \simeq 0.50$

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: $\dfrac{L}{E} \lesssim 1\,\dfrac{\text{m}}{\text{MeV}} \quad \Longrightarrow \quad \Delta m^2_{\text{SBL}} \gtrsim 1\,\text{eV}^2$

- Necessary introduction of at least one new massive neutrino: 4-ν Mixing

$$\text{Mass Basis: } \nu_1 \quad \nu_2 \quad \nu_3 \quad \nu_4$$

$$\text{Flavor Basis: } \nu_e \quad \nu_\mu \quad \nu_\tau \quad \nu_s$$

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

- Effective SBL Oscillation Probabilities:

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

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

Gallium Anomaly

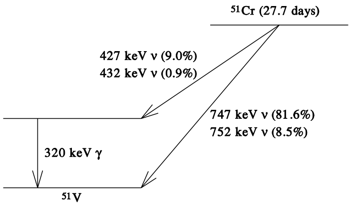
Gallium Radioactive Source Experiments

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

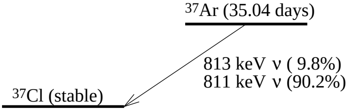
Detection Process: $\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$

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

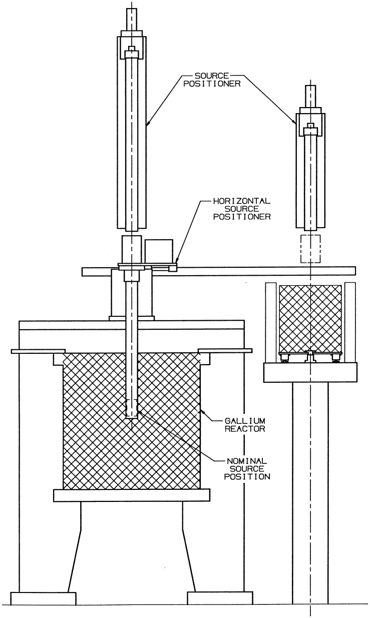
	^{51}Cr				^{37}Ar	
E [keV]	747	752	427	432	811	813
B.R.	0.8163	0.0849	0.0895	0.0093	0.902	0.098



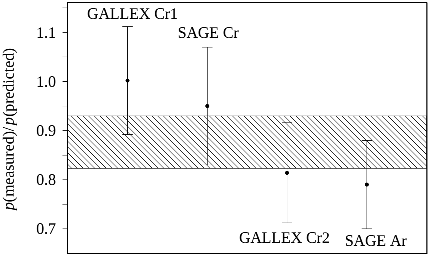
[SAGE, PRC 59 (1999) 2246, hep-ph/9803418]



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



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



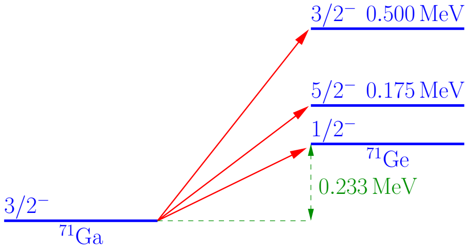
[SAGE, PRC 73 (2006) 045805, nucl-ex/0512041]

$$R_{\text{Ga}} = 0.86 \pm 0.05$$

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

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

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

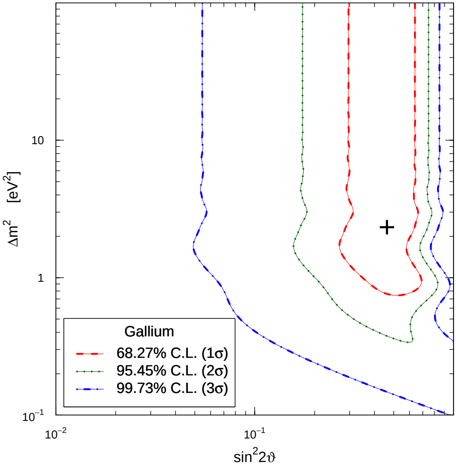
3σ upper limit: $\frac{\text{BGT}_{175\,\text{keV}}}{\text{BGT}_{\text{G.S.}}} < 0.056 \times 2 \qquad \frac{\text{BGT}_{500\,\text{keV}}}{\text{BGT}_{\text{G.S.}}} = 0.146 \times 2$

$$\sigma({}^{51}\text{Cr}) = 58.1 \times 10^{-46}\,\text{cm}^2 \left(1^{+0.036}_{-0.028}\right)_{1\sigma} \Longrightarrow \boxed{R_{\text{Ga}} = 0.86 \pm 0.05}$$

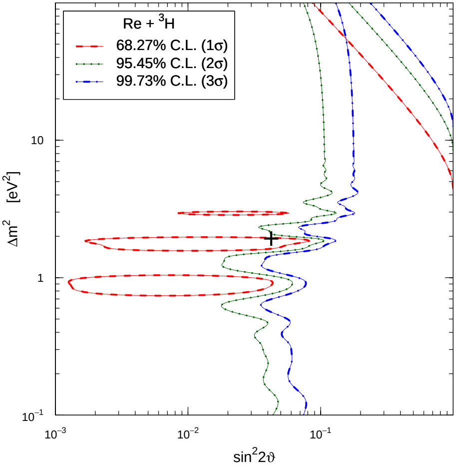
- Haxton: [Hata, Haxton, PLB 353 (1995) 422, nucl-th/9503017; Haxton, PLB 431 (1998) 110, nucl-th/9804011]

  "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."

$$\sigma({}^{51}\text{Cr}) = 63.9 \times 10^{-46}\,\text{cm}^2\,(1 \pm 0.106)_{1\sigma} \Longrightarrow \boxed{R_{\text{Ga}} = 0.76^{+0.09}_{-0.08}}$$



[Giunti, Laveder, arXiv:1006.3244]

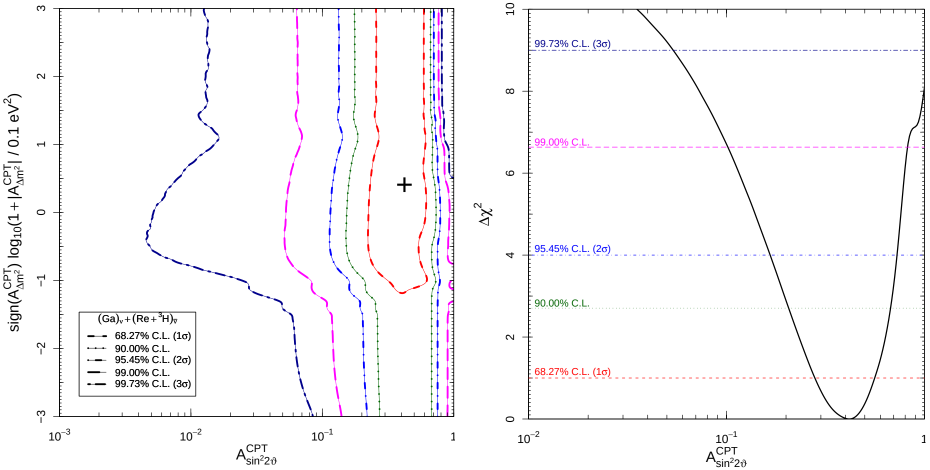


[Giunti, Laveder, PRD 82 (2010) 053005, arXiv:1005.4599]

$\Delta m^2_{\text{SBL}} \gtrsim 1\,\text{eV}^2$ 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, PRD in press, arXiv:1008.4750]

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

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

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

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: [Antusch, Fernandez-Martinez, PLB 665 (2008) 190, arXiv:0804.2820]

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

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

- Neutrino Factory experiments: [Giunti, Laveder, Winter, PRD 80 (2009) 073005, arXiv:0907.5487]

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

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

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

  [Giunti, Laveder, PRD in press, arXiv:1008.4750]

- LENS (Low Energy Neutrino Spectroscopy): [Agarwalla, Raghavan, arXiv:1011.4509]

$$\nu_e + {}^{115}\text{In} \to {}^{115}\text{Sn} + e^- + 2\gamma \qquad E_{\text{th}} = 0.1\,\text{MeV}$$

$$\bar{\nu}_e + p \to n + e^+ \qquad E_{\text{th}} = 1.8\,\text{MeV}$$

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.
- Check needs 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)