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: $\nu_L, \nu_R^c \implies$ 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

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

▶ 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

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

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

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

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

\( f_{\beta R} \) 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 ($\nu_e, \nu_\mu, \nu_\tau$) can oscillate into Sterile Neutrinos ($\nu_s$)

- 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

Atmospheric
\( \nu_\mu \rightarrow \nu_\tau \)

Accelerator
\( \nu_\mu \) disappearance

Two scales of \( \Delta m^2 \) ↔ 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: \( \frac{L}{E} \lesssim 1 \frac{m}{\text{MeV}} \implies \Delta m_{\text{SBL}}^2 \gtrsim 1 \text{eV}^2 \)

Necessary introduction of at least one new massive neutrino: 4-\( \nu \) 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:

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

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

Gallium Radioactive Source Experiments

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

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

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

\[ R_{Ga} = 0.76^{+0.09}_{-0.08} \]

Haxton cross section and uncertainty

[Giunti, Laveder, arXiv:1006.3244]

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

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

[Giunti, Laveder, arXiv:1006.3244]

[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

$$\frac{3}{2}^- 0.500 \text{ MeV}$$

$$\frac{5}{2}^- 0.175 \text{ MeV}$$

$$\frac{1}{2}^-$$

$$^{71}\text{Ge} 0.233 \text{ MeV}$$

$$^{3/2^-} ^{71}\text{Ga}$$

$$\sigma_{\text{G.S.}}$$ 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:
from \( p + ^{71}\text{Ga} \rightarrow ^{71}\text{Ge} + n \) measurements
\[
\frac{\text{BGT}_{175\text{keV}}}{\text{BGT}_{\text{G.S.}}} < 0.056 \Rightarrow \frac{\text{BGT}_{175\text{keV}}}{\text{BGT}_{\text{G.S.}}} = \frac{0.056}{2} \quad \frac{\text{BGT}_{500\text{keV}}}{\text{BGT}_{\text{G.S.}}} = 0.146
\]
3\(\sigma\) 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\(\sigma\) upper limit:
\[
\frac{\text{BGT}_{175\text{keV}}}{\text{BGT}_{\text{G.S.}}} < 0.056 \times 2 \quad \frac{\text{BGT}_{500\text{keV}}}{\text{BGT}_{\text{G.S.}}} = 0.146 \times 2
\]
\[
\sigma(^{51}\text{Cr}) = 58.1 \times 10^{-46} \text{ cm}^2 \left(1^{+0.036}_{-0.028}\right)_1\sigma
\]

Haxton:
“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.”
\[
\sigma(^{51}\text{Cr}) = 63.9 \times 10^{-46} \text{ cm}^2 (1 \pm 0.106)_1\sigma
\]
\[ \Delta m^2_{\text{SBL}} \gtrsim 1 \text{ eV}^2 \quad \text{is OK} \]

\[ \sin^2 2\theta_\nu > \sin^2 2\theta_\nu \quad \text{CPT violation?} \]

Parameter Goodness-Of-Fit: \[ \Delta \chi^2_{\text{min}} = 12.1, \quad \text{NDF} = 2, \quad \text{GoF} = 0.2\% \]
$A_{\sin^2 2\vartheta}^{\text{CPT}} = \sin^2 2\vartheta_\nu - \sin^2 2\vartheta_\bar{\nu}$

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

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

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

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

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

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Future

- New Gallium source experiments: $\nu_e$ disappearance [Gavrin et al, arXiv:1006.2103]
- CPT test: $\nu_e$ and $\bar{\nu}_e$ disappearance
- Beta-Beam experiments:
  \[
  N(A, Z) \rightarrow N(A, Z + 1) + e^- + \bar{\nu}_e \quad (\beta^-) \\
  N(A, Z) \rightarrow N(A, Z - 1) + e^+ + \nu_e \quad (\beta^+) 
  \]
- Neutrino Factory experiments:
  \[
  \mu^+ \rightarrow \bar{\nu}_\mu + e^+ + \nu_e \\
  \mu^- \rightarrow \nu_\mu + e^- + \bar{\nu}_e 
  \]
- New $\nu_e$ 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 $\nu_e$ disappearance with $\Delta m^2 \gtrsim 1$ eV$^2$ and $\sin^2 2\theta \gtrsim 0.1$

- Tension with reactor $\bar{\nu}_e$ disappearance limit $\sin^2 2\theta \lesssim 0.1$

- Hint of CPT violation: $A_{\sin^2 2\theta}^{CPT} > 0$ at $3.5\sigma$.

- Needed high-precision $\nu_e$ and $\bar{\nu}_e$ disappearance experiments

- Short-Baseline $\nu_e$ disappearance maybe connected with LSND and MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ signal (work in progress)