Multiple Probes of Lorentz Violation with Reactor Antineutrinos

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DPF, 8/16/2013

Outline

• Introduction to Double Chooz
• Introduction to Lorentz violation
• A search for a time-dependent oscillation signal
• A search for neutrino-antineutrino mixing
Double Chooz
(The north of France, a few miles from Belgium)
In a \textit{disappearance experiment}, we look for a deficit of antineutrinos.
The last mixing angle

An analysis comparing only the total observed number of IBD candidates in each integration period to the expectations produces a best fit of
\[ \sin^2 2\theta_{13} \equiv \frac{C_{13}^2}{C_{18}} = 0.170 \]
\[ \text{NDF} = 1.052 \]

at
\[ \Delta m^2 = 0.00232 \text{ eV}^2 \]
\[ \chi^2 / \text{d.o.f.} = 42.1 / 35 \]

from fit to two integration periods.

The compatibility probability for the rate-only and rate+shape measurements is about 30% depending on how the correlated errors are handled between the two measurements.

A reprocessing of the data set used for the first Double Chooz publication was performed using the current analysis techniques. A fit using only a single integration period yielded a best-fit value of
\[ \sin^2 2\theta_{13} \equiv \frac{C_{13}^2}{C_{18}} = 0.0744 \]
\[ \text{NDF} = 1.046 \]

with
\[ \Delta m^2 = 0.00131 \text{ eV}^2 \]
\[ \chi^2 / \text{d.o.f.} = 18.3 / 17 \]

An analysis of only the data taken since the first publication yielded a best fit of
\[ \sin^2 2\theta_{13} \equiv \frac{C_{13}^2}{C_{18}} = 0.143 \]
\[ \text{NDF} = 9.54 \]

The data and best-fit spectra for each of these cases is shown in Fig. 16.

Our predicted fission cross section is
\[ 5.723 \pm 0.096 \text{ cm}^2 / \text{fission} \]

using the Bugey4 anchoring measurement and corresponding to the values of \( k \) in Table I.

The background subtracted reactor antineutrino event rate is 7751.9 events, corresponding to 91.85% of the rate expected in the absence of oscillations. Our measured fission cross section is
\[ 5.257 \pm 0.105 \text{ cm}^2 / \text{fission} \]

A further cross-check of the analysis was carried out by imposing cuts to eliminate the vast majority of the cosmogenic isotope background at the cost of reduced livetime. The best-fit case of this analysis was found at
\[ \sin^2 2\theta_{13} \equiv \frac{C_{13}^2}{C_{18}} = 0.109 \]
\[ \Delta m^2 = 0.00232 \text{ eV}^2 \]

in good agreement with the standard analysis.

Confidence intervals for the standard analysis were determined using a frequentist technique. This approach accommodates the fact that the true distributions may vary.

Events/(0.5 MeV)

Energy [MeV]

Events/(0.5 MeV)

(Data - Predicted)

(Data/Predicted)

Energy [MeV]

What is Lorentz violation?

- Lorentz invariance requires that the behavior of a particle is independent of its direction or boost velocity.

- Basically, LV means that the universe has a preferred direction.

- Our SM particles can couple to this background field and create observable effects.

- LV has never been seen.
Neutrino oscillation and LV

If the mass eigenstates have different couplings to a Lorentz violating field, the oscillation pattern will be affected.

Neutrino eigenvalue difference is comparable to the target scale of Lorentz violation (Planck scale)....$<10^{-19}$ GeV

Neutrino oscillations are natural interferometers!
Is there any hope of ever seeing LV with neutrinos?

- First and foremost, “You can’t see if you don’t look”.
- Note that neutrinos generally do not provide the best sensitivity to LV. Measurements of gamma ray burst photons set the best limits.
- Gamma rays from GRBs all seem to arrive at the same time, despite having different energies/frequencies and traveling a very long way.
- Neutrinos are special because they only feel the weak force and thus can avoid QED constraints.
- Neutrinos are also special because we don’t understand them very well.
How to look for it?

- Strange energy dependence (i.e. non-L/E behavior).
- CPT violation (differences between neutrinos and antineutrinos).
- Neutrino-antineutrino mixing.
- Periodicity (in time) of neutrino oscillation.

An example of a sidereal dependence of oscillation probability.
Rate and time

We search for a sidereal modulation among the 8249 electron antineutrino candidates

\[
\text{IBD} = \overline{\nu}_e p \rightarrow e^+ n
\]
What to fit?

The Standard Model Extension (SME) is a framework for all possible types of Lorentz violation and separates the different experimental effects that may be seen.

The full SME equation for electron antineutrino disappearance:

\[
P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} \simeq 1 - P_{\bar{\nu}_e \rightarrow \bar{\nu}_\mu} - P_{\bar{\nu}_e \rightarrow \bar{\nu}_\tau} = 1 - \frac{|(h_{\text{eff}})_{\bar{\nu}_e \bar{\nu}_\mu}|^2 L^2}{(\hbar c)^2} - \frac{|(h_{\text{eff}})_{\bar{\nu}_e \bar{\nu}_\tau}|^2 L^2}{(\hbar c)^2}
\]

\[
= 1 - \frac{L^2}{(\hbar c)^2} \left[ |(C)_{\bar{\nu}_e \bar{\nu}_\mu} + (A_s)_{\bar{\nu}_e \bar{\nu}_\mu} \sin \omega T\oplus + (A_c)_{\bar{\nu}_e \bar{\nu}_\mu} \cos \omega T\oplus + (B_s)_{\bar{\nu}_e \bar{\nu}_\mu} \sin 2\omega T\oplus + (B_c)_{\bar{\nu}_e \bar{\nu}_\mu} \cos 2\omega T\oplus|^2 \right]
\]

\[
- |(C)_{\bar{\nu}_e \bar{\nu}_\tau} + (A_s)_{\bar{\nu}_e \bar{\nu}_\tau} \sin \omega T\oplus + (A_c)_{\bar{\nu}_e \bar{\nu}_\tau} \cos \omega T\oplus + (B_s)_{\bar{\nu}_e \bar{\nu}_\tau} \sin 2\omega T\oplus + (B_c)_{\bar{\nu}_e \bar{\nu}_\tau} \cos 2\omega T\oplus|^2 \right]
\]

Kostelecký & Mewes, PRD 69, 016005 (2004)
Kostelecký & Mewes, PRD 85, 096005 (2012)

contains 28 SME coefficients

10 params.
We perform the following fits:

Assume e-\(\mu\) terms are zero:

\[
P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} \simeq 1 - \frac{L^2}{(\hbar c)^2} \left[ |(C)_{\bar{e}\bar{\tau}} + (A_s)_{\bar{e}\bar{\tau}} \sin \omega_\oplus T_\oplus + (A_c)_{\bar{e}\bar{\tau}} \cos \omega_\oplus T_\oplus + (B_s)_{\bar{e}\bar{\tau}} \sin 2\omega_\oplus T_\oplus + (B_c)_{\bar{e}\bar{\tau}} \cos 2\omega_\oplus T_\oplus |^2 \right]
\]

Assume e-\(\tau\) terms are zero:

\[
P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} \simeq 1 - \frac{L^2}{(\hbar c)^2} \left[ |(C)_{\bar{e}\bar{\mu}} + (A_s)_{\bar{e}\bar{\mu}} \sin \omega_\oplus T_\oplus + (A_c)_{\bar{e}\bar{\mu}} \cos \omega_\oplus T_\oplus |^2 \right]
\]

5 params.

3 params.
Fit technique

- We use a least squares fitting technique to extract the best fit parameters.

$$X^2 = \sum_{ij}^N [r_{i,\text{data}} - P_{\bar{\nu}_e \rightarrow \bar{\nu}_e(t, \text{SME})} \cdot r_{i,\text{MC}}] \cdot M_{ij}^{-1} [r_{j,\text{data}} - P_{\bar{\nu}_e \rightarrow \bar{\nu}_e(t, \text{SME})} \cdot r_{j,\text{MC}}]$$

**Systematics covariance matrix (sidereal)**

<table>
<thead>
<tr>
<th>Source</th>
<th>Variance wrt data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stats.</td>
<td>1.10%</td>
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<tr>
<td>MC correction</td>
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<td>Background</td>
<td>1.69%</td>
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<td>Reactor+detector</td>
<td>1.75%</td>
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<td>Total</td>
<td>2.85%</td>
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</table>
Best fit results

\[ P(\bar{\nu}_e \rightarrow \nu_e) \approx 1 - \frac{L^2}{(\hbar c)^2} \left[ (C) \bar{e}_\mu + (A_s) \bar{e}_\mu \sin \omega \Theta \Theta + (A_c) \bar{e}_\mu \cos \omega \Theta \Theta \right]^2 \]

\[ P(\bar{\nu}_e \rightarrow \nu_e) \approx 1 - \frac{L^2}{(\hbar c)^2} \left[ |(C) \bar{e}_\tau + (A_s) \bar{e}_\tau \sin \omega \Theta \Theta + (A_c) \bar{e}_\tau \cos \omega \Theta \Theta \right. \\
\left. + (B_s) \bar{e}_\tau \sin 2\omega \Theta \Theta + (B_c) \bar{e}_\tau \cos 2\omega \Theta \Theta |^2 \right] \]
Is oscillation probability independent of time?

A frequentist study is used to determine the significance of the results.

\[ \Delta \chi^2 = \chi^2 \text{(1 parameter fit)} - \chi^2 \text{(3 parameter fit)} \]

Fake data \( \Delta \chi^2 \) distribution

4180/9999 flatness

Data \( \Delta \chi^2 \) is in the middle of the fake data \( \Delta \chi^2 \) distribution. In other words, the data is consistent with a flat hypothesis.

No Lorentz violation is seen!
Limits on SME coefficients

With no sidereal time dependence apparent, we proceed to set limits on the relevant SME coefficients

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
SME coefficients & $e - \tau$ fit & $e - \mu$ fit \\
\hline
$\text{Re}(a_L)^T$ or $\text{Im}(a_L)^T$ & $7.8 \times 10^{-20}$ GeV & \text{---} \\
$\text{Re}(a_L)^X$ or $\text{Im}(a_L)^X$ & $4.4 \times 10^{-20}$ GeV & $1.6 \times 10^{-21}$ GeV \\
$\text{Re}(a_L)^Y$ or $\text{Im}(a_L)^Y$ & $9.0 \times 10^{-20}$ GeV & $6.1 \times 10^{-20}$ GeV \\
$\text{Re}(a_L)^Z$ or $\text{Im}(a_L)^Z$ & $2.7 \times 10^{-19}$ GeV & \text{---} \\
$\text{Re}(c_L)^{XY}$ or $\text{Im}(c_L)^{XY}$ & $3.4 \times 10^{-18}$ & \text{---} \\
$\text{Re}(c_L)^{XZ}$ or $\text{Im}(c_L)^{XZ}$ & $1.8 \times 10^{-17}$ & \text{---} \\
$\text{Re}(c_L)^{YZ}$ or $\text{Im}(c_L)^{YZ}$ & $3.8 \times 10^{-17}$ & \text{---} \\
$\text{Re}(c_L)^{XX}$ or $\text{Im}(c_L)^{XX}$ & $3.9 \times 10^{-17}$ & \text{---} \\
$\text{Re}(c_L)^{YY}$ or $\text{Im}(c_L)^{YY}$ & $3.9 \times 10^{-17}$ & \text{---} \\
$\text{Re}(c_L)^{ZZ}$ or $\text{Im}(c_L)^{ZZ}$ & $4.9 \times 10^{-17}$ & \text{---} \\
$\text{Re}(c_L)^{TT}$ or $\text{Im}(c_L)^{TT}$ & $1.3 \times 10^{-17}$ & \text{---} \\
$\text{Re}(c_L)^{TX}$ or $\text{Im}(c_L)^{TX}$ & $5.2 \times 10^{-18}$ & \text{---} \\
$\text{Re}(c_L)^{TY}$ or $\text{Im}(c_L)^{TY}$ & $1.1 \times 10^{-17}$ & \text{---} \\
$\text{Re}(c_L)^{TZ}$ or $\text{Im}(c_L)^{TZ}$ & $3.2 \times 10^{-17}$ & \text{---} \\
\hline
\end{tabular}
\caption{Upper limits on each individual SME coefficient.}
\end{table}

2σ limits
# Neutrino coverage of LV

Current coverage of renormalizable SME coefficients \( (d = 3, 4) \)

(CPT-odd) \( (a_{\text{eff}}^{(3)})_{jm}^{ab} \)

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(CPT-even) \( (c_{\text{eff}}^{(4)})_{jm}^{ab} \)

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This result

From J. Diaz

- Double Chooz/LSND/MiniBooNE/MINOS ND
- Double Chooz
- MINOS FD/IceCube
- Unexplored

Joshua Spitz

MIT
Physics statements

- Double Chooz’s second publication disappearance result by itself rules out a number of alternative oscillation models motivated by Lorentz violation.

- Double Chooz finds no evidence of Lorentz violation. We set the first limits on fourteen of the SME coefficients associated with e-tau transitions and set two competitive limits on coefficients associated with e-mu transitions.
A search for neutrino-antineutrino oscillations

(work with J. Diaz, T. Katori, and J. Conrad)


• Lorentz violation can lead to the coupling of neutrinos and antineutrinos.

• Neutrino-antineutrino mixing would lead to enhanced disappearance as well as an unconventional energy dependence of the events.

\[
P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = P_{\bar{\nu}_e \rightarrow \bar{\nu}_e}^{(0)} - P_{\bar{\nu}_e \rightarrow \nu_x}^{(2)}
\]

\[
1 - \sin^2 2\theta_{13} \sin^2 (1.267 \Delta m^2_{\text{atm}} L/E)
\]

(conventional mass-based oscillations)

has terms containing E and E^2
Double Chooz spectral info

- We explore the possibility that the observed reactor antineutrino disappearance in Double Chooz may have two components: mass-based oscillations and neutrino-antineutrino oscillations due to Lorentz violation.

- Double Chooz has provided a public data release which includes energy spectra data, prediction, and background(s). Covariance matrices and software to analyze the information are also given.

http://doublechooz.in2p3.fr/Scientific/Data_release
What to fit?

\[ P_{\bar{\nu}_e \rightarrow \nu_x}^{(2)} = L^2 \left| \sum_{c=e,\mu\tau} \sum_{d=\bar{e},\bar{\mu}\bar{\tau}} (\mathcal{M}_{x\bar{e}}^{(1)})_{cd} \delta h_{cd} \right|^2 \]

Factors depend on conventional oscillation parameters as well as experimental parameters including location, orientation, baseline, and energy.

\[ \delta h_{cd} = C_{cd}^{(0)} + C_{cd}^{(1)} E \]

Encodes the coefficients controlling Lorentz Violation; parameterized as:

A fit to the energy spectrum can potentially distinguish between L/E (mass-based) oscillations and (LV) oscillations that grow with \( E^2 \).
The fit

- The technique is basically identical to the sidereal-time one. We employ a least squares fitting technique for comparing the Monte Carlo prediction plus background expectation and the data and extracting the best fit parameters.

- After minimization, a confidence region map is formed and then checked with a frequentist study.

- Six different fits are performed, for each of the $c\bar{d}$ terms.
Results

- We find no evidence for Lorentz violating neutrino-antineutrino oscillations.
- We set limits on 15 previously unexplored SME coefficients.
- This work completes the coverage of operators in the minimal SME producing neutrino-antineutrino mixing.

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<td>$g_{\mu\mu}$</td>
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<td>$g_{\tau\tau}$</td>
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<td>$H_{e\mu}$</td>
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<td>$H_{\mu\tau}$</td>
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<td>$H_{\mu\tau}$</td>
<td>$1.5 \times 10^{-15}$</td>
<td>$H_{\mu\tau}$</td>
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Limits at 90% C.L. for the 15 independent SME coefficients that produce neutrino-antineutrino oscillations. The coefficients for CPT-conserving Lorentz violation $H^{Z}_{c\bar{d}}$ are given in units of GeV and the coefficients for CPT-violating Lorentz violation $g^{\alpha\beta}_{c\bar{d}}$ are dimensionless.
Last words

• As a community, we have lots of neutrinos and antineutrinos in the book. Let’s spend some (perhaps small) fraction of our time (thoroughly) looking for the unexpected.

• Maybe our proton decay $\theta_{13}$ experiment(s) will discover neutrino oscillations Lorentz violation. Supernova Sterile neutrinos wouldn’t be so bad either.

Joshua Spitz

MIT
Spokesperson: H. de Kerret (IN2P3)  
Project Manager: Ch. Veyssière (CEA-Saclay)  
Web Site: www.doublechooz.org/
\[ P_{\bar{\nu}_e \to \bar{\nu}_e} \simeq 1 - \frac{L^2}{(\hbar c)^2} \left( (C)_{\bar{e}T}^2 + (C)_{\bar{e}\mu}^2 \right) \]

A normalization-only fit finds \((C)_{\bar{e}T}^2 + (C)_{\bar{e}\mu}^2 = 34.2 \pm 9.2\)

Generally we interpret the sidereal time independent disappearance observed (consistent with the Double Chooz second publication) as due to \(\theta_{13}\) in the 3 flavor neutrino oscillation framework rather than LV.

\(\theta_{13}\) and Lorentz violation

All measured time dependent parameters are consistent with zero. However, the time independent parameter is non-zero at 2.1 sigma.
Three parameter fit

The time dependent parameters are consistent with zero.

The time independent parameter is non-zero at 2.1 sigma.

\[ P_{\tilde{\nu}_c \to \tilde{\nu}_c} \approx 1 - \frac{L^2}{(\hbar C)^2} \left[ |(C)_{e\mu} + (A_s)_{e\mu} \sin \omega T + (A_c)_{e\mu} \cos \omega T|^2 \right] \]
Rate and (solar) time