MSW Oscillations - LMA and Subdominant Effects

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Outline

- Standard LMA solution: basic features
- Subdominant effects: status and prospects
  - 3-ν oscillations (briefly)
  - Searching for non-standard ν interactions
  - Searching for ν magnetic moments
- Solar neutrinos must be considered together with atmospheric, reactor, and ν beam experiments + astrophysics/colliders
  - Precision neutrino physics → important mode of searching for new physics
- By no means exhaustive; not considered here
  - effects of density fluctuations (negligible)
  - sterile neutrinos
  - neutrino couplings to hypothetical light scalars
  - ...

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How does LMA work?

- $^8\text{B}$ survival probability is $\sim 30\%$, approx. flat in $E_{\nu} + \text{day/night is small}$
- **GALLIUM** experiments see about $54\%$ of the SSM prediction $\rightarrow$ survival probability must be higher for low energy $pp$ neutrinos
Adiabatic survival probability

\[ p_{ee}^{AD} = \cos^2 \theta_{\odot} \cos^2 \theta + \sin^2 \theta_{\odot} \sin^2 \theta \]

Two limits:

- **Matter dominates** $\Delta m^2/2E < 2^{1/2}G_F N_{\odot} \Rightarrow \theta_{\odot} \rightarrow \pi/2$
  \[ \Rightarrow p_{ee} \rightarrow \sin^2\theta \]

- **Vacuum dominates** $\Delta m^2/2E > 2^{1/2}G_F N_{\odot} \Rightarrow \theta_{\odot} \rightarrow \theta$
  \[ \Rightarrow p_{ee} \rightarrow \cos^4\theta + \sin^4\theta = 1 - (\sin^2 2\theta)/2 \geq 1/2 \]

averaged vacuum oscillations
Designing LMA

- Fine-tune $\Delta m^2$ such that the transition between the regimes occurs at the intermediate solar energies $\Delta m^2 \sim G_F N_\odot (10^6 \text{eV}) \sim \text{a few } \times 10^{-5} \text{ eV}^2$

- Remarkably, checks with KamLAND reactor $\nu$ osc.!
Designing the whole spectrum

- Tune solar splitting to matter potential in solar center
  - $\Delta m^2 \sim G_F N_\odot (10^6 \text{eV}) \sim \text{a few } \times 10^{-5} \text{ eV}^2$
  - make mixing angle large, so that could be checked with reactor antineutrinos (basically oscillations in vacuum)

- The 2nd splitting should be discoverable with atmospheric neutrinos:
  - set vacuum oscillation length for typical $E_{\text{atm}} \sim 10^9 \text{ GeV}$ to be $\sim 10^3 \text{ km}$ $\rightarrow \Delta m^2_{\text{atm}} \sim 10^{-3} \text{ eV}^2$
  - make mixing angle large (basically oscillations in vacuum)

- Make $\theta_{13}$ small, so as not to confuse people
  - two-neutrino analysis for both solar and atmospheric neutrinos
**Subdominant effect I: $\theta_{13}$**

\[
\sin^2 \theta_{13} - \sin^2 \theta_{13}
\]

\[
\cos^2 \theta_{13} \sin^2 \theta - \cos^2 \theta_{13} \sin^2 \theta_{\odot}
\]

\[
\cos^2 \theta_{13} \cos^2 \theta - \cos^2 \theta_{13} \cos^2 \theta_{\odot}
\]

\[
P_{ee}^{3\nu} \approx \sin^4 \theta_{13} + \cos^4 \theta_{13} P_{ee}^{2\nu}
\]

- **CHOZ (+ global):** $\sin^2 \theta_{13} \lesssim 0.02$
  - at the limit, $P_{ee}^{3\nu} \approx 4 \times 10^{-4} + 0.96 \times P_{ee}^{2\nu}$
  - a few percent change

see, e.g., G.L. Fogli, E. Lisi, A. Marrone, A. Palazzo, hep-ph/0506083 for a recent analysis and refs.
**Subdominant effect II: novel neutrino NC interactions**

- Idea is as old as matter effects in neutrino oscillations
  - (L. Wolfenstein, PRD 17, 2369 (1978))
  - ... and many, many others
Some neutrino interactions are very poorly known to this day!

- Parameterize additional contributions due to heavy scalar/vector exchange as

\[ L^{NSI} = -2\sqrt{2}G_F (\bar{\nu}_\alpha \gamma^\rho \nu_\beta) (\epsilon^{f \bar{f} L}_{\alpha \beta} \bar{f}_L \gamma^\rho f_L + \epsilon^{f \bar{f} R}_{\alpha \beta} \bar{f}_R \gamma^\rho f_R) + h.c. \]

- Well established only for the \( \mu \)-neutrino

\[ \epsilon_{e\mu} \lesssim 10^{-3}, \quad \epsilon_{\mu\mu} \lesssim 10^{-3} - 10^{-2} \]

- Poorly known for the e-neutrino and especially for the \( \tau \)-neutrino

\[-0.4 < \epsilon^{uuR}_{ee} < 0.7, \quad |\epsilon^{uu}_{Te}| < 0.5, \quad |\epsilon^{dd}_{Te}| < 0.5, \quad |\epsilon^{uuR}_{\tau\tau}| < 3 \]

Bounds from charged leptons don’t necessarily apply

- In addition to the SU(2)-preserving operators
  \[
  \frac{1}{M^2} \bar{L}L q_R q_R \rightarrow \frac{1}{M^2} (\bar{q}_R \gamma^{\mu} q_R)(\bar{\nu} \gamma_{\mu \nu})
  \]
  there could be large potential contributions from SU(2) breaking operators*, e.g.,
  \[
  \frac{1}{M^4} \bar{q}_R (H^\dagger \sigma^a L) (\bar{L} \sigma^a H) q_R \rightarrow \frac{\nu^2}{M^4} (\bar{q}_R \gamma^{\mu} q_R)(\bar{\nu} \gamma_{\mu \nu})
  \]

*charge lepton operators would be induced at one loop

- Important if new physics is close to EW scale
Need a “ντ beam”!

- Both solar and atmospheric neutrinos partially oscillate into the tau-neutrino state
  - In the standard case, the oscillation parameters are quite well known by now
- Neutrino beams (K2K, MINOS) also produce ντ by oscillations
- Look for anomalies in the NC event rate caused by ντ (detection effect)
- Modified interactions of ντ with matter may make the oscillation pattern incompatible with the data (propagation effect)
**Flavor-changing NSI: effects on solar neutrino energy spectrum**

- Transition from the “vacuum regime” (low $E_{\nu}$) to the matter dominated regime (high $E_{\nu}$) deviates from the canonical MSW prediction

\[ \varepsilon_{e\tau} \equiv \sum_{f=u,d,e} \frac{\varepsilon_{e\tau}^f n_f}{n_e} \]

\[ \varepsilon_{e\tau}^f \equiv \varepsilon_{e\tau}^{fL} + \varepsilon_{e\tau}^{fR} \]

**\( \varepsilon \) per quark \( \sim 10^{-1} \) of the SM**
Flavor-changing NSI: effects on solar neutrino energy spectrum

- Survival probability at SNO could show more or less energy dependence, depending on the sign (phase) of the NSI!
- Low-energy bin at SNO/SK critical!

\[ \epsilon_{\alpha\beta} \equiv \sum_{f=u,d,e} \epsilon_{\alpha\beta}^f \frac{n_f}{n_e} \]

\[ \epsilon_{\alpha\beta}^f \equiv \epsilon_{\alpha\beta}^f L + \epsilon_{\alpha\beta}^f R \]
More radical effects on solar $\nu$'s

Guzzo, de Holanda, Peres, Phys.Lett. B591, 1 (2004);
Miranda, Tortola, Valle, hep-ph/0406280
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Survival probability for LMA-0

Atmospheric neutrino oscillations and new interactions

- The same flavor-changing neutrino interactions can be probed with atmospheric neutrinos!
- Large NSI cannot be excluded by present data; $\varepsilon_{ee}$, $\varepsilon_{e\tau}$, $\varepsilon_{\tau\tau}$ NSI parameters correlated in a certain way.
- The key is to do a full 3-generation analysis.

A.F., C. Lunardini, M. Maltoni, Phys. Rev. D70, 111301 (2004);
Effect of NSI on the oscillation fit

- The best-fit region shifts to smaller $\theta$ and larger $\Delta m^2$:

$$\begin{align*}
\epsilon_{e\tau} &= 0, \epsilon_{\tau\tau} = 0; \\
\epsilon_{e\tau} &= 0.30, \epsilon_{\tau\tau} = 0.106; \\
\epsilon_{e\tau} &= 0.60, \epsilon_{\tau\tau} = 0.424; \\
\epsilon_{e\tau} &= 0.90, \epsilon_{\tau\tau} = 0.953.
\end{align*}$$

*Phys.Rev.D70 111301, (2004)*
MINOS, $\nu_\mu \rightarrow \nu_\tau$ mode

- $\nu_\mu \rightarrow \nu_\tau$ mode: measure "true" vacuum parameters
- $25 \times 10^{20}$ protons on target
- Either discover new physics, or place best constraints

*hep-ph/0606101*
MINOS, $\nu_\mu \rightarrow \nu_e$ mode

- $\nu_\mu \rightarrow \nu_e$ mode: direct conversion due to new flavor changing interactions
- $25 \times 10^{20}$ protons on target: shrinks currently allowed parameter space by a factor of 2
- $\theta_{13}$ or New interactions?

hep-ph/0606101
Subdominant effect III: magnetic (transition) moment

- Again, as an alternative to oscillations, a very old idea
- Renaissance in mid-1980’s, to explain Homestake time variation
  - … and many others
- As late as 2002 (before KamLAND) could still fit all solar data with this mechanism (spin-flavor flip in the radiative zone)
Neutrino magnetic moment: basics

- Effective low-energy operator
  \[ \mathcal{L}_{EM} = -\frac{1}{2} \mu_{ab}(\nu^\alpha)_a(\sigma^{\mu\nu})^\alpha_\beta(\nu_\beta)_b F_{\mu\nu} + h.c. \]
  \[ = i\mu_{ab}(\bar{\chi})_a\bar{\sigma}(\nu)_b(\bar{E} + i\bar{B}) + h.c. \]

- Dim 7 when SU(2) × U(1) structure restored

\[
\begin{align*}
[O_B]_{ab} &= g'_L(\bar{\ell}c_a\epsilon H)\sigma^{\mu\nu}(H\epsilon P_L\ell_b)B_{\mu\nu}, \\
[O_W]_{ab} &= ig\epsilon_{mnp}(\bar{\ell}c_a\epsilon\tau^m P_L\ell_b)(H\epsilon\tau^n H)W^p_{\mu\nu}
\end{align*}
\]

- Majorana neutrino: flavor-diagonal moments vanish identically (spinors anticommute); flavor-changing (transition) moments are allowed

- Ultrarelativistic Majorana \( \nu \) undergoes \textit{spin-flavor precession} in external magnetic fields
Majorana neutrino transition moment: bounds (short version)

- **Direct bounds:** $2\mu_{e\beta} < 0.9 \times 10^{-10} \mu_B$
  \[ \mu_B \equiv e/(2m_e) \]
  - reactor antineutrino scattering

- **Astrophysics** $\mu \lesssim 3 \times 10^{-12} \mu_B$
  - red giant cooling via plasmon decay to $\nu\bar{\nu}$
Magnetic moment and mass: naturalness considerations

- Magn. mom. operator radiatively generates neutrino mass
  - While for Dirac neutrinos this leads to a naturalness bound
    \[ \mu_\nu \lesssim 10^{-14} \mu_B \]
  - for Majorana neutrinos the analogous bound is much weaker (because of the Voloshin symmetry, Voloshin 1987)
    \[ \mu_\nu \lesssim 10^{-10} \mu_B \]

- Again, new physics scale required to be close to EW scale to be near the bound
Searching for $\mu_\nu$ with solar $\nu$’s at KamLAND

- Interaction with solar magnetic fields + flavor oscillations: $\nu_e \rightarrow \text{anti-}\nu_e$ (Majorana neutrinos)

- KamLAND is VERY sensitive to anti-$\nu_e$ from the Sun
  - looks for events above 8.3 MeV where there are no reactor antineutrinos; excess over predicted background would indicate conversions of solar $^8$B neutrinos
  - Current bound: $\lesssim 3 \times 10^{-4}$ $\nu_e \rightarrow \text{anti-}\nu_e$ conversion

Solar magnetic fields

- **radiative zone** ($r < 0.7 \, R_{\text{SUN}}$)
  - possible primordial fields
  - Strength constrained to be $\lesssim$ a few MG by oblateness, stability arguments (A.F., A. Gruzinov, Astrophys. J. 601, 570, 2004)

- **convective zone** ($r > 0.7 \, R_{\text{SUN}}$)
  - fields generated by turbulence
  - bounds on $B$ from observations at the surface, turbulent equipartition, energy arguments (e.g., Y. Fan, Rev. Solar Phys. 1, 1 (2004))
Radiative zone: quantitative analysis

- The effect could be large (order one!) for small mixing angles (resonance).
- For large mixing angles, including the experimentally measured oscillation parameters the effect is (as yet unobservably) small.
- CAUTION: For large mixing angles resonance condition modified!

\[ \mu = 10^{-11} \mu_B \]

A. F., hep-ph/0505165

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Convective zone: neutrino in turbulent fields

- “Turbulent” magnetic field resets oscillation phase → random walk in the flavor space
- Depending on the model for the magnetic field, get
  \[ P(\nu_e \rightarrow \bar{\nu}_e) \sim (10^{-5} - 10^{-4}) \left( \frac{\mu}{10^{-11}\mu_B} \right)^2 \]
  - Sensitivity already competitive with laboratory experiments; may improve with the next KamLAND data release

A.F., hep-ph/0505165
Searching for new physics with neutrinos

- New physics at $\gtrsim M_{EW}$ could generate effective low-energy operators that modify
  1. $\nu$ interactions with matter
  2. $\nu$ interactions with EM fields

- Resulting subdominant effects could be detectable with precision measurements (SNO, Borexino, KamLAND, MINOS)
  - Solar, atmospheric, reactor and beams all probe NC interactions; combined analyses needed
  - If deviations from SM found, implications would be profound
  - Even if not, we will learn about neutrino properties
    - At present neutral current interactions of $\nu_\tau$ are basically unknown

- Solar neutrinos may reveal neutrino transition moment. Future KamLAND data on anti-$\nu_e$ from the Sun very important!