Astro 596/496 NPA
Lecture 28
Oct. 28, 2009

Announcements:

- Preflight 5 due noon Friday

Last time: Neutrino Oscillations

SNO total neutrino flux $\rightarrow$ solar models correct

$\rightarrow$ observed ν_e deficit due to new neutrino physics

Q: what do solar neutrino experiments require of new physics?

Q: in what way to neutrinos "oscillate"?

Q: what is the role of quantum mechanics?

Disappearance probability for ν_e

$$P(\nu_e \to \nu_x) = \sin^2 2\theta_V \ \sin^2 \left[12.7 \frac{\Delta m^2 (10^{-4}\,\text{eV}^2) R(\text{km})}{E(\text{MeV})} \right]$$

Q: what is θ_V? Δm^2?

Solar neutrino experiments $\longrightarrow$ E-dependent ν_e suppression
more suppression at higher E

if neutrinos have *different nonzero* masses, possible that
mass/propagation eigenstates $\neq$ *production/Weak eigenstates*
evolving quantum phases $\rightarrow$ interference $\rightarrow$ oscillations

Probability of *remaining* ν_e:

$$P(\nu_e^{\text{birth}} \rightarrow \nu_e^{\text{detect}}) = \| \langle \nu_e(0) | \nu_e(t) \rangle \|^2 = 1 - \sin^2 2\theta_{\text{V}} \, \sin^2\left(\frac{\pi L}{L_{\text{V}}}\right)$$

where $L_V = 4\pi\hbar E/\Delta m^2 = 0.75\ \text{km}\ (E_\nu/1\ \text{GeV})\ (1\ \text{eV}^2/\Delta m^2)$

for source sizes $R \gg L_V$ and observed distances $L \gg L_V$

$$\langle P(\nu_e^{\text{birth}} \rightarrow \nu_e^{\text{detect}}) \rangle = 1 - \sin^2 2\theta_{\text{V}} \left\langle \sin^2 \pi \frac{L}{L_{\text{V}}} \right\rangle = 1 - \frac{1}{2}\sin^2 2\theta \geq \frac{1}{2}$$

but we need suppression $> 50\%$!
can't do this with vacuum oscillations!

Neutrino Oscillations in Matter

MSW = Mikheyev, Smirnov, Wolfenstein

νs pass thru matter twice (in Sun, in Earth)
all ν types can have NC interactions
but ν_e have extra CC interactions ($\nu e \rightarrow \nu e$)
selectively modifies ν_e flux

ν_e potential in matter: $V_e(r) = \sqrt{2}\, G_\mathsf{F} n_e(r)$
put $\langle \nu_e(0) | \nu_e(t) \rangle = c_e(t)$, similar $c_x(t)$
Schrödinger equation + algebra:

$$i\hbar \frac{d}{dt} \begin{pmatrix} c_e \\ c_x \end{pmatrix} = \frac{1}{4E} \begin{pmatrix} -\Delta m^2 \cos 2\theta_\mathsf{V} + 2\sqrt{2}\, G_\mathsf{F} n_e E & \Delta m^2 \sin 2\theta_\mathsf{V} \\ \Delta m^2 \sin 2\theta_\mathsf{V} & \Delta m^2 \cos 2\theta_\mathsf{V} - 2\sqrt{2}\, G_\mathsf{F} n_e E \end{pmatrix} \begin{pmatrix} c_e \\ c_x \end{pmatrix}$$

Q: evolution as $n_e \rightarrow \infty$? $n_e \rightarrow 0$?

Q: condition for maximal mixing?
Q: so how will ν states evolve when propagating from solar core?

maximal mixing ("resonance") when diagonal elements zero:

$\rightarrow 2\sqrt{2}\, E G_{\mathrm{F}} n_e = \Delta m^2 \cos 2\theta_{\mathrm{V}}$: density-dependent!

$$
\begin{aligned}
m_u n_e^{\mathrm{crit}} &= \frac{m_u \Delta m^2 \cos 2\theta_{\mathrm{V}}}{2\sqrt{2} G_{\mathrm{F}} E} \\
&= 66 \text{ g cm}^{-2} \cos 2\theta_{\mathrm{V}} \left(\frac{E}{10 \text{ MeV}} \right)^{-1} \left(\frac{\Delta m^2}{10^{-4} \text{ eV}^2} \right)
\end{aligned}
$$

Can happen in Sun! No fine tuning needed!

- start as ν_e, in dense region where $n_e > n_e^{\mathrm{crit}}$
  neutrinos leave, seeing a dropping electron density
- reach $n_e = n_e^{\mathrm{crit}}$ $\rightarrow$ *change to* ν_x
- continue to Earth

works for range of Δm^2 *Q: how?*

But note energy dependence:

Q: what energies, ν *populations, experience MSW?*

Solar Neutrino Solutions

Using all solar ν data, most favored solution:

$\star$ $\theta_V = 32.5^\circ$

$\star$ $\Delta m^2 = 7.1 \times 10^{-5}$ eV^2

Implications

- "large mixing angle" (LMA)

  Q: what angle gives maximal vacuum mixing*? ...hint:*

$$\begin{pmatrix} \nu_e \\ \nu_x \end{pmatrix} = \begin{pmatrix} \cos\theta_V & \sin\theta_V \\ -\sin\theta_V & \cos\theta_V \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

- $\Delta m^2 = |m_2^2 - m_1^2|$ does *not* give either m_1 or m_2

  but does set *minimum* mass for either:

  $m_{\nu,\mathrm{min}} = \sqrt{\Delta m^2} = 8 \times 10^{-3}$ eV

Q: how to test this solution in the lab?

Laboratory test: KamLAND

(Kamiokande Liquid Scintillator Anti-Neutrino Detector)
sources: anti-neutrinos from Japanese nuke reactors

- $E_\nu = 2.6 - 8$ MeV
- avg distance $R \sim 180$ km

$\rightarrow$ if LMA, disappearance probability is

$$P_{\rm dis} = \sin^2 2\theta_{\rm V} \ \sin^2 \left(2\pi \frac{R}{350{\rm km}} \right) \tag{1}$$

Kamland observes flux *reduction*: $P_{\rm dis} = 0.66$
E_ν spectrum $\rightarrow \Delta m^2 = 7.9^{+0.6}_{-0.5} \times 10^{-5}$ eV^2
$\rightarrow$ confirms oscillations in general, and LMA in particular!
`www: KamLAND plots`

Solar Neutrino Problem Solved!

Q: remaining questions? experiments?

Next Step: Precision Neutrino Astronomy

- measure monoenergetic ^{7}Be neutrinos
  now detected in real-time!
  flux consistent with MSW LMA
  `www: Borexino`
- measure pp flux to $\sim 1\%$ $\Rightarrow$ better $\theta_{\rm V}$
  `www: DUSEL--proposed, under review`

New questions:

What are ν masses?

oscillations only measure splittings Δm^2

$\rightarrow$ know masses are *different* and *nonzero*

but don't even know hierarchy: is $m_1 < m_2$ or the reverse?

Is ν_i identical to $\bar{\nu}_i$?

yes: "Majorana" neutrinos

no: "Dirac" neutrinos, right-hand ν exist

can test with "neutrinoless double beta decay"

(rare nuclear decays, only go if Majorana)

Do neutrinos violate CP?

if so: maybe important in baryogenesis...

"leptogenesis" scenario: generate net *lepton* number, then translate this to net baryon number

Massive Stars

Neutrinos and Nucleosynthesis

Evolution of Massive Stars

in our context, massive $\rightarrow$ core-collapse: $M \gtrsim 8-10M_\odot$

Main sequence:

- short MS lifetime ($\lesssim$ 30 Myr)
- $T_c \sim 3 \times 10^7$ K
- burn $p \rightarrow {}^4$He via CNO cycle

when H exhausted:

- homologous contraction
- H shell burning begins $\rightarrow$ red giant • heat core $\rightarrow$ ignite...

He burning via $3\alpha \rightarrow {}^{12}$C

a 3-body reaction *Q: how might this work*