Astro 596/496 NPA
Lecture 26
Oct. 23, 2009

Announcements:
- Problem Set 4 due
- Preflight 5 posted, due noon next Friday

Last time: The Nuclear Sun

$$
\begin{aligned}
p + p &\rightarrow d + e^{+} + \nu_e \\
d + p &\rightarrow {}^{3}\mathrm{He} + \gamma
\end{aligned}
$$

Then: 3 branches

PP-I

$${}^{3}\mathrm{He} + {}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + p + p$$

$${}^{3}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{7}\mathrm{Be} + \gamma$$

PP-II

$${}^{7}\mathrm{Be} + e \rightarrow {}^{7}\mathrm{Li} + \nu_e$$
$${}^{7}\mathrm{Li} + p \rightarrow {}^{4}\mathrm{He} + {}^{4}\mathrm{He}$$

PP-III

$${}^{7}\mathrm{Be} + p \rightarrow {}^{8}\mathrm{B} + \gamma$$
$${}^{8}\mathrm{B} \rightarrow {}^{8}\mathrm{Be} + e^{+} + \nu_e$$
$${}^{8}\mathrm{Be} \rightarrow {}^{4}\mathrm{He} + {}^{4}\mathrm{He}$$

Standard Solar Neutrino Production

Rxn	$E_{\nu,\text{max}} = Q$	$\langle E_\nu \rangle$	Total SSM Flux Φ_ν (10^{10} ν cm^{-2} s^{-1})
$pp \to de\nu$	0.420 MeV	0.265 MeV	6.0
^{7}Be $e \to {}^7$Li ν	lines: $^7\text{Li}^{\text{gs}} = 0.861$ MeV; $^7\text{Li}^* = 0.383$ MeV		0.47
^{8}B$\to{}^8$Be e ν	17.98 MeV	9.63 MeV	5.8×10^{-4}

Q: Why are the ^{7}Be neutrinos monoenergetic?

`www: Bahcall neutrino spectrum`

pp neutrinos largest flux, but low energies

^{7}Be neutrinos monoenergetic, strong $\sim T_c^8$ dependence

^{8}B neutrinos continuum, ultrastrong $\sim T_c^{20}$ dep

What should this mean for production vs radius?

`www: Bahcall fig of production vs` R

Standard Solar Model Predictions

What are key SSM ν ingredients, predictions?

- time variations: at source? in detectors?

- $L_\odot$ fixes what?

- what connection between $\Phi_\nu(^7\text{Be})$ and$\Phi_\nu(^8\text{B})$?

- ν spectra: determined by what?

SSM Predictions

SSM Key Predictions:

- at source: steady ν_e flux from Sun

- elliptical Earth orbit $\rightarrow$ annual flux variation
  $\Delta\Phi_\nu/\Phi_\nu \simeq 2\delta r_\oplus/r_\oplus \sim 4e_\oplus \sim 7\%$

- pp flux $\sim$ fixed by $L_\odot$

- ^{7}Be, ^{8}B flux T-dep, but $\Phi_\nu(^7\mathrm{Be}) > \Phi_\nu(^8\mathrm{B})$

- neutrino spectra fixed by β decay
  indep of solar model (since $T_{c,\odot} \sim 1\mathrm{keV} \ll \mathrm{Q_{nuke}}$)

Solar Neutrino Experiments

Original motivation (Davis, Bahcall):

- confirm nuke energy generation
- measure $T_{\odot,c}$

Facts of life:

1. $\nu \rightarrow$ small σ
2. $E_\nu \lesssim few$ MeV $\rightarrow$ large natural background
   e.g., radioactivity, cosmic ray muons

Q: what is needed for neutrino observatory?

Neutrino Observatories: Design Requirements

1. **Large** detector.

ν-nucleus absorption $\sigma_{\nu A} \sim 10^{-44}\ \mathrm{cm}^2$

$\Rightarrow$ event rate per target $\Gamma_\nu(A) = \Phi_\nu \sigma_{\nu A} \sim 10^{-36}\ \mathrm{s}^{-1}$

Solar Neutrino Unit: 1 SNU $= 10^{-36}$ event s^{-1} target^{-1}

Want net rate $R = N_{\mathrm{targ}} \Gamma \gtrsim 1\ \mathrm{day}^{-1} \sim 10^{-5}\ \mathrm{s}^{-1}$

$\Rightarrow$ Need $N_{\mathrm{targ}} = R/\Gamma \sim 10^{31}$

$$M_{\mathrm{targ}} = A m_u N_{\mathrm{targ}} \sim 10^9 \left(\frac{A}{50}\right)\ \mathrm{g}\ \sim \left(\frac{A}{50}\right)\ \text{kiloton}$$

big!

2. Go **underground**.

"Clean" lab, low-background material

Radiochemical Experiments: Chlorine

Homestake Mine Lead, SD, USA: 1967-1995

`www: Homestake, note Ray Davis`

target: chlorine (cleaning fluid!, 0.61 kton)

process: $^{37}\mathrm{Cl} + \nu_e \rightarrow {}^{37}\mathrm{Ar} + e$ (endothermic)

threshold: ν must supply $|Q| = 0.814$ MeV

$\Rightarrow$ only measure ^{7}Be, ^{8}B νs

procedure: cycle fluid $\rightarrow$ filter, collect ^{37}Ar atoms: $\sim few/$week!

Measure:

$$\Gamma_{\mathrm{obs}} = 2.56 \pm 0.16 \pm 0.16 \text{ SNU} \tag{1}$$

Compare to SSM prediction:

$$\frac{\Gamma_{\mathrm{obs}}}{\Gamma_{\mathrm{SSM}}} = 0.33 \pm 0.03 \pm 0.05 \ll 1! \tag{2}$$

Only see $\sim 1/3$ of predicted flux!

$\Rightarrow$original *Solar ν problem*

Radiochemical Experiments: Gallium

- GALLEX: Gran Sasso, Italy (1990's)
- SAGE: Baksan, Russia (1990's)

target: (liquid) gallium metal
process: $^{71}\mathrm{G} + \nu \rightarrow ^{71}\mathrm{Ge} + e$
threshold $Q = 0.233$ MeV $\rightarrow$ can see pp νs!
calibrated with megacurie source!

Measure:

$$\Gamma_{\mathrm{SAGE}} = 75 \pm 7 \pm 3 \text{ SNU} \tag{3}$$

$$\Gamma_{\mathrm{GALLEX}} = 78 \pm 6 \pm 5 \text{ SNU} \tag{4}$$

Compare:

$$\frac{\Gamma_{\mathrm{obs}}}{\Gamma_{\mathrm{SSM}}} = 0.59 \pm 0.06 \pm 0.04 \tag{5}$$

Significant deficit! *Solar ν problem #2*
Note: no info on neutrino energy spectrum

Water Čerenkov Experiments

target: water

process: electron scattering $\boxed{\nu e \to \nu e}$

for $E_\nu \gtrsim 0.5$ MeV, recoil electron $v_e \sim c$

but in water, refactive index $n = 1.34 \Rightarrow v_e > c/n$

emit "sonic boom" photons: Čerenkov radiation

"optical shock wave," cone of light

cone opening angle depends on $v_e \to E_e$

`www: Super-K events`

Q: advantages of water Čerenkov vs radiochemical?

In praise of Water Čerenkov

- detect neutrinos in "real time"
- $E_e \to \nu$ energy $\to$ spectrum
- cone orientation $\to \nu$ direction info!

Super-Kamiokande. Kamioka Mine, Japan: 1996-

`www: Super-K image`

Super-K fortune cookie

direction: νs point back to Sun (check)

`www: Neutrino image of the Sun`

$e\nu$ elastic scattering in pure water

Energy threshold: 5 MeV $\Rightarrow$ see only ^{8}B νs

spectrum: shape matches SSM

...but $\Phi(^{8}\mathrm{B})_{\mathrm{SK}}/\Phi(^{8}\mathrm{B})_{\mathrm{SSM}} \sim 50\%$!

Solar ν problem #3

Sudbury Neutrino Observatory (SNO)

Sudbury, Ontario, Canada: 1999-
ultrapure heavy water: D_2O

Rxns:

$\nu_e + d \rightarrow e^- + p + p$ *Feynman diagram*

Charged current: *ν_e only*

Threshold: 1.4 MeV $\rightarrow$ ^{8}B only

$\nu_x + d \rightarrow \nu'_x + p + n$ *Feynman diagram*

ν' flavor = ν flavor

Neutral current: *all flavors*

Threshold: 2.2 MeV $\rightarrow$ ^{8}B only

also: Salt phase – dissolve NaCl in SNO tank
big σ for $^{35}\text{Cl}(n,\gamma)^{36}\text{Cl}$ $\rightarrow$ improved NC

SNO Results

Charged-current (ν_e flux):

$$\Phi_{\mathrm{CC}}^{\mathrm{SNO}} = \left[1.59^{+0.08}_{-0.07}(\mathrm{stat})^{+0.06}_{-0.08}(\mathrm{sys})\right] \times 10^6 \ \nu \ \mathrm{cm}^{-2} \ \mathrm{s}^{-1} \tag{6}$$

Neutral-current (all-ν flux):

$$\Phi_{\mathrm{NC}}^{\mathrm{SNO}} = [5.21 \pm 0.27(\mathrm{stat}) \pm 0.38(\mathrm{sys})] \times 10^6 \ \nu \ \mathrm{cm}^{-2} \ \mathrm{s}^{-1} \tag{7}$$

Thus we have

$$\frac{\Phi_{\mathrm{CC}}^{\mathrm{SNO}}}{\Phi_{\mathrm{NC}}^{\mathrm{SNO}}} = \frac{\nu_e \ \mathrm{flux}}{\mathrm{all} \ \nu \ \mathrm{flux}} = 0.306 \pm 0.026(\mathrm{stat}) \pm 0.024(\mathrm{sys}) \tag{8}$$

 Which means...

Implications: New Neutrino Physics!

The Sun makes only ν_e

Q: why? e.g., why not ν_μ*?*

$\longrightarrow$ if no new ν physics, only ν_e at Earth

$\longrightarrow$ predict $\Phi_{\mathrm{CC}}(\nu_e) = \Phi_{\mathrm{NC}}(\nu_x)$

SNO measures $\Phi_{\mathrm{CC}}(\nu_e) > \Phi_{\mathrm{NC}}(\nu_x)$!

with *very* high confidence!

non-ν_e flux arriving in detector!

A big deal:

- demands new neutrino physics
- indep. of detailed solar model