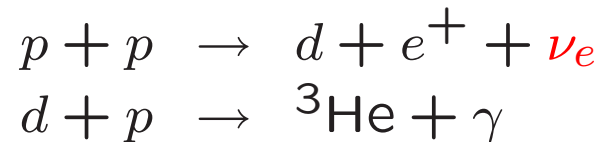


Astro 596/496 NPA
Lecture 26
Oct. 23, 2009

Announcements:

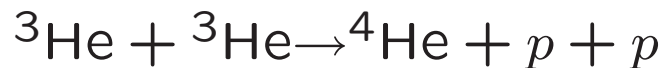
- Problem Set 4 due
- Preflight 5 posted, due noon next Friday

Last time: The Nuclear Sun

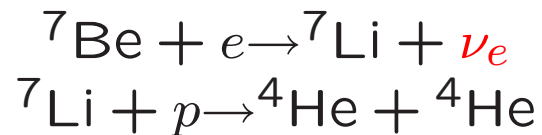


Then: 3 branches

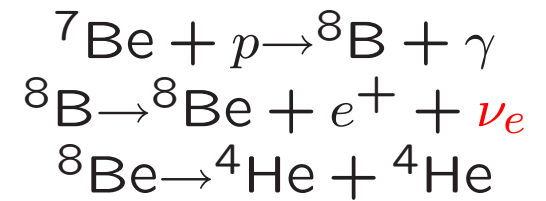
PP-I



PP-II



PP-III



Standard Solar Neutrino Production

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

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

www: Bahcall neutrino spectrum

pp neutrinos largest flux, but low energies

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

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

\approx 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
- ${}^7\text{Be}$, ${}^8\text{B}$ flux T -dep, but $\Phi_\nu({}^7\text{Be}) > \Phi_\nu({}^8\text{B})$
- neutrino spectra fixed by β decay
indep of solar model (since $T_{c,\odot} \sim 1\text{keV} \ll Q_{\text{nuke}}$)

Solar Neutrino Experiments

Original motivation (Davis, Bahcall):

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

Facts of life:

1. $\nu \rightarrow$ **small σ**
2. $E_{\nu} \lesssim \text{few MeV} \rightarrow$ 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 $\sigma_{\nu A} \sim 10^{-44} \text{ cm}^2$

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

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

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

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

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

big!

2. Go **underground**.

- o “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: $^{37}\text{Cl} + \nu_e \rightarrow ^{37}\text{Ar} + e$ (endothermic)

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

\Rightarrow only measure ^7Be , ^8B ν s

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

Measure:

$$\Gamma_{\text{obs}} = 2.56 \pm 0.16 \pm 0.16 \text{ SNU} \quad (1)$$

Compare to SSM prediction:

$$\frac{\Gamma_{\text{obs}}}{\Gamma_{\text{SSM}}} = 0.33 \pm 0.03 \pm 0.05 \ll 1! \quad (2)$$

\checkmark 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: ${}^{71}\text{G} + \nu \rightarrow {}^{71}\text{Ge} + e$

threshold $Q = 0.233$ MeV \rightarrow can see *pp* ν s!

calibrated with megacurie source!

Measure:

$$\Gamma_{\text{SAGE}} = 75 \pm 7 \pm 3 \text{ SNU} \quad (3)$$

$$\Gamma_{\text{GALLEX}} = 78 \pm 6 \pm 5 \text{ SNU} \quad (4)$$

Compare:

$$\frac{\Gamma_{\text{obs}}}{\Gamma_{\text{SSM}}} = 0.59 \pm 0.06 \pm 0.04 \quad (5)$$

∞

Significant deficit! *Solar ν problem #2*

Note: no info on neutrino energy spectrum

Water Čerenkov Experiments

target: water

process: electron scattering $\nu e \rightarrow \nu e$

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

but in water, refractive 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 $v_e \rightarrow E_e$

www: Super-K events

- Q: advantages of water Čerenkov vs radiochemical?

In praise of Water Čerenkov

- detect neutrinos in “real time”
- $E_e \rightarrow \nu$ energy \rightarrow spectrum
- cone orientation $\rightarrow \nu$ direction info!

Super-Kamiokande. Kamioka Mine, Japan: 1996-

www: Super-K image

Super-K fortune cookie

direction: ν s 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 ${}^8\text{B}$ ν s

spectrum: shape matches SSM

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

Solar ν problem #3

Sudbury Neutrino Observatory (SNO)

Sudbury, Ontario, Canada: 1999-
ultrapure **heavy** water: D₂O

Rxns:

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

Charged current: ν_e *only*

Threshold: 1.4 MeV \rightarrow ⁸B only

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

ν' flavor = ν flavor

Neutral current: *all flavors*

Threshold: 2.2 MeV \rightarrow ⁸B only

II 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):

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

Neutral-current (all- ν flux):

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

Thus we have

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

12 *Which means...*

Implications: New Neutrino Physics!

The Sun makes only ν_e

Q: *why? e.g., why not ν_μ ?*

→ if no new ν physics, only ν_e at Earth

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

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

with very high confidence!

non- ν_e flux arriving in detector!

A big deal:

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