Astro 404

Lecture 15

Sept. 27, 2021

Announcements:

- **Problem Set 5 due Friday**
- Distinguished lecture this week!
  Illinois alumna Vicky Kalogera
  "Einstein's Waves: Cosmic Sounds from Black Holes and Neutron Stars"
  Wed Sept 29, 7–8pm, Lincoln Hall Theater and online
  Canvas has registration link and *Bonus Points assignment*

Last time: nuclear reactions in the Sun – the pp Chain

Q: why pp? why chain?

Q: net effect–that is, particles in an out of chain?

The pp Chain

Dominant nuclear reactions in the Sun: "pp" Chain

$$p + p \rightarrow {}^2\mathrm{H} + e^+ + \nu$$

$$e^- + e^+ \rightarrow \gamma + \gamma$$

$${}^2\mathrm{H} + p \rightarrow {}^3\mathrm{He} + \gamma$$

$${}^3\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + 2p$$

Net effect:

$$4p + 2e^- \rightarrow \boxed{2n2p} = {}^4\mathrm{He} + \text{energy} + \ldots$$

Q: what's a neutrino? why is it present?

What's a Neutrino?

a **neutrino** ν is a subatomic particle that

- was postulated by Pauli (1930) to explain some nuclear decays needed to conserve energy, momentum, and angular mom.

  "I have done a terrible thing,

  I have postulated a particle that cannot be detected."

- is very *weakly interacting*

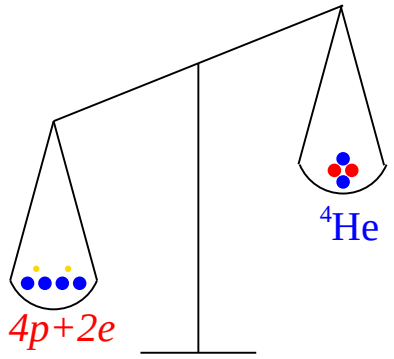
- is *produced only in some nuclear reactions and decays* that is: the Weak interactions

- is **required** to change a proton to neutron or vice versa

Fusion Energy

Where does the energy come from? **mass!**
Einstein: mass m at rest contains energy $E_{\text{rest}} = mc^2$

Observed fact:
$m(^4\text{He}_{\text{atom}}) < m(4p + 2e)$!
whole $<$ parts!



Do the math:

$$\begin{array}{rrl} & m(4p+2e) & = 6.694 \times 10^{-27}\ \text{kg} \\ - & m(^4\text{He}) & = 6.644 \times 10^{-27}\ \text{kg} \\ \hline = & \Delta m & = 5 \times 10^{-29}\ \text{kg} \end{array}$$

fusion $\rightarrow$ mass reduction!
$\rightarrow$ rest mass decrease $\rightarrow$ energy release!

Where Does the Energy Go?

nuclear reaction energy "supply" is from changes in mass
but *where does it go when released?*

recall pp chain:

$$p + p \rightarrow {}^2\mathrm{H} + e^+ + \nu \quad (1)$$

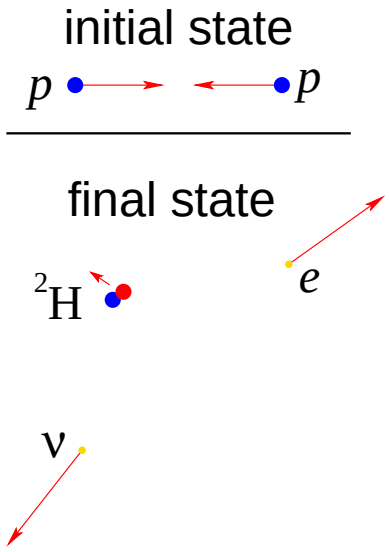
$$e^+ + e^- \rightarrow \gamma\gamma \quad (2)$$

$${}^2\mathrm{H} + p \rightarrow {}^3\mathrm{He} + \gamma \quad (3)$$

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

in each reaction in chain
mass energy is released: $m_{\mathrm{final}} < m_{\mathrm{initial}}$
Q: where does that energy go?
Q: how does this ultimately lead to Sunlight?

$$
\begin{aligned}
p + p &\rightarrow {}^2\mathrm{H} + e^+ + \nu \\
e^+ + e^- &\rightarrow \gamma\gamma \\
{}^2\mathrm{H} + p &\rightarrow {}^3\mathrm{He} + \gamma \\
{}^3\mathrm{He} + {}^3\mathrm{He} &\rightarrow {}^4\mathrm{He} + p + p
\end{aligned}
$$



★ for final state **nuclei**:
energy goes to *motion*: $v_{\mathrm{nucleus}} \gg v_T$
$\Rightarrow$ large *kinetic energy*

then gradually slow, mostly via Coulomb scattering
$\rightarrow$ *heats* the gas, also generates many photons

★ for final state **photons**:
carry momentum and very high energy: *gamma rays*!
then scatter violently, also *heat* the gas (plasma)

in each reaction mass $\rightarrow$ energy (kinetic, photons)
total for each $4p \rightarrow$ ^{4}He fusion:
$Q = \Delta E_{\text{rest}} = \Delta mc^2 = 27$ MeV $= 4.5 \times 10^{-12}$ Joules

Estimate Solar fusion energy supply:

$$E_{\text{fuse}} = \frac{\#\text{ nuclei in Sun}}{4\text{nuclei/fusion}} \times Q \sim 1.3 \times 10^{45} \text{ Joules} \qquad (5)$$

if *all* Sun's hydrogen is fuel, can burn for
$\tau_{\text{fuse}} = E_{\text{fuse}}/L = 3 \times 10^{18}$ sec $=$ 100 billion years!

Poll: Solar Nuclear Lifetime

if all Sun's hydrogen is fuel, nuclear fusion can burn for $\tau_{\text{fuse}} = E_{\text{fuse}}/L = 3 \times 10^{18}$ sec = 100 billion years!

Vote your conscience!

This is a crude estimate of the solar fusion lifespan–but how?

A this is an *over*estimate of the lifespan

B this is an *under*estimate of the lifespan

Solar Life Expectancy

We have overestimated fuel available for fusion:
we assumed Sun can burn all if its hydrogen

- fusion requires violent collision: high T, ρ
- surface of the Sun is far too cool
- fusion only occurs in inner core of Sun
  will see: enclosed core mass $m_{\rm core} \sim 0.1 M_\odot$

true lifetime: $\tau_\odot \sim 1 \times 10^{10}$ yr $= 10$ billion yrs
$\rightarrow$ *Sun is middle aged*
will last another ~ 5 billion yrs

Q: how test that sun is nuke powered?

How Do We Know?

By the 1930's we knew that the Sun is nuclear powered

`www: Nobel Prize: Hans Bethe`

> The Sun is a mass of incandescent gas
> a gigantic nuclear furnace
> Where hydrogen is burned into helium,
> at temperatures of millions of degrees
> – Lou Singer and Hy Zaret, 1959; cover: They Might Be Giants 1993

Q: how could we be so sure?

Can we get even more direct confirmation?

Q: is another way to confirms the Sun is a nuclear reactor? A "smoking gun" signature?

The Evidence: Solar Neutrinos

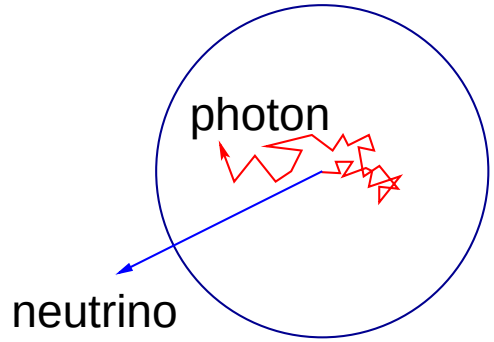
If the Sun takes $4p \rightarrow {}^4\mathrm{He} =$ 2p2n
then it *must* convert $2p \rightarrow 2n$
$\rightarrow$ *must* produce neutrinos!
in fact: most made via $pp \rightarrow de^+\nu$

The Sun radiates neutrinos as well as photons!

...we are bathed in solar "neutrinoshine"

Moreover:

- since ν are weakly interacting
  they come directly from the solar core
  $\rightarrow$ messengers from the center of the Sun!
- but luckily, *weakly* interacting $\neq$ *non*-interacting
  $\Rightarrow$ solar neutrinos are potentially observable!
- clever experiments can try to "catch" them



In Search of Solar Neutrinos

experiments have been built to "see" solar neutrinos

strategy: observing rare cases of ν interactions
with nuclei or electrons

all use huge underground detectors
Q: why huge? why underground?

Solar Neutrino Measurements I: Radiochemical Detectors

- target: huge vats of fluid
- effect: solar ν changes one nucleus to another–alchemy!
- detection: capture atoms of new elements
  infer existence and flux of solar neutrinos

pioneer: **Raymond Davis, Jr.**, 1960's
built experiment in Homestake Mine: Lead, South Dakota
10^5 gallons $=$ 400 tons of dry-cleaning fluid containing *chlorine*
solar neutrinos create argon atoms:

$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$$

collect and count Ar atoms (radioactive!), about one per day(!)
`www: Davis chlorine experiment at Homestake mine`

Q: pros and cons of this technique?

Solar Neutrino Measurements II: Scattering Detectors

target: huge vessels of ultra-pure water

effect: solar neutrino elastically scatters on electron at rest

$$\nu_e + e \to \nu_e + e$$

electron recoils with speed $v_e \sim c$!
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

detection: surround water with sensitive phototubes
see light pulses and image Čerenkov cones
Q: advantages?

In praise of Water Čerenkov

- detect neutrinos in "real time"
- electron energy $E_e \rightarrow \nu_e$ energy $\rightarrow$ spectrum
- cone orientation $\rightarrow \nu_e$ direction info!

pioneer: Masatoshi Koshiba, Japan, 1980's

Super-Kamiokande. Kamioka Mine, Japan: 1996-today. Upgrade 2018.

`www: Borexino,SNO`

`www: Super-K Sun image` direction: νs point back to Sun (check)

Solar Neutrino Experiments: Results

- ⋆ All experiments detect solar νs!
- ⋆ Scattering experiments show neutrinos come from the Sun!
- ⋆ Amount (flux) is just as predicted!

Q: what fundamental fact(s) is/are confirmed?

Solar Neutrino Results

I. proof that Sun powered by nuke fusion

II. νs give direct view into solar core

III. these underground vats are ν telescopes!

A new window on the Universe:

Nobel Prize 2002!

Raymond Davis Jr. and Masatoshi Koshiba

Using the Sun to probe neutrino transformation and mass:

Nobel Prize 2015!

Arthur MacDonald and Taakaki Kajita

Solar Neutrino Experiments: A Deeper View

1960s: original chlorine radiochemical experiment (Ray Davis):
- sensitive only to a small component of very high-energy νs
- signal detected, but flux $\Phi_\nu^{\rm obs} \approx \Phi_\nu^{\rm predicted}/3$

  birth of **"solar neutrino problem"** – where did they go?

1990's: solar neutrino deficit confirmed

possible explanations:
- theory of solar nuclear reactions is wrong/incomplete
- neutrino theory incomplete

it was already known that: *neutrinos have 3 varieties ("flavors")*
ν_e, ν_μ, ν_τ: named for partner they appear with
solar neutrinos produced as ν_e: should remain so
$\rightarrow$ unless neutrinos can transform into different flavors!

Q: how to test for the latter possibility?

The Sun Reveals New Neutrino Physics

if neutrino flavor transformations exist
• some particles born in Sun as ν_e
• can arrive at Earth as ν_μ or ν_τ • but radiochemical experiments only "see" ν_e

To test:
build detectors sensitive to *all flavors*
this was done: Sudbury Neutrino Observatory (SNO)

early 2000s: SNO results weigh in
• ν_μ and ν_τ *detected* from Sun!
• *total flux* for *all* ν *agrees* with Solar model!
• **confirms new neutrino physics**
• also *transformations require neutrinos have mass!*
non-obvious property of the quantum flavor transformations

Cosmic Gall

by John Updike

Telephone Poles and Other Poems

1963

Neutrinos, they are very small.
They have no charge and have no mass
And do not interact at all.

The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.

They snub the most exquisite gas,
Ignore the most substantial wall,
Cold-shoulder steel and sounding brass,
Insult the stallion in his stall.

And, scorning barriers of class,
Infiltrate you and me! Like tall
And painless guillotines, they fall
Down through our heads into the grass.

At night, they enter at Nepal
And pierce the lover and his lass
From underneath the bed–you call
It wonderful; I call it crass.

Cosmic Gall

by John Updike

Telephone Poles and Other Poems

1963 + 2019 Update!

Neutrinos, they are very small.
They have no charge and ~~have no~~ tiny mass
And ~~do not~~ hardly interact at all.

The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.

They snub the most exquisite gas,
Ignore the most substantial wall,
Cold-shoulder steel and sounding brass,
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Director's Cut Extras

An Alternative to the pp Chain

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

$^7\mathrm{Be} + p \rightarrow {}^8\mathrm{B} + \gamma$

$^8\mathrm{B} \rightarrow {}^8\mathrm{Be} + e^+ + \nu_e$

$^8\mathrm{Be} \rightarrow {}^4\mathrm{He} + {}^4\mathrm{He}$

minor additions to energy and neutrino generation:

pep 3-body reaction: $pp e^- \rightarrow d \nu_e$

hep weak reaction: $^3\mathrm{He}\, p \rightarrow {}^4\mathrm{He}\ e^+\ \nu_e$

PP-II and PP-III chains: different ^{3}He *fate*

^{7}Be branching is key:

e capture rate $\sim 1000\times$ p capture rate

- ^{7}Be: 15% of ν production
- ^{8}B: $\sim 0.02\%$ of ν production