

Astro 404  
Lecture 15  
Sept. 30, 2019

Announcements:

- **Problem Set 5 next Friday**

see Homework Discussion on Compass for FAQs

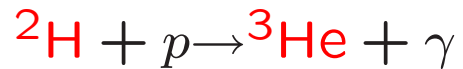
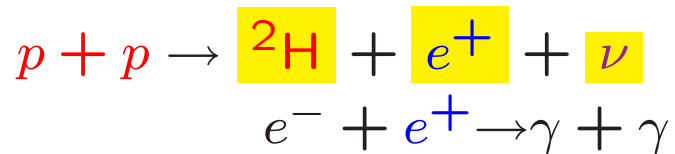
Last time: nuclear reactions in the Sun – the *pp* Chain

*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



**Net effect:**



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

# What's a Neutrino?

a **neutrino**  $\nu$  is a subatomic particle that

- was postulated by Pauli 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

ω

- 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  $\epsilon = mc^2$

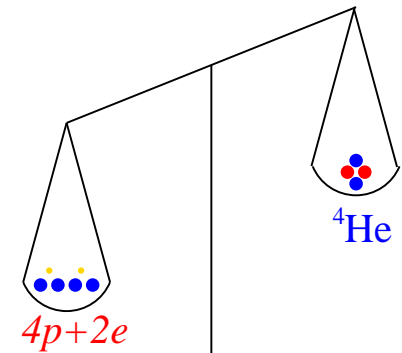
Observed fact:

$$m(^4\text{He}_{\text{atom}}) < m(4p + 2e)!$$

whole < parts!

Do the math:

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

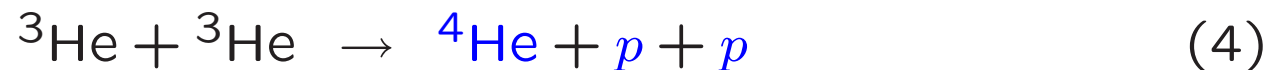
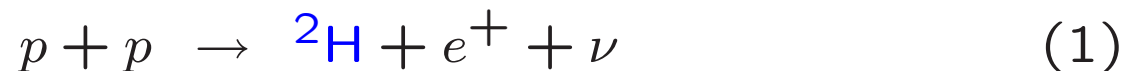


- ↳ fusion → mass reduction!
- rest mass decrease → energy release!

## Where Does the Energy Go?

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

recall *pp* chain:

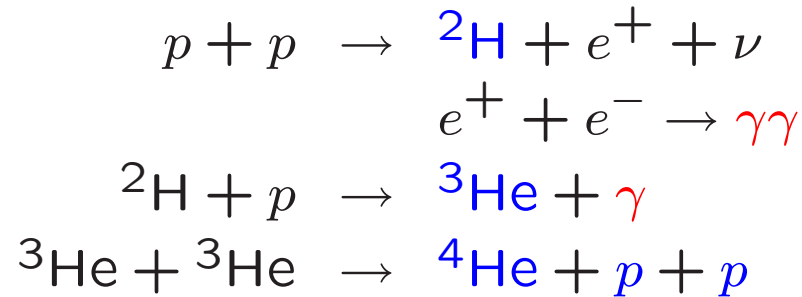


in each reaction in chain

mass energy is released:  $m_{\text{final}} < m_{\text{initial}}$

Q: *where does that energy go?*

Q: *how does this ultimately lead to Sunlight?*

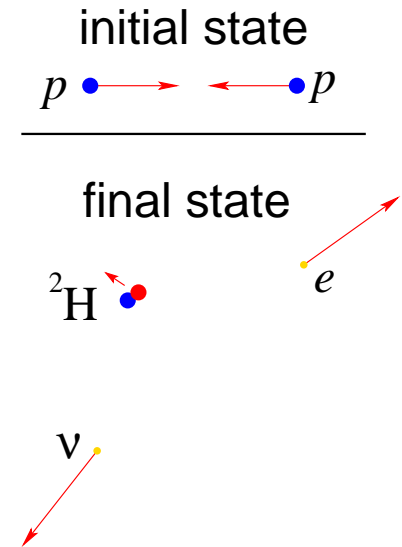


★ for final state **nuclei**:

energy goes to *motion*:  $v_{\text{nucleus}} \gg v_T$

⇒ large *kinetic energy*

then gradually slow, mostly via Coulomb scattering  
 → *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**  $4p \rightarrow {}^4\text{He}$  fusion:

$$Q = \Delta\varepsilon = \Delta mc^2 = 28 \text{ MeV} = 4.5 \times 10^{-12} \text{ Joules}$$

Estimate Solar fusion energy supply:

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

if **all** Sun's hydrogen is fuel, can burn for

$$\tau_{\text{fuse}} = E_{\text{fuse}}/L = 3 \times 10^{18} \text{ sec} = 100 \text{ billion years!}$$

## iClicker Poll: Solar Nuclear Lifetime

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

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 of its hydrogen*

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

true lifetime:  $\tau_{\odot} \sim 1 \times 10^{10} \text{ yr} = 10 \text{ billion yrs}$

→ *Sun is middle aged*

will last another  $\sim 5$  billion yrs

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*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

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*Q: how could we be so sure?*

Can we get even more direct confirmation?

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*Q: is another way to confirm the Sun is a nuclear reactor? A  
“smoking gun” signature?*

## The Evidence: Solar Neutrinos

If the Sun takes  $4p \rightarrow {}^4\text{He} = \boxed{2p2n}$

then it *must* convert  $2p \rightarrow 2n$

→ *must* produce neutrinos!

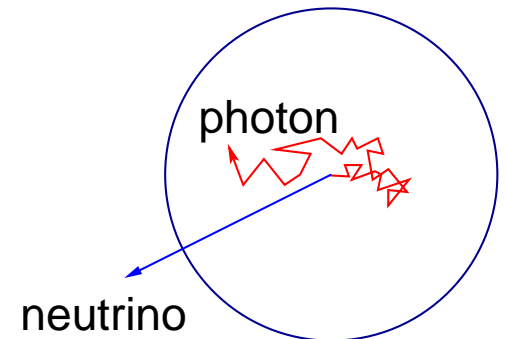
in fact: most made via  $pp \rightarrow de^+ \nu$

The Sun radiates neutrinos as well as photons!

...we are bathed in solar “neutrinoshine”

Moreover:

- since  $\nu$  are weakly interacting  
they come directly from the solar core  
→ messengers from the center of the Sun!
- but luckily, *weakly* interacting  $\neq$  *non*-interacting  
⇒ 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  $\nu$  interactions  
with nuclei or electrons

all use huge underground detectors

*Q: why huge? why underground?*

# Solar Neutrino Measurements I: Radiochemical Detectors

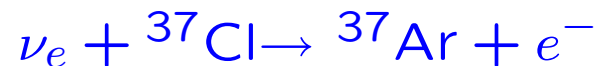
- **target:** huge vats of fluid
- **effect:** solar  $\nu$  changes one nucleus to another—alchemy!
- **detection:** capture atoms of new elements  
infer existence and flux of solar neutrinos

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:



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

$$\nu_e + e \rightarrow \nu_e + e$$

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:  $\nu$ s point back to Sun (check)

## Solar Neutrino Experiments: Results

- ★ All experiments detect solar  $\nu_s$ !
- ★ 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.  $\nu$ s give direct view into solar core
- III. these underground vats are  $\nu$  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 Takaaki Kajita

## Solar Neutrino Experiments: A Deeper View

**1960s:** original chlorine radiochemical experiment (Ray Davis):

- sensitive only to a small component of very high-energy  $\nu$ s
  - signal detected, but flux  $\Phi_{\nu}^{\text{obs}} \approx \Phi_{\nu}^{\text{predicted}}/3$
- 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”)*

$\nu_e, \nu_{\mu}, \nu_{\tau}$ : named for partner they appear with

solar neutrinos produced as  $\nu_e$ : should remain so

→ 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  $\nu_e$
- can arrive at Earth as  $\nu_\mu$  or  $\nu_\tau$  ● but radiochemical experiments only “see”  $\nu_e$

To test:

build detectors sensitive to *all flavors*

this was done: Sudbury Neutrino Observatory (SNO)

**early 2000s:** SNO results weigh in

- $\nu_\mu$  and  $\nu_\tau$  *detected* from Sun!
- *total flux* for *all  $\nu$*  *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.

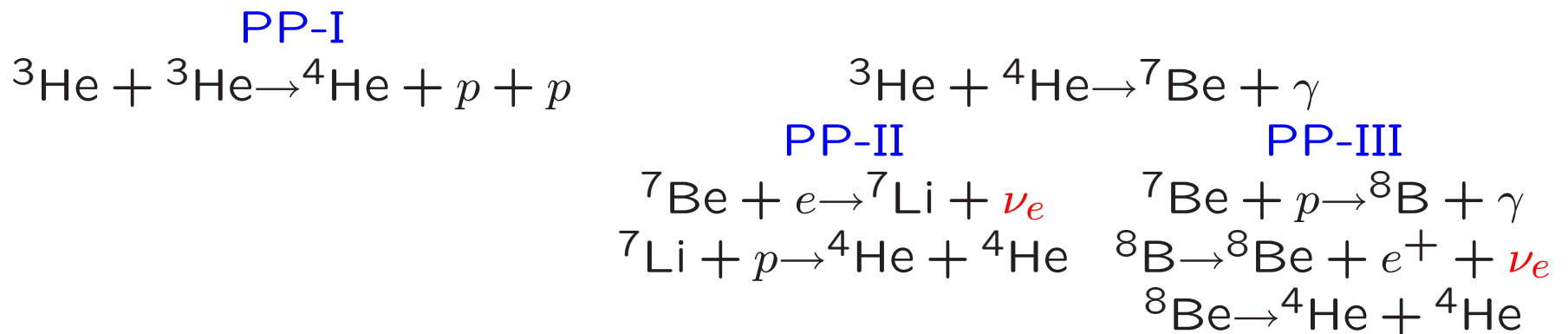
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# Director's Cut Extras

## An Alternative to the $pp$ Chain



minor additions to energy and neutrino generation:

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

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

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

${}^7\text{Be}$  branching is key:

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

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