The Structure of the Sun

Lecture 2

The energy source of the Sun

and

measuring the central temperature of the Sun

1939 H.Bethe conceives the CNO cycle:

Fusion of 4p into He with CNO nuclei as catalysts.

1950-60 Fowler et al. conceive the pp-chain: direct formation of heavier elements by Hydrogen fusion.

Today we know that stars with masses < 1.5Msun generate energy via the pp and more massive stars via the CNO cycle.

The slowest step

The pp chain

Reaction		Products	Mean life time In the Sun
p + p	→	$^2D + e^+ + \nu$	7.9×10^{9} *yrs*
^2D + p	→	$^3He + \gamma$	4.4×10^{-8} *yrs*
$^3He + {}^3He$	→	^4He + 2p	2.4×10^{5} *yrs*
$^3He + {}^4He$	→	$^7Be + \gamma$	9.7×10^{5} *yrs*
$^7Be + e^-$	→	$^7Li + \gamma + \nu$	3.9×10^{-1} *yrs*
^7Li + p	→	$^4He + {}^4He$	1.8×10^{-5} *yrs*
^7Be + p	→	$^8B + \gamma$	6.6×10^{1} *yrs*
^8B	→	$^8Be + e^+ + \nu$	
^8Be	→	$^4He + {}^4He$	3×10^{-8} *yrs*

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p + p ⟶ $He^2 + \gamma$ + Q **Can this happen?**

He^2 ⟶ $D^2 + e^+ + \nu$ + Q

He^2 does not exist in nature. The strong force does not generate a nuclear potential well that is deep enough to have a bound state.

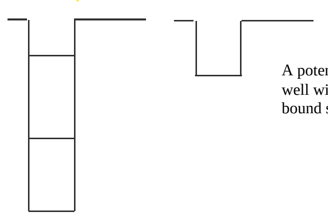
The basic difference between the two processes is that in (i) the available time is the passage time while in (ii) there is all the time.

If He^2 existed in Nature than the rate would have been 10^{19} times faster (the ratio strong force/weak force)

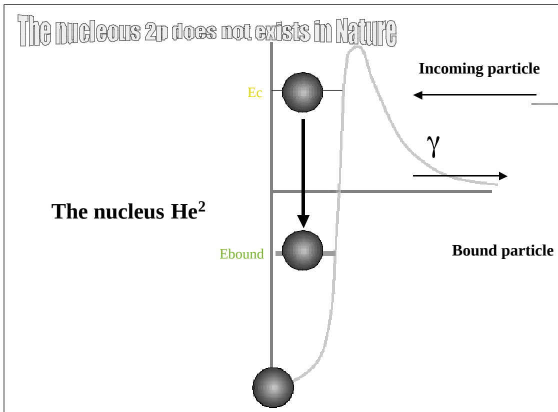
$$\frac{\text{scattering}}{D^2\text{formation}} \approx \frac{\text{Coulomb force constant}}{\text{Weak force constant}}$$

$$= \frac{\left(e^2 / \hbar c\right)^2}{g_\beta^2} = \frac{10^{-4}}{10^{-23}} = 10^{19}$$

A potential well with bound states



A potential well without bound states



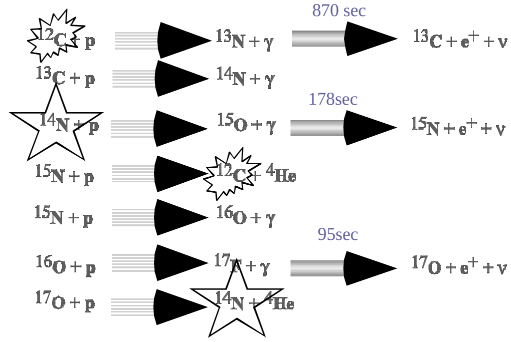
If the rate of fusion is increases, than the extreme energy would have caused an expansion of the sun until its energy generation would agree with what the surface can radiate (Balance of energies)

Recall $T = \alpha \dfrac{GM}{(k/m)R}$

So, the expansion cools the sun and reduces the nuclear reaction.

The exact calculation shows that if the rate would have been the one dictated by the strong force than Rsun ~ 1AU=the radius of the Earth orbit.

The CNO Cycle



Can we trace the nuclear reaction by capturing the neutrinos?

We are familiar with the historic astronomy in the visible

We saw the Sun in x-rays

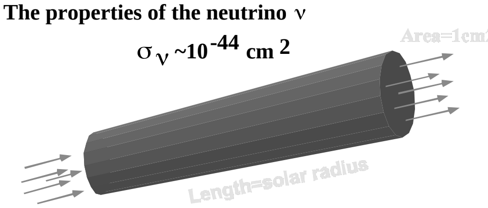
So far we discussed only photons

Observations of particles emitted by cosmic objects

The new era of neutrino astrophysics

The properties of the neutrino ν

$\sigma_\nu \sim 10^{-44}$ cm ^{2}



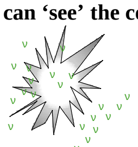
$$P = \sigma_\nu R_{sun} \langle \rho \rangle N_A$$

$$= 10^{-44} \; 6.96 \times 10^{10} \; 1.4 \; 6.0 \times 10^{23}$$

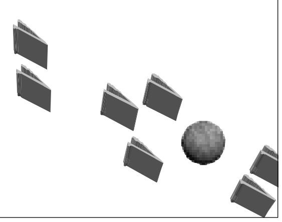
$$= 6 \times 10^{-10}$$

Practically, ALL neutrinos formed in the sun escape.

The sun is transparent to neutrinos. With neutrinos we can 'see' the core of the sun. If we could detect them.



The idea is to detect the ν from the sun and 'observe' the core of the sun.



What is the mean free path of the ν in the Universe?
Mean galactic density 1particle/cc
Mean Universe density: much lower

$$l_\nu = \frac{1}{\sigma_\nu n} = 10^{44} cm = 10^{26} lyrs$$

This distance is much greater than the distance to the horizon, which is the age of the Universe in light years.

So all ν released by stars during the history of the Universe fly in all directions throughout the entire cosmos. The Universe is full of neutrinos!

What is the photon mean free path in the sun?

$$\sigma_{ph} \quad 10^{-24} cm^2$$

$$l_{photon} \sim \frac{1}{\sigma_{ph}\rho N_A} = 1cm$$

How long it takes for a photon to escape from the Sun?

The total distance is the radius of the Sun

which is N=R_{sun}/l_{photon}= 7x10^{10} steps

But the process is a random process and hence the γ needs N^2 steps.

Hence the time to escape is:

$$t = \frac{N^2 1cm}{c} = 1.2 \times 10^5 yrs$$

A more accurate calculation yields exactly the Kelvin-Helmholtz timescale.

If energy generation in the sun ceases, it will take the Kelvin-Helmholtz years for the surface to change!

What is the neutrino flux at the Earth?

The solar constant (the solar energy flux at the top of the atmosphere) is: $1.97 cal/cm^2 \min$

which is: $0.88 MeV \times 10^{12} MeV$

But: $4p \rightarrow He^4 + 2\nu + 26.2 MeV$

In the conversion of H to He there are two β decays and hence two ν are emitted per one He.

$$\varphi_\nu = 2 \times 0.88 \times 10^{12} / 26.2 = 7 \times 10^{10} \ \nu / cm^2 \sec$$

Is it possible to detect this flux of ν?

Consider a 1ton detector with density of 1gm/cc. Assume the detector exposes 1cm^2 but contains 1ton of matter. The number of ν per day going through this detector is:

$$6.7 \times 10^{10} \times 8.6 \times 10^4 = 5.8 \times 10^{15}$$

The number of events per day in the detector is :

$$10^{-44} \times 5.8 \times 10^{15} \times 10^6 N_A = 58$$

It is in principle doable, but the problem in cosmic noise.

The first experiment in ν astronomy: Davis experiment

The Homestake solar neutrino experiment (Davis):

$$Cl^{37} + \nu_{solar} \ \nu \ Ar^{37} + e^- - 0.814 MeV$$

Take the liquid CCl_4 **or** C_2Cl_4

Expose it to the sun and collect the Argon gas. The Argon decays back and the Chlorine atom is recovered. The decay is via the emission of an X-ray photon and an electron.

The threshold for the reaction is 0.814MeV.

Hence, the pep neutrinos cannot be detected in this experiment.

Only ν from two reactions can be observed in the Homestake experiment:

$$Be^7 + e^- \longrightarrow Li^7 + \nu + 0.861 MeV$$

$$B^8 \longrightarrow (Be^8)^* + e^+ + \nu + 7.7 MeV$$

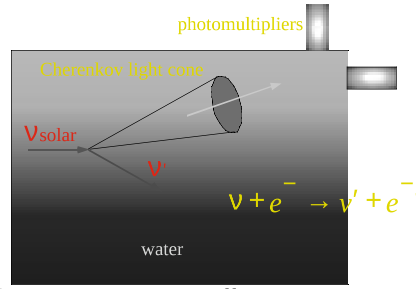
a) The basic Cl reaction has a resonance at 5.14Mev

b) The cross-section increases very quickly with energy

The Davis experiments measures the Boron ν. One in 10000 He nuclei is formed this way.

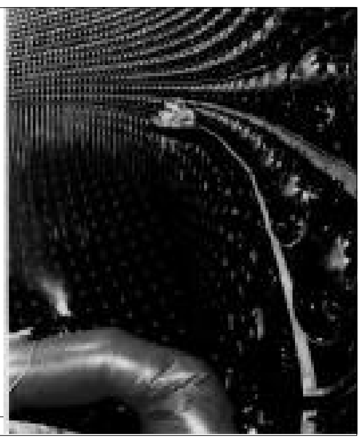
There are so many neutrinos that few can be captured by a giant detector!

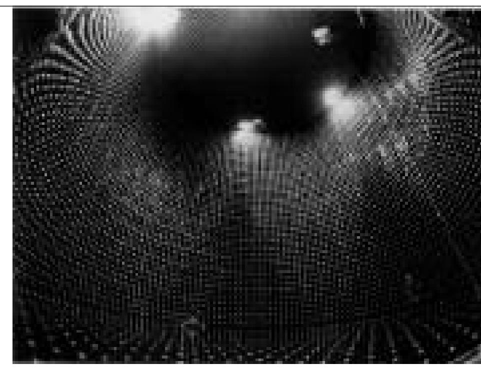
The Super Kamiokanda Underwater experiment



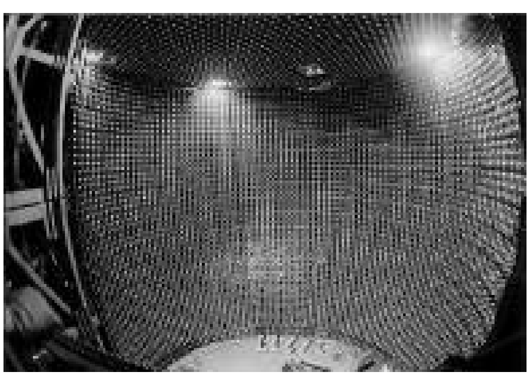
The 'neutrino Compton effect'

Inside the Super Kamiokanda clean water tank

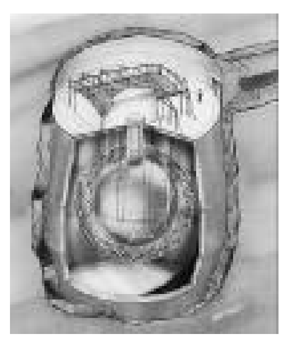


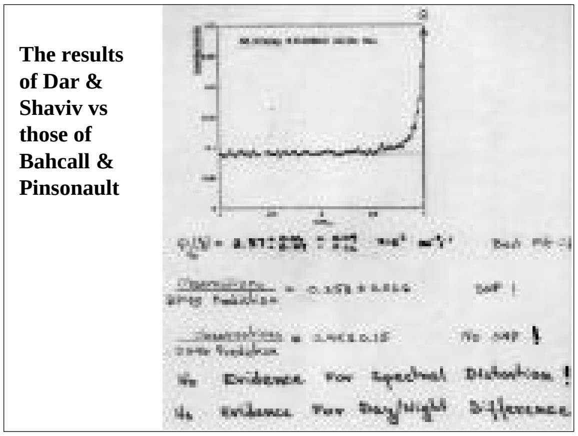


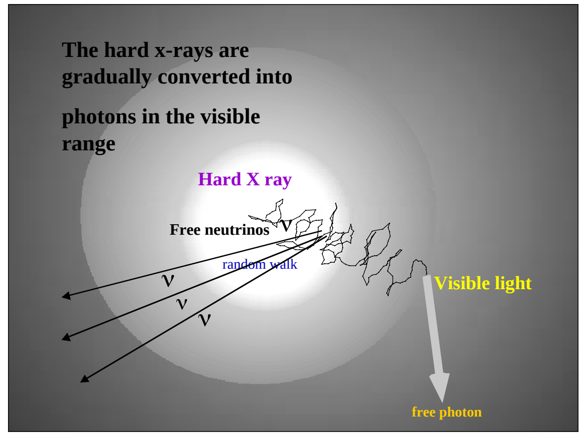
The famous boat of super kamiokanda

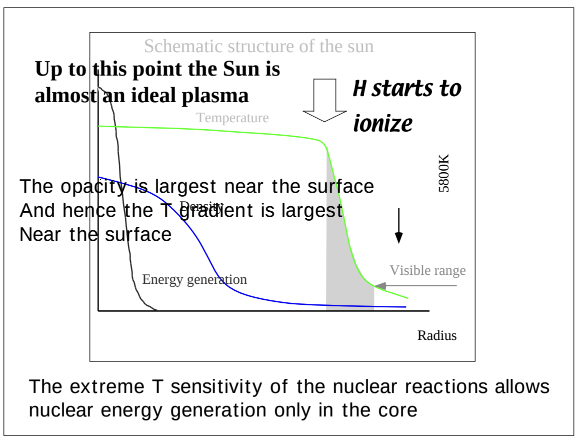


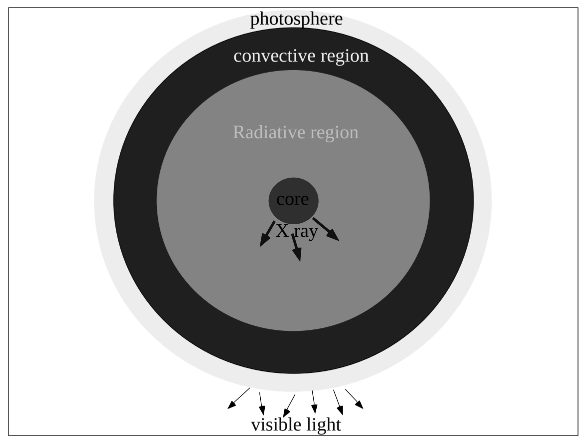
The SNO experiment




The results
of Dar &
Shaviv vs
those of
Bahcall &
Pinsonault


The hard x-rays are
gradually converted into
photons in the visible
range
Hard X ray
Free neutrinos
ν
random walk
ν
ν
ν
Visible light
free photon


Schematic structure of the sun
Up to this point the Sun is
almost an ideal plasma
H starts to
ionize
Temperature
5800K
The opacity is largest near the surface
And hence the T gradient is largest
Near the surface
Density
Energy generation
Visible range
Radius
The extreme T sensitivity of the nuclear reactions allows
nuclear energy generation only in the core


photosphere
convective region
Radiative region
core
X ray
visible light