Universe starts w/ all hydrogen

(Any free n's decay)

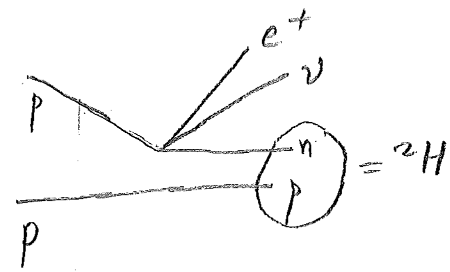
How do heavier elements form?

Need neutrons

$p \not\rightarrow n e^+ \nu$

but

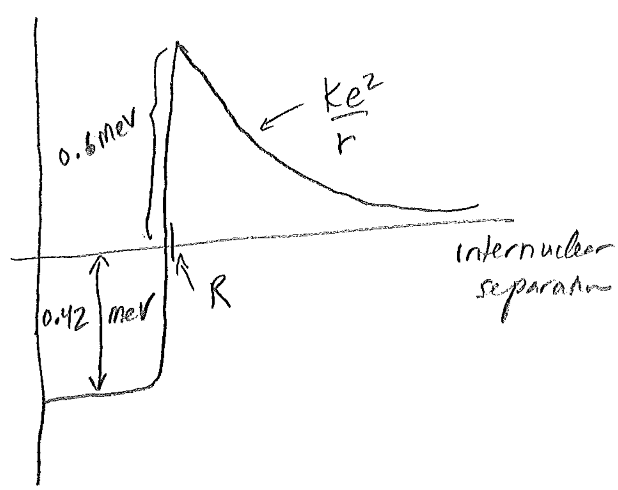
$pp \longrightarrow {}^2H\, e^+ \nu$



$$Q = 2[\Delta(^1H) - m(e^-)] - [\Delta(^2H) - m(e^-)] - m(e^+) - m(\nu) = 0.420 \text{ MeV}$$

$$[\,2(7.289) - 13.136 - 1.022 = 0.420\,]$$

Coulomb barrier to fusion



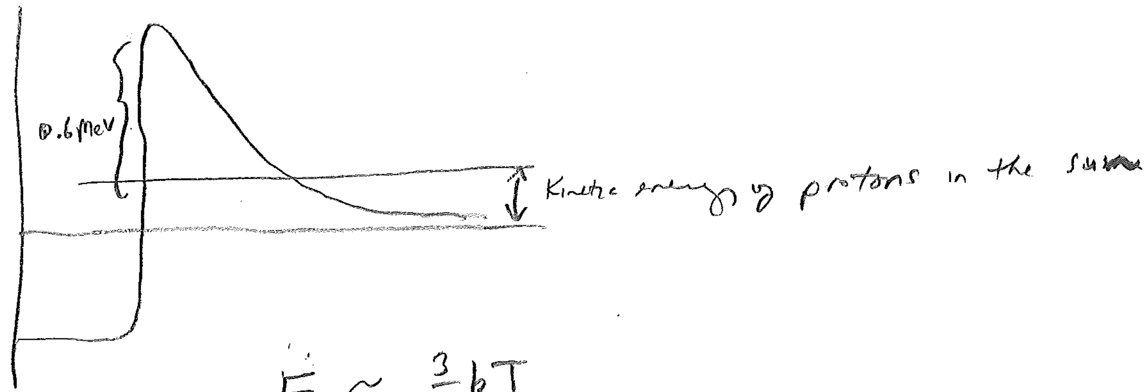
If $R = 2r_0 = 2.4$ fm

$$U = \frac{ke^2}{R} = \frac{ke^2}{\hbar c}\frac{\hbar c}{R}$$

$$= \frac{1}{137}\frac{(200 \text{ MeV fm})}{(2.4 \text{ fm})} = 0.6 \text{ MeV}$$

If protons can get close enough (despite EM force), the weak force can convert $p \rightarrow n e^+ \nu$ and the strong force cause $n + p$ to form ^2H, releasing energy.

[delicate interplay btw 3 forces (actually 4) because need gravity to cause compression & produce high temps]



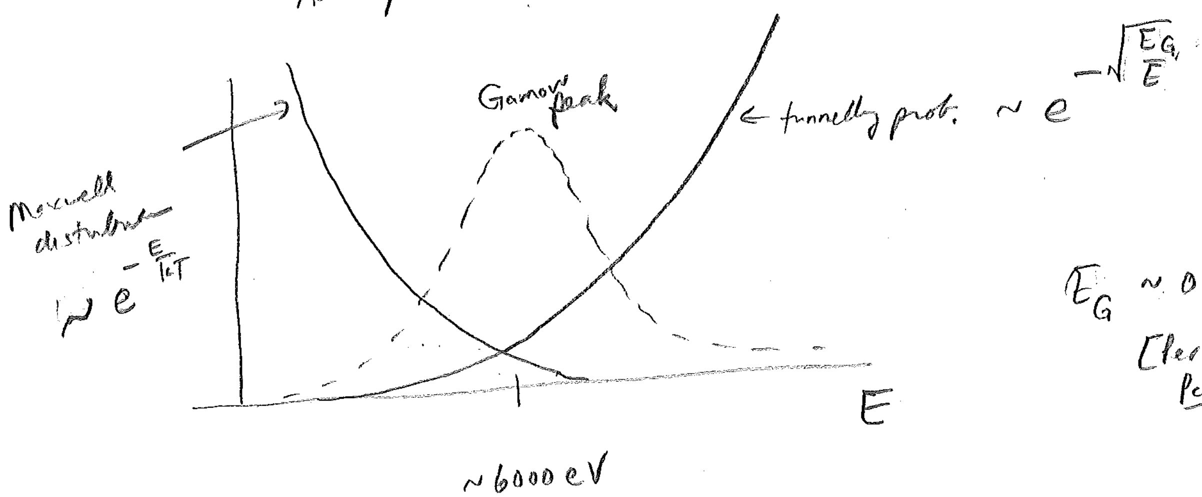
$$E \sim \frac{3}{2} kT$$

$T \sim 15.8$ million K $\Rightarrow \frac{3}{2}\left(\frac{1.5E7}{3E2}\right)\frac{1}{40}\,eV = 2000\ eV$

(would need $T \sim 5\times10^{9}$ K to overcome barrier)

but protons have a Maxwellian distribution (tail)

Also protons can tunnel through barrier



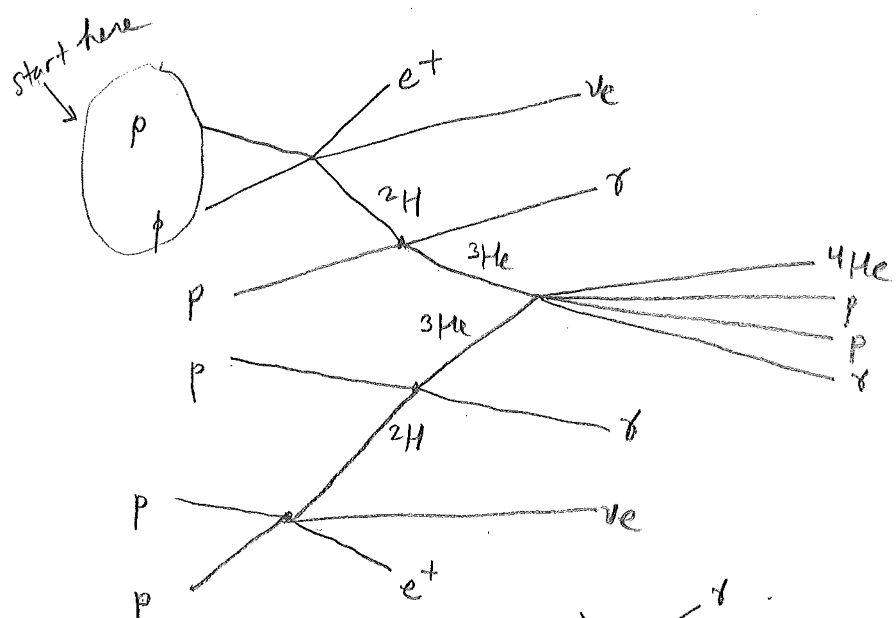
$E_G \sim 0.49$ MeV, [Phillips, p. 192] Phil Astro

Next stages

$p\ {}^2H \longrightarrow {}^3He\ \gamma$ $Q = 5.50$ MeV   [5.494]

85% ${}^3He\ {}^3He \longrightarrow {}^4He\ p\ p\ \gamma$ $Q = 12.86$ MeV   [12.859]

Altogether



[Then add in 2 places]

↳ releases $2(0.511\text{ MeV}) = 1.02$ MeV

Total pp cycle:

$$6p + 2e^- \longrightarrow {}^4He + 2p + 7\gamma + 2\nu_e$$

Energy released in pp cycle:

$2(0.42) + 2(5.50) + 12.86 + 2(1.02) = 26.7$ MeV

Alternatively

$6[\Delta(^1H) - m(e^-)] + 2m(e^-) - [\Delta(^2He) - 2m(e^-)] - 2[\Delta(^1H) - m(e^-)]$

$= 4\,\Delta(^1H) - \Delta(^4He)$

$= 26.732$ MeV

But 0.5 MeV lost to ν so

26.2 MeV released for each ^4He produced

ie 6.5 $\frac{\text{MeV}}{\text{proton}}$ [about 0.6% of rest energy, more than fission] which is 1 MeV/proton

---

How long will sun shine? $M_\odot = 2\times10^{30}$ kg $= 2\times10^{33}$ g

How many protons? $=(2\times10^{33})(6\times10^{23}) = 1.2\times10^{57}$ protons

Assume that 10% of protons undergo fusion

Total energy release $\sim (1.2E57)(6.5\text{ MeV}) = 8\times10^{56}$ MeV

Solar output 4×10^{26} W $= 2.5\times10^{39}$ $\frac{\text{MeV}}{\text{sec}}$

At this rate, sun will last $\frac{8E56}{2.5E39} = 3E17$ sec

$= 10^{10}$ years

$= 10$ billion

We are about halfway thru.

If chemical rxns powered sun $\sim 10^4$ yrs $= 10{,}000$ yrs.
(0.5 eV/proton, but assume 100% $\Rightarrow$ factor of 10^6)

How many ν's emitted by sun?

$$\frac{\#\ ^4He\ \text{produced}}{\text{sec}} = \frac{2.5\times10^{39}\ \frac{\text{MeV}}{\text{sec}}}{26.2\ \text{MeV}} \sim 10^{38}\ \frac{^4He}{\text{sec}}$$

$$\Rightarrow 2\times10^{38}\ \frac{\nu}{\text{sec}}$$

Solar ν flux at earth $F = \dfrac{2\times10^{38}\ \frac{\nu}{\text{sec}}}{4\pi D^2} = 7\times10^{14}\ \dfrac{\nu}{m^2\cdot s}$

Ray Davis only found $\frac{1}{3}$ as many
"Solar neutrino deficit"

[visible photon flux at earth
$1600\ \frac{W}{m^2} = 10^{22}\ \frac{eV}{m^2\cdot s} = 3\times10^{21}\ \frac{\gamma}{m^2\cdot s}$
for 3 eV photons]

[ν energy flux at earth $= \left(7\times10^{14}\ \frac{\nu}{m^2\cdot s}\right)(0.25\ \text{MeV}) = \frac{2\times10^{20}\ eV}{m^2\cdot s} = 30\ \frac{W}{m^2}$

(avg E_ν → 0.25 MeV)

$(1600)\frac{(0.5)}{(26.7)}$ ✓

Extra

Other rxns relevant for solar neutrinos

$pe^- p \rightarrow {}^2H\ \nu \Rightarrow$ monochrom $E_\nu = \underline{1.442\ MeV}$

but this is 3 body rxn $\Rightarrow$ suppressed

15% $\quad {}^3He\ {}^4He \rightarrow {}^7Be\ \gamma \qquad Q = 1.587\ MeV$

then $\quad$ 99.9% $\quad e^-\ {}^7Be \rightarrow {}^7Li\ \nu \qquad E_\nu = \{0.383\ MeV,\ 0.861\ MeV\}$

$p\ {}^7Li \rightarrow {}^4He\ {}^4He$

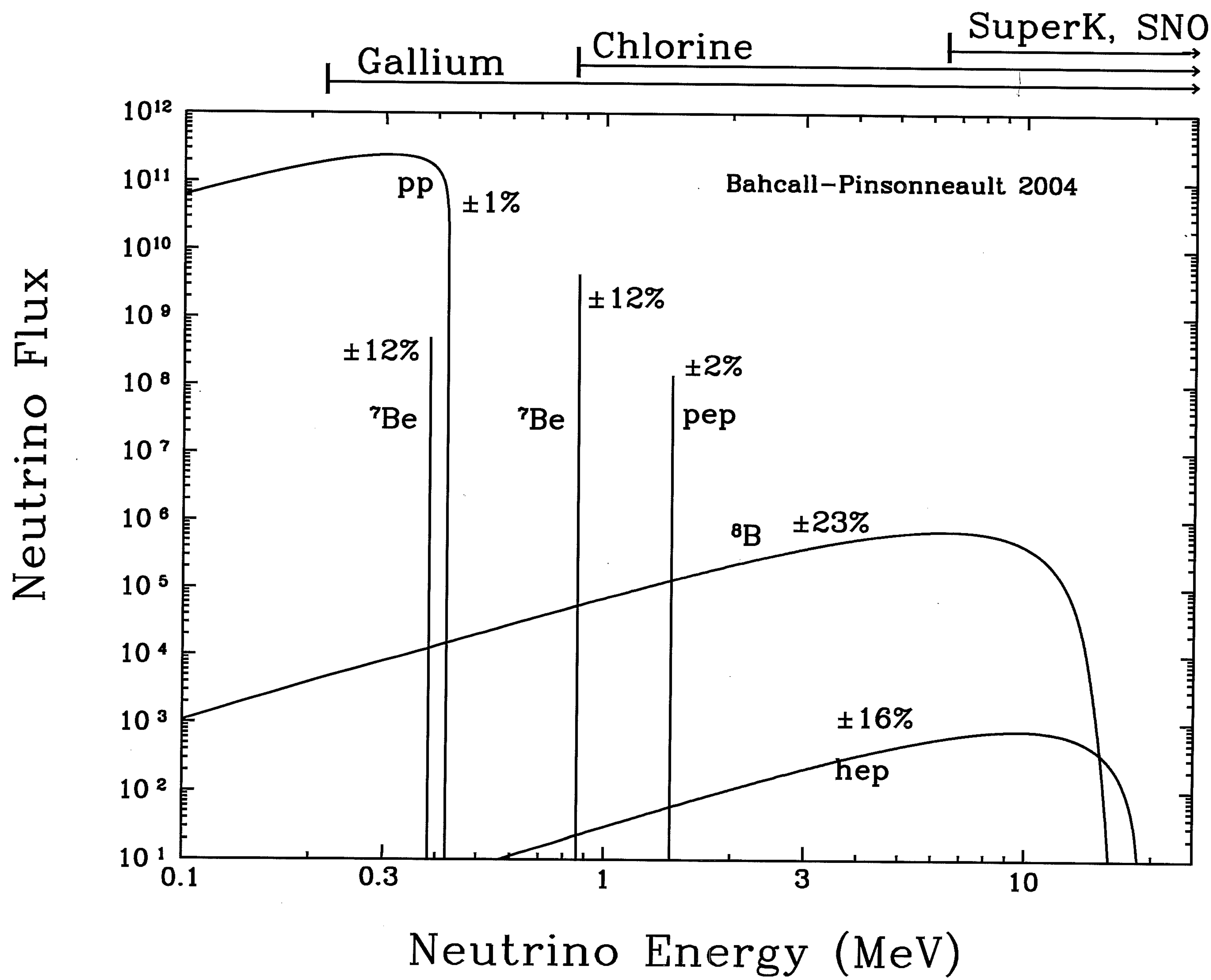
or $\quad$ 0.1% $\quad p\ {}^7Be \rightarrow {}^8B\ \gamma$

${}^8B \rightarrow {}^8Be\ e^+\ \nu \qquad (E_{\nu,max} = 15\ MeV)$

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

Also, above 15E6 K, CNO cycle is more important in Sun

$${}^4He + {}^4He + {}^4He \rightarrow {}^{12}C + \gamma \qquad Q = 7.3\ MeV$$



Gallium
Chlorine
SuperK, SNO
Bahcall−Pinsonneault 2004
pp
±1%
±12%
^{7}Be
^{7}Be
±12%
±2%
pep
^{8}B
±23%
±16%
hep
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
0.1
0.3
1
3
10
Neutrino Flux
Neutrino Energy (MeV)

(15%) $3He\ ^4He \to \gamma\ ^7Be$

99.9% $e^-\ ^7Be \to \nu_e\ ^7Li$ ($E_\nu = 0.383,\ = 0.861$)

$p\ ^7Li \to ^4He\ ^4He$

0.1% $p\ ^7Be \to \gamma\ ^8B$

$^8B \to ^8Be\ e^+ \nu_e$ $\Rightarrow (E_\nu)_{max} \approx 15$ MeV

$^8Be \to ^4He\ ^4He$

show standard graph of ν's from sun

(perchloroethylene)

Ray Davis, Homestake gold mine, SD, 1970 → present

looked for ν_e from ^8B + ...

only found $\frac{1}{3}$ ⇒ cd ν oscillate? ⇒ or is solar model prediction wrong?

$\nu_e\ ^{71}Ga \to e^-\ ^{71}Ge$ threshold 0.23 MeV

SAGE (Russia)
GALLEX (Rome) } about $\frac{1}{2}$?

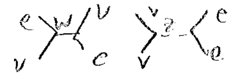
Kamiokande $\nu_e e^- \to \nu_e e^-$ ↳ Cerenkov threshold ≈ 7 MeV

(about $\frac{1}{2}$ expected)

SNO: $\nu_e d \to e^- pp \Rightarrow \phi(\nu_e)$

$\nu_e d \to \nu p n \Rightarrow \phi(\nu_e) + \phi(\nu_\mu) + \phi(\nu_\tau)$

$\nu e^- \to \nu e^- \Rightarrow \phi(\nu_e) + \frac{\phi(\nu_\mu) + \phi(\nu_\tau)}{6.5}$



$\Rightarrow$ SNO $\Rightarrow \frac{\phi(\nu_e)}{\phi(tot)} = 0.3$ indep of flux p.i.e. for fusion reactor

Fusion reactions : ~~require~~

$d + d \longrightarrow {}^3He + n$ $Q = 3.3$ MeV

$\longrightarrow {}^3H + p$ $Q = 4.0$ MeV

$d + t \longrightarrow {}^4He + n$ $Q = 17.6$ MeV

$t = {}^3H$

require: 400 million K

(deuterium = $\frac{1}{6500}$ Hydrogen)

Origins of Supernovae

Major thermonuclear reactions:

Reaction	Ignition temperature (in millions of deg K)
$4\ {}^{1}H \dashrightarrow {}^{4}He$	10
$3\ {}^{4}He \dashrightarrow {}^{8}Be + {}^{4}He \dashrightarrow {}^{12}C$	100
${}^{12}C + {}^{4}He \dashrightarrow {}^{16}O$	
$2\ {}^{12}C \dashrightarrow {}^{4}He + {}^{20}Ne$	600
${}^{20}Ne + {}^{4}He \dashrightarrow n + {}^{23}Mg$	
$2\ {}^{16}O \dashrightarrow {}^{4}He + {}^{28}Si$	1500
$2\ {}^{16}O \dashrightarrow 2\ {}^{4}He + {}^{24}Mg$	4000
$2\ {}^{28}Si \dashrightarrow {}^{56}Fe$	6000

$n = \frac{\# \text{protons}}{cm^3} = \left(2 \frac{\text{protons}}{\text{molecule}}\right)\left(6E23 \frac{\text{molecules}}{\text{mole}}\right)\left(\frac{\text{mole}}{18\,g}\right)\left(\frac{g}{cm^3}\right) = 0.7 \times 10^{23} \frac{p}{cm^3}$

Vol = 4 × 10^5 cm^3 = 400 l

18.3 cm × 182 cm × 2(7.6 cm)

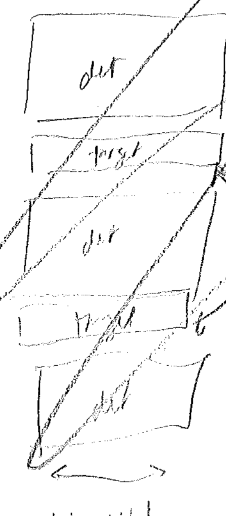
6'' × 4 1/2'' × 6'' = 4 × 10^5 cm^3

(Asimov)

flux = 1.2 × 10^{13} ν/cm²/sec

3 events/hour

1956 announced → = 70 events (hour)/day (w/ reactor running)



$\sigma = \frac{\text{event rate}}{F \cdot n \cdot V \cdot \text{eff}}$ = $\frac{(3.0/3600\ s^{-1})}{(1.2E13\ cm^{-2}s^{-1})(0.7E23\ cm^{-3})(4E5\ cm^3)}\left(\frac{1}{\text{eff}} = \frac{1}{0.025}\right)$

2.7 × 10^{28}

= 1E−43 cm^2

1956: σ_{exp} = 6E−44 cm^2 ± 25%

(10^{-43} cm expected at E_ν = 1 MeV) ← ave energy from Uranium fission fragments

(p-p ... 2.2 × 10 ... ??)

$\frac{1}{n\sigma} = \frac{cm}{10^{23} \cdot 10^{-43}} = 10^{20}$ cm = 100 ly

1 light yr = (3×10^7 s)(3×10^{10} cm/s) = 10^{18} cm

HW

10^{-19} barn

10^{-24} cm² = 1 b

10^{14} b

10^{-28} m² = 1 b

10^{-19} cm²

Asimov

^{238}U 6200 ν/s·kg crust

^{40}K 900 ν/s·kg

232 370 ν/s·kg

⇒ 1.75E26 ν/sec for earth's crust

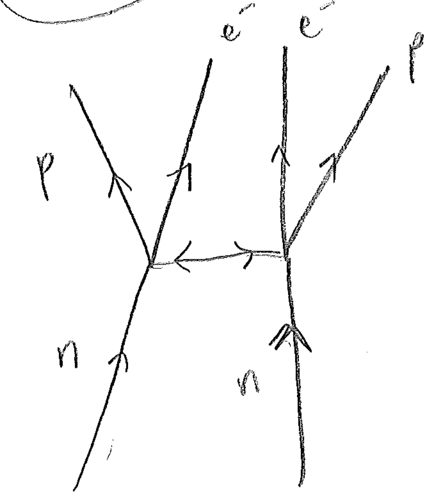
~~BD~~
~~DK~~
~~DT~~

Beyond the standard model

New type of neutrino (Majorana neutrino)
is its own antiparticle

=> double β-decay =>

0νββ



So far negative

β-decay ⇒ flavor change

$n \to p e^- \bar{\nu}_e$

$p \to n e^+ \nu_e$

Neutron-rich nuclei

${}^{A}_{Z}X \to {}^{A}_{Z+1}Y\, e^- \bar{\nu}_e$ ← show chart

Proton-rich nuclei

${}^{A}_{Z}X \to {}^{A}_{Z-1}Y\, e^+ \nu_e$ then $e^+e^- \to \gamma\gamma$ so $E_\gamma = 0.511$ MeV ⇒ γ prod.

or

$e^- \, {}^{A}_{Z}X \to {}^{A}_{Z-1}Y\, \nu_e$ electron capture

↳ S-shell electron

Double β-decay (single is energetically impossible)

${}^{A}_{Z}X \to {}^{A}_{Z+2}Y\, e^- e^- \bar{\nu}_e \bar{\nu}_e$ very long lifetime

eg ${}^{82}Se \to {}^{82}Kr$ (1987) $\tau = 10^{20}$ yrs.

[${}^{48}Ca \to {}^{48}Ti$ (1996)]