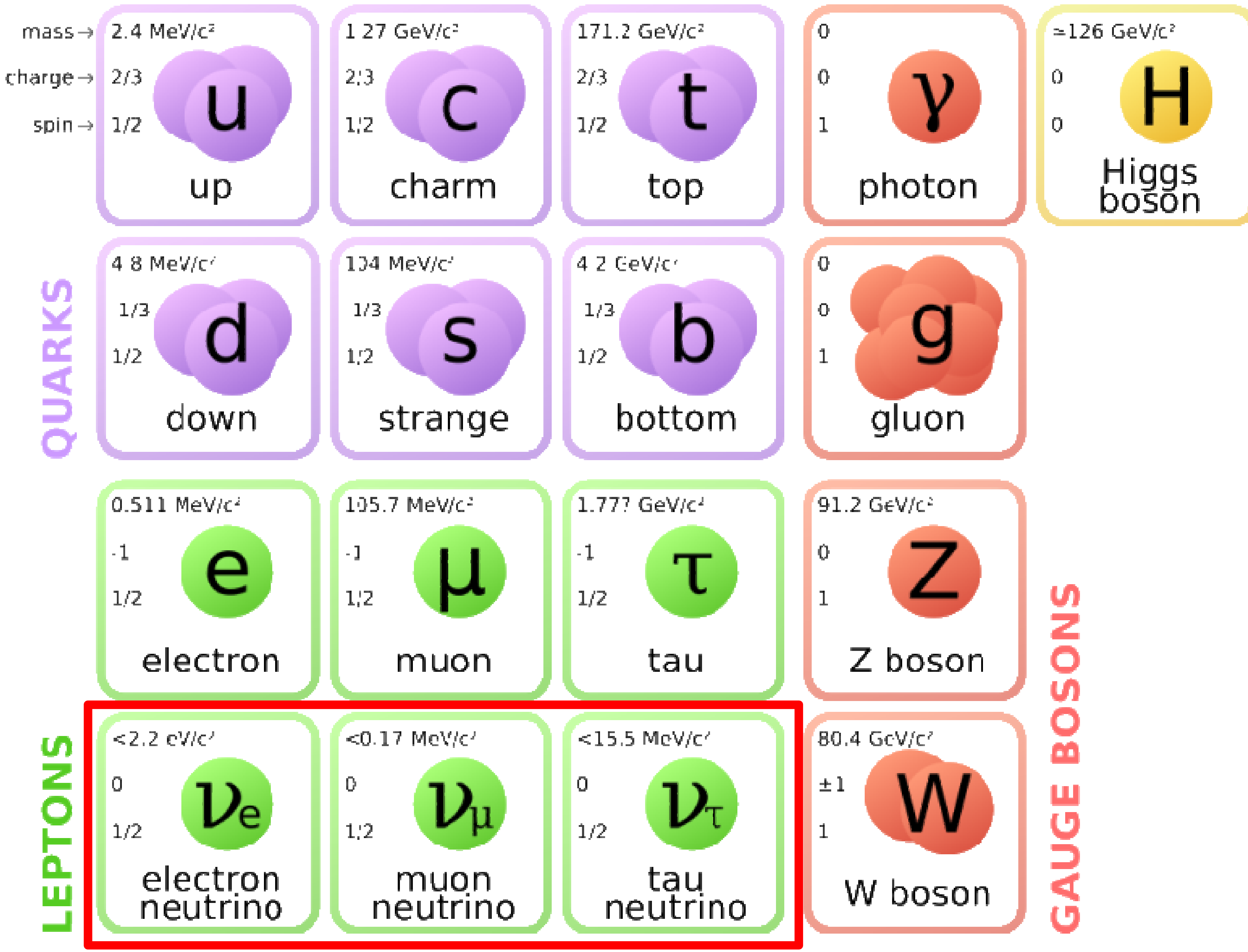
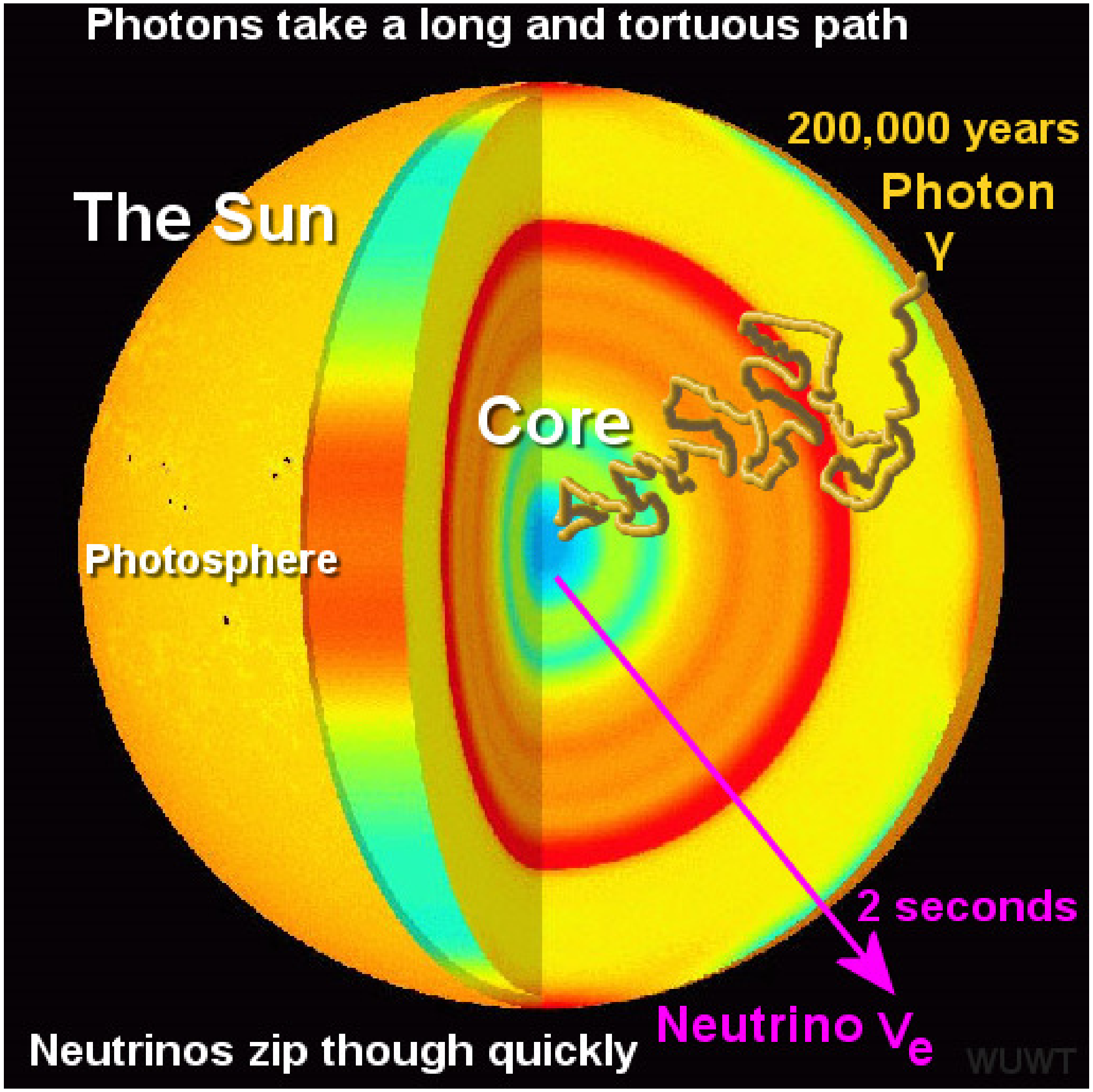
Neutrinos: the ghosts of the Universe



Credit: Wiki Commons

The puzzle of missing solar neutrinos



http://wattsupwiththat.com/2010/08/27/follow-up-on-the-solar-neutrinos-radioactive-decay-story/

A brief introduction:

What is the source of energy that makes the Sun shine?

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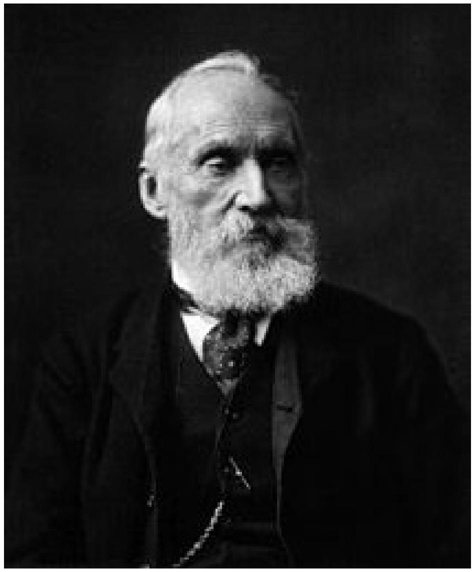


The Lord Kelvin
1824-1907
(William Thomson)

Absolute temperatures are stated in units of kelvin in his honor. He determined correct value of a lower limit to temperature (absolute zero) as –273.15 degree Celsius.

Kelvin's idea #1: meteors and asteroids might fall into the Sun at a regular rate, releasing large amounts of energy as they struck the Sun. Some of that energy would turn into heat, which in turn would radiate into space.

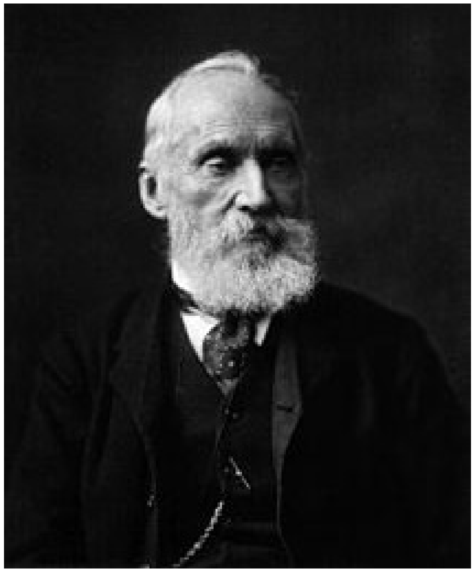
Idea #2: Sun formed from a giant gas cloud.

Gravity would eventually cause the cloud to collapse into a ball, since each molecule attracts all the other molecules.

As with any falling mass, the potential energy of molecules in the cloud would turn into kinetic energy as they fall and that energy will turn into heat.

http://rhig.physics.wayne.edu/~sean/Sean/Course_information_files/kelvinsunF.pdf

Lord Kelvin vs. Darwin

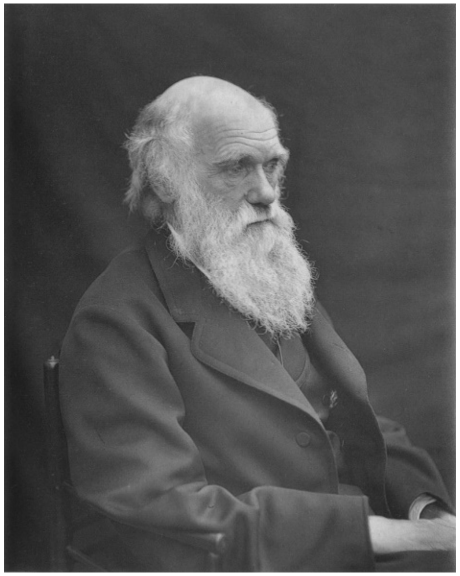


The Lord Kelvin
1824-1907
(William Thomson)

Resulting age of the Sun estimate:
~ 30 000 000 years

In contradiction with Darwin's estimate in the first edition of *On The Origin of the Species by Natural Selection* of 300 000 000 years.

Using thermodynamics, Kelvin also calculated that the temperature of Earth would have been too high even as recently as a million years ago to allow for life.



Charles Darwin
1809 - 1882

Major problem for the Darwin's theory of evolution:
1 000 000 years is too short for it to work!

http://rhig.physics.wayne.edu/~sean/Sean/Course_information_files/kelvinsunF.pdf

Albert Michelson

1852 –1931

Attitude at the end of the nineteenth Century

“**The more important fundamental laws and facts of physical science have all been discovered, and these are so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote.**”

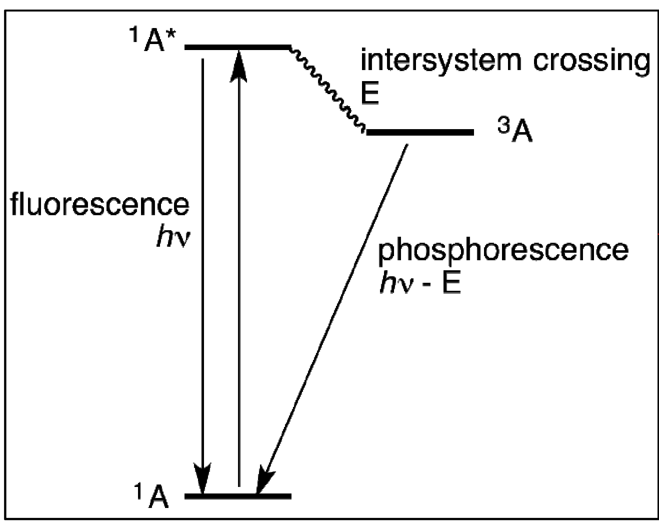
“… An eminent physicist remarked that the future truths of physical science are to be looked for in the sixth place of decimals.”

Source: 1894, dedication of Ryerson Physical Laboratory, quoted in Annual Register 1896, p.159

1896: Becquerel accidentally discovers radioactivity

Röntgen discovered i(invisible) X-rays in 1895. He determined that the X-rays could not be reflected by surface, or refracted by a prism or deflected by magnetic field so they appeared to be either light or charged particles.

Becquerel was looking for X-rays. He studied phosphorescence. Phosphorescent material re-emit the radiation it absorbs with a time delay and at a different wavelength. **Becquerel theorized that some material exposed to the Sun will then emit X-rays.**

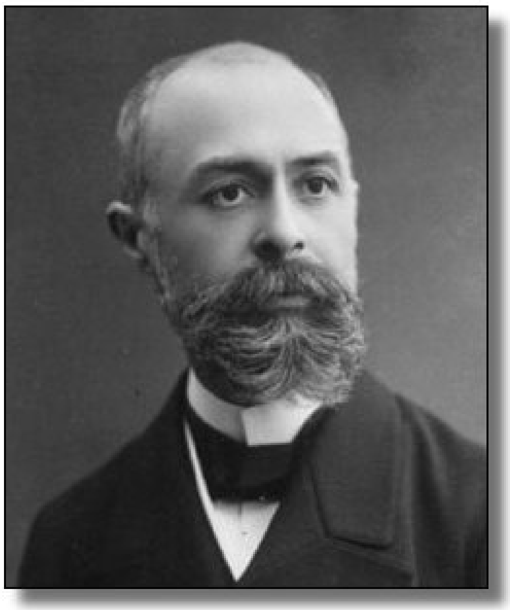


Here is how phosphorescence works but this nothing to do with radioactivity. You can't generate X-rays from visible light either.

By Wilhelm Röntgen. - [1] (National Aeronautics and Space Administration)., Public Domain, https://commons.wikimedia.org/w/index.php?curid=5059748

https://en.wikipedia.org/wiki/Phosphorescence#/media/File:JablonskiSimple.png

1896: Becquerel accidentally discovers radioactivity



Antoine Henri Becquerel 1852-1908

Becquerel theorized that some material exposed to the Sun will then emit X-rays.

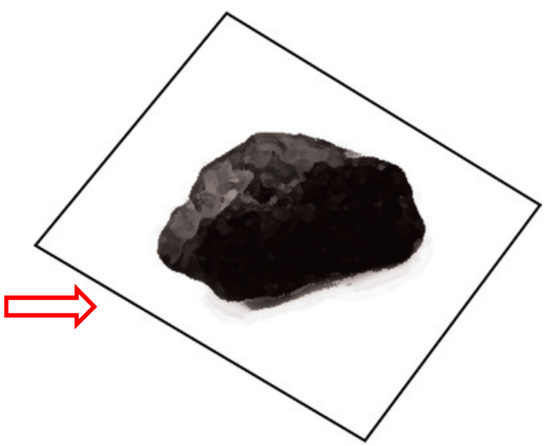
His experiment:

Rock resting on covered film.

Develop photographic plate

If no image, use another material

Becqurel was Professor at the Natural History Museum in Paris and has essentially inexhaustible supply of samples to try. He finally found that potassium uranul disulphate $K_2UO_2(SO_4)_2 2H_2O$ will blacken the photographic plate.



Shadow on developed film.

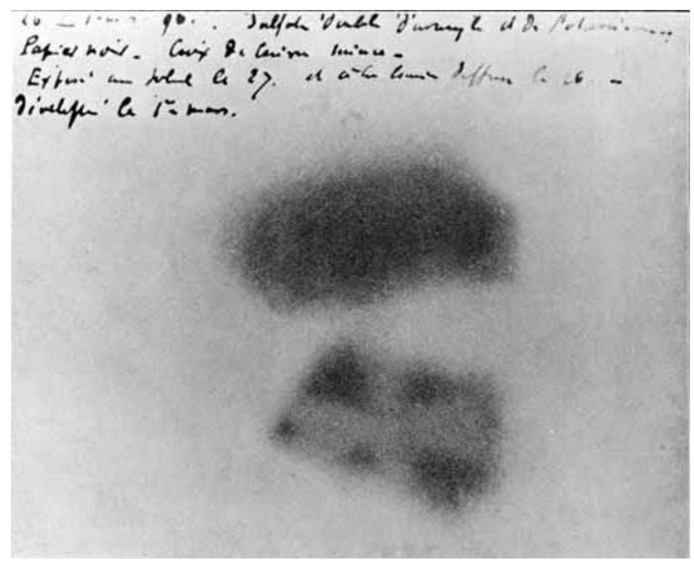
http://www.ck12.org/

1896: Becquerel accidentally discovers radioactivity

By some reason he still developed that photographic plate and still found a very clear image!

He repeated this experiment in the dark with the same effect.

In a different experiment, he was able to prove that the image was not caused by X-rays.



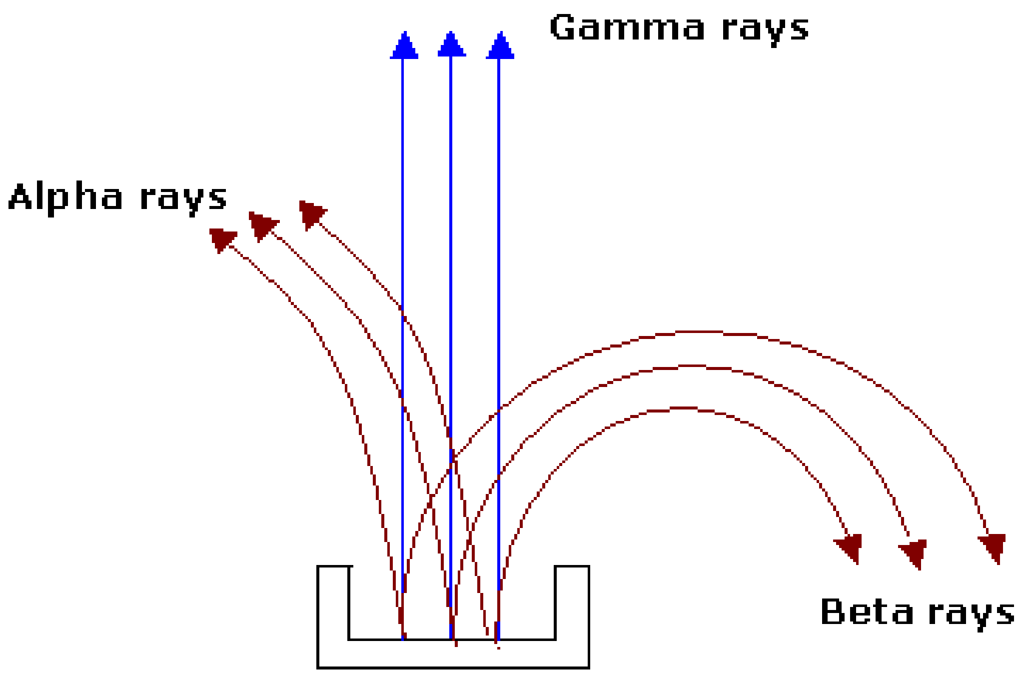
https://www.awesomestories.com/asset/view/Henri-Becquerel-Discovers-Radioactivity

Radioactivity … source of Sun energy???

Marie Curie studied this effect and named it “radioactivity”.
Radioactivity was proposed as source of Sun energy – but with obvious problem that Sun did not seem to have uranium, thorium, radium, etc. …

It did take quite time to sort out what radioactivity was … three different types of “rays” were identified.

Marie Curie
1903 Nobel Prize in Physics
1911 Nobel Prize in Chemistry



Deflection in magnetic field

What is the source of energy that makes the Sun shine?

Marie Curie studied this effect and named it "radioactivity". Radium salts constantly release heat so radioactivity was proposed as source of Sun energy – but with obvious problem that Sun did not seem to have uranium, thorium, radium, etc. …

It did take quite time to sort out what radioactivity was … three different types of "rays" were identified.

Marie Curie
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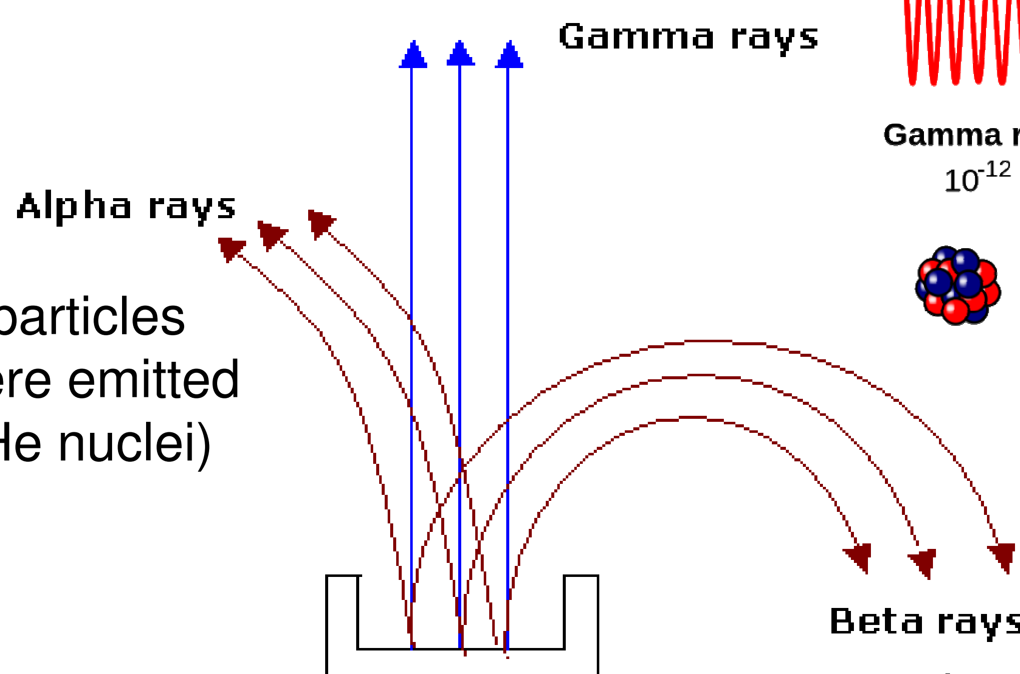
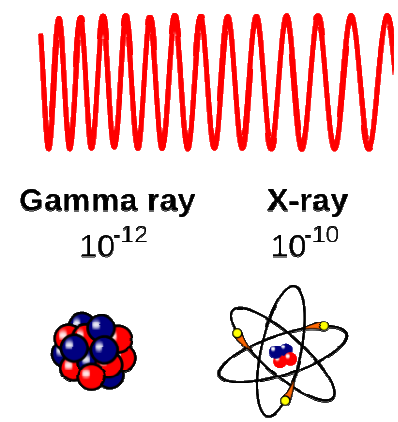




α-particles were emitted (^{4}He nuclei)

electrons were emitted

Deflection in magnetic field

Ernest Rutherford

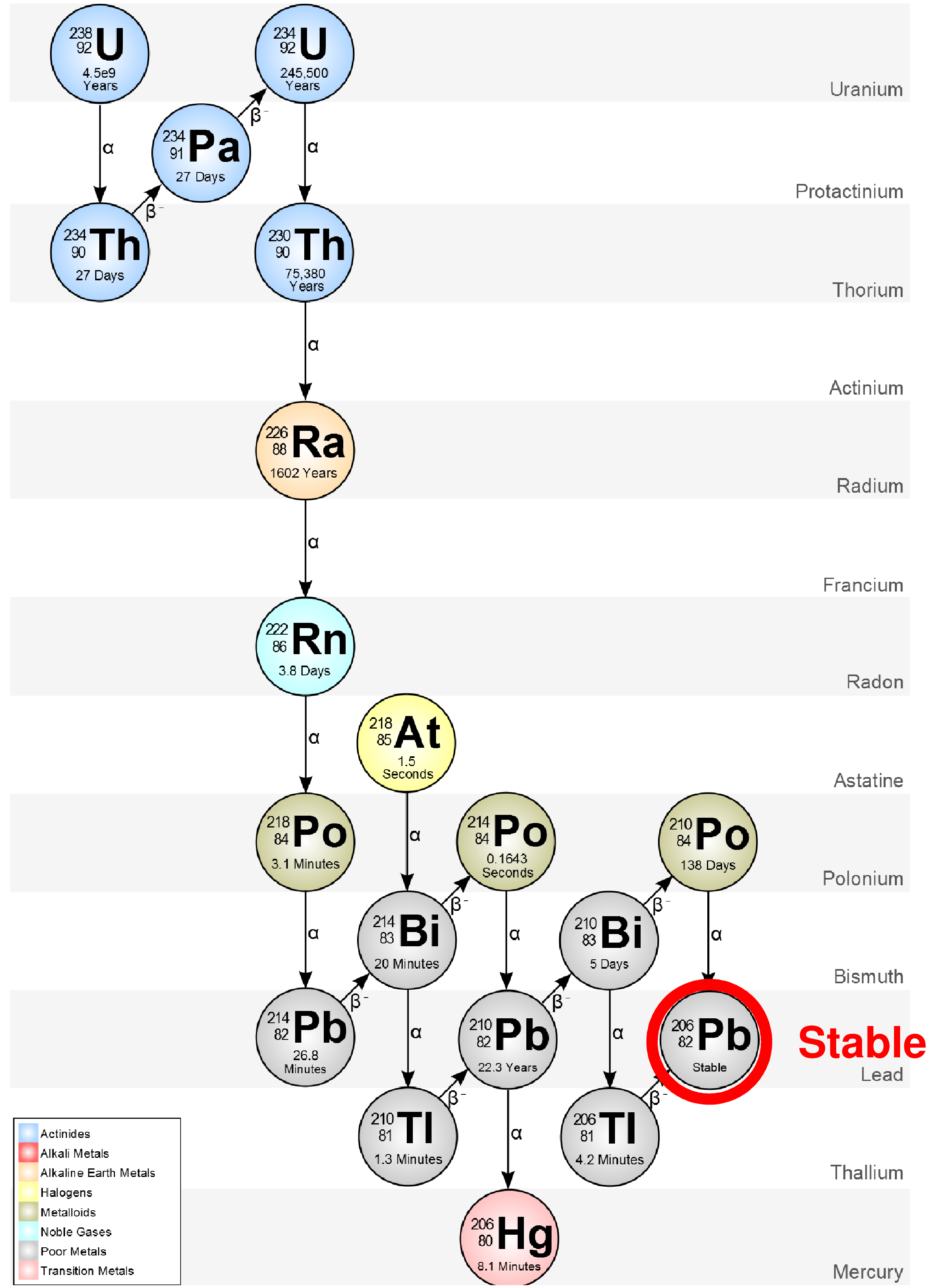
^{238}U

Radioactive decay chain

Note:
238 is atomic weight A
92 is nuclear charge Z

No wonder that it took some time to figure it out!

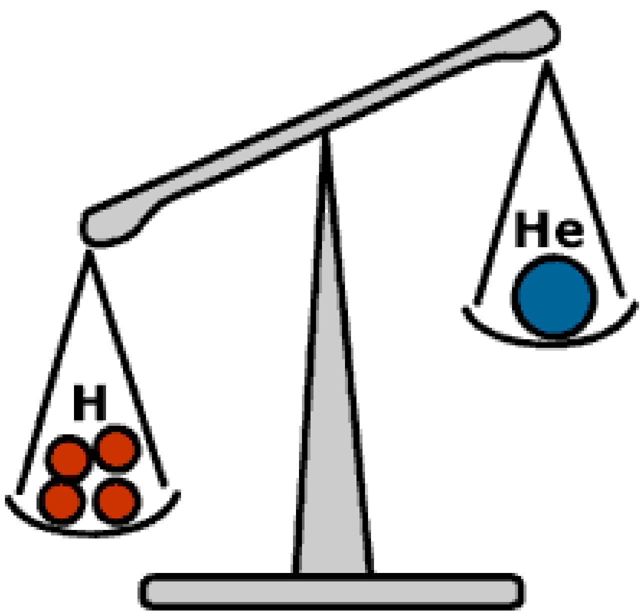
However, not relevant to Sun energy production.



The sun energy source

Einstein's equation $E = mc^2$ showed that a tiny amount of mass could, in principle, be converted into a tremendous amount of energy.

F.W. Aston discovered in 1920 that four hydrogen nuclei were heavier than a helium nucleus.



Sir Arthur Eddington argued in his 1920 presidential address to the British Association for the Advancement of Science that Aston's measurement of the mass difference between hydrogen and helium meant that the sun could shine by converting hydrogen atoms to helium.

This burning of hydrogen into helium would (according to Einstein's relation between mass and energy) release about 0.7% of the mass equivalent of the energy. In principle, this could allow the sun to shine for about a 100 billion years.

http://www.nobelprize.org/nobel_prizes/themes/physics/fusion/

Now we are ready to move to neutrinos …

Neutrinos were (sort of) proposed in 1930 by Pauli.

Wolfgang Pauli
1945 Nobel Prize
in Physics

He was trying to solve two problems with one particle.

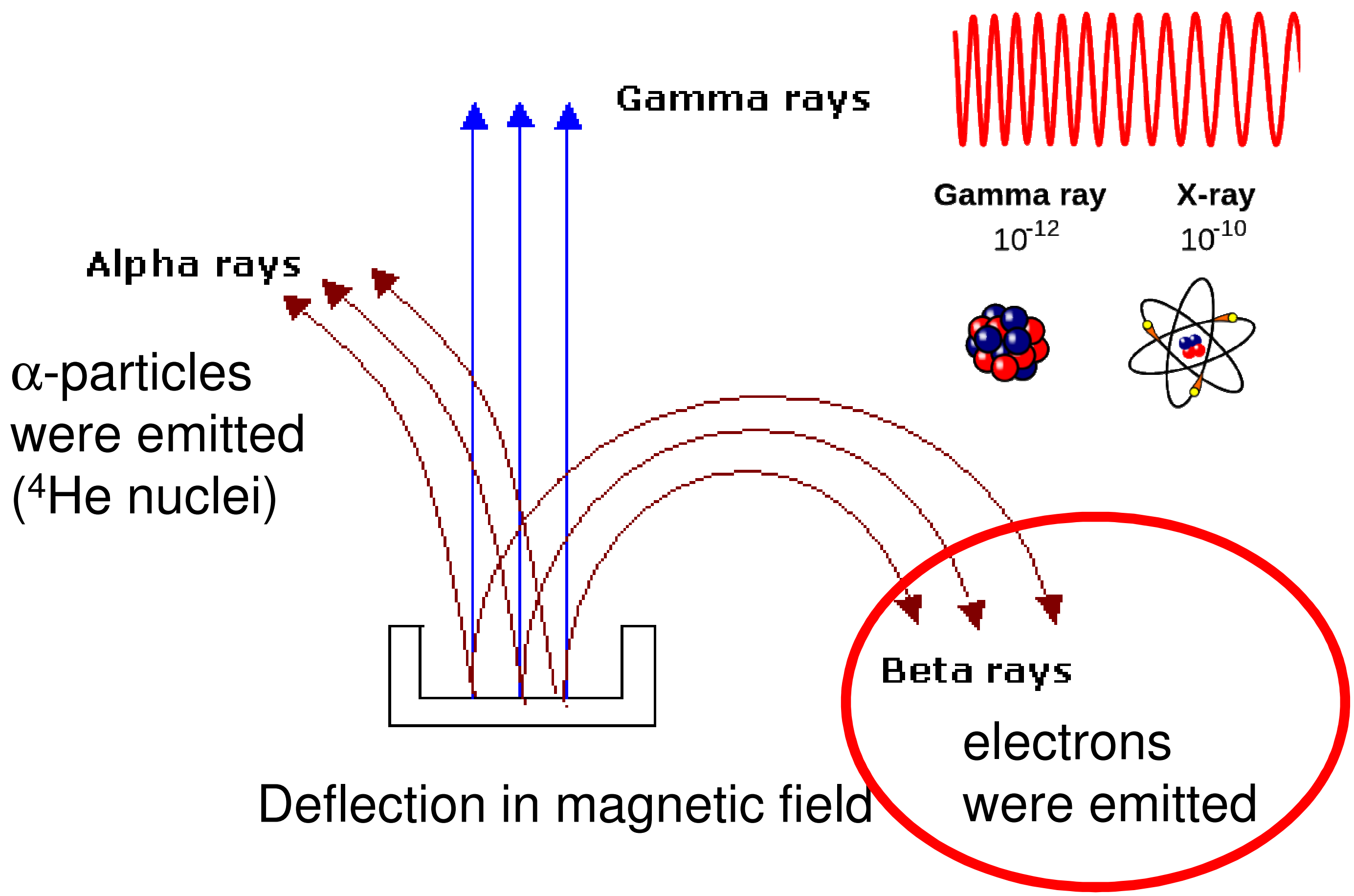
Problem #1: Wrong statistics

Atomic nuclei were known to have mass A but charge Z
One proton is about 1 mass unit here.
So, they ended up with nuclei having A protons.
This gave wrong nuclei charge – A instead of Z.
they were fixing it adding A-Z electrons.
Then nuclei charge is A-(A-Z) = Z and there are Z more electrons in the atom.

Protons and electrons are both fermions, ½ and obey Fermi-Dirac quantum statistics. *Total number of particle in the nuclear was 2A-Z, so ^{6}Li (Z=3) and ^{14}N (Z=7) nuclei should be fermions, but they appear to be bosons, obeying different Bose-Einstein quantum statistics.*

Problem #2:

Beta-decay: beta spectrum was continuous – the energy was missing



December 4, 1930: letter from Pauli to the meeting in Tübingen.

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, because of the "wrong" statistics of the N- and Li-6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" (1) of statistics and the law of conservation of energy.

*Namely, the possibility that **in the nuclei there could exist electrically neutral particles, which I will call neutrons**, that have spin 1/2 and obey the exclusion principle … in beta decay, in addition to the electron, a neutron is emitted such that the sum of the energies of neutron and electron is constant ...*

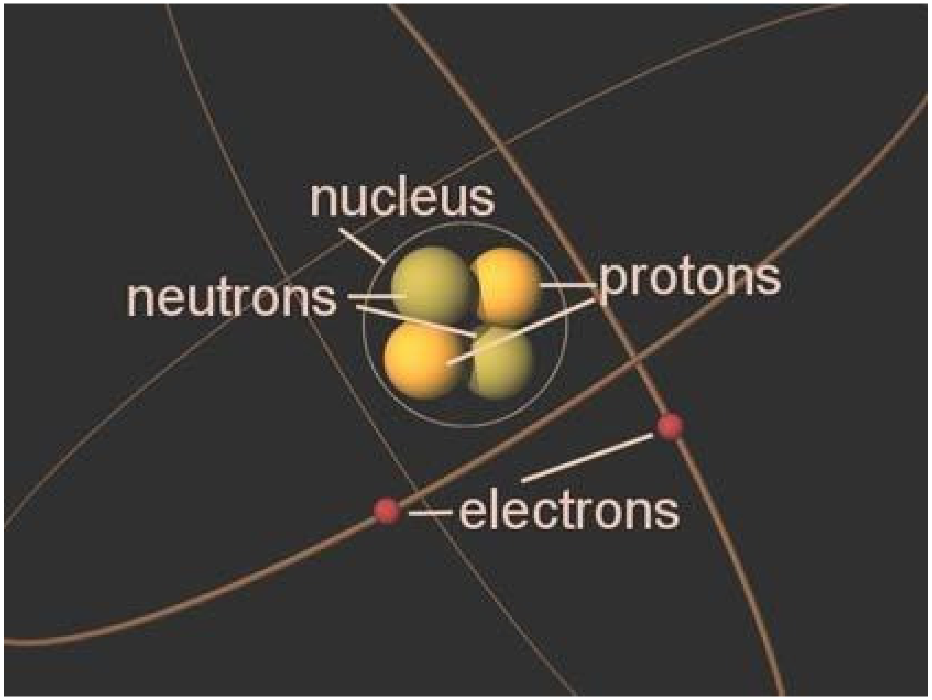
I admit that my remedy may seem almost improbable because one probably would have seen those neutrons, if they exist, for a long time…

Unfortunately, I cannot personally appear in Tübingen since I am indispensable here in Zürich because of a ball on the night from December 6 to 7 …

W. Pauli

Chadwick discovered neutrons in 1932

They do indeed fix the problem #1.
Nuclei has Z protons and A-Z neutrons! Atom has Z electrons.
Is has spin ½ and mass slightly higher than a proton.



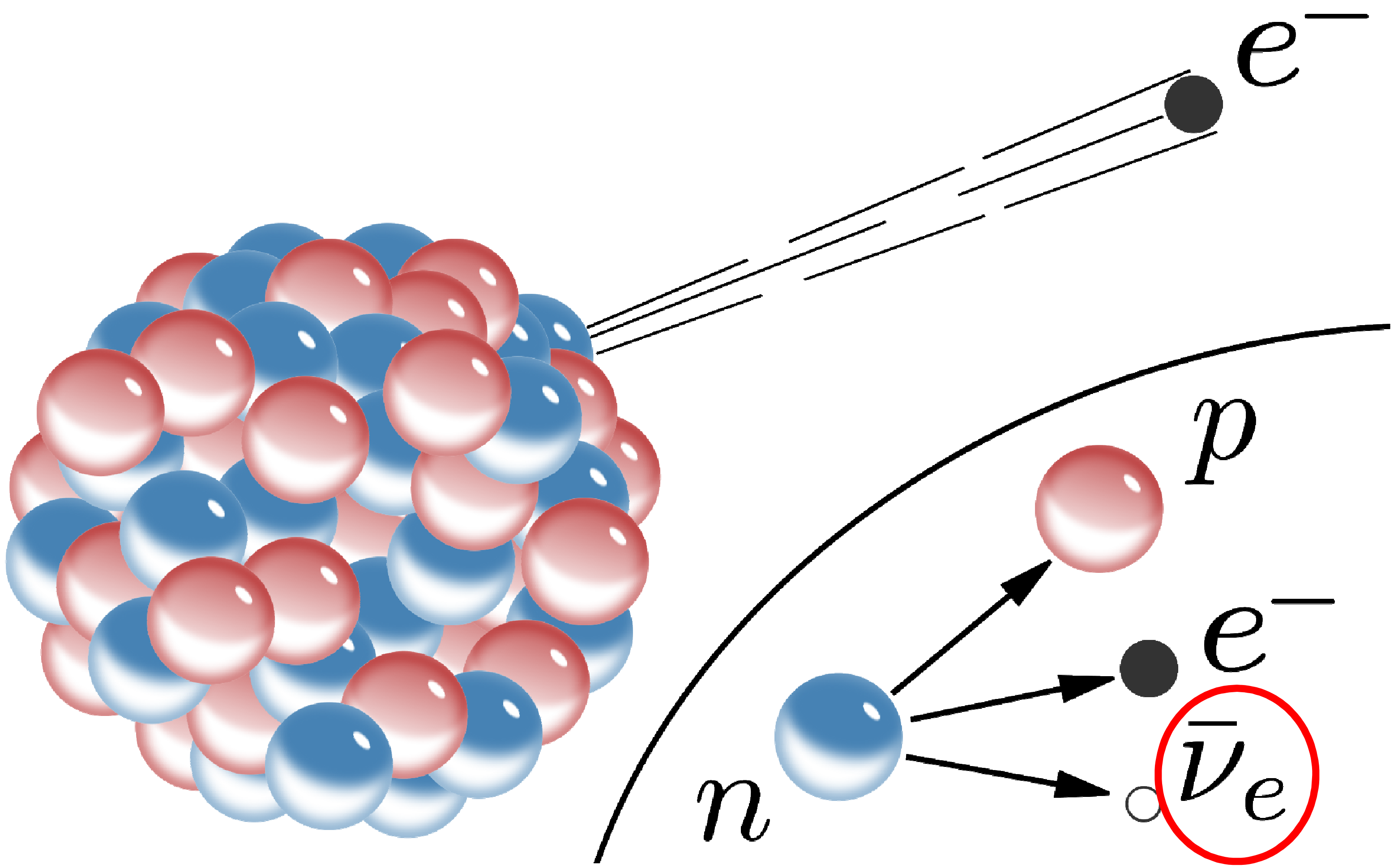
Li isotopes:

^{6}Li:
A=6 Z=3
3 protons, 3 neutrons, 3 electrons

^{7}Li:
A=7 Z=3
3 protons, 4 neutrons, 3 electrons

Neutron does not fix Problem #2:
it is not the particle that carries away extra energy in b-decay!
So need one more particle.

1933: Fermi's Theory of Beta Rays



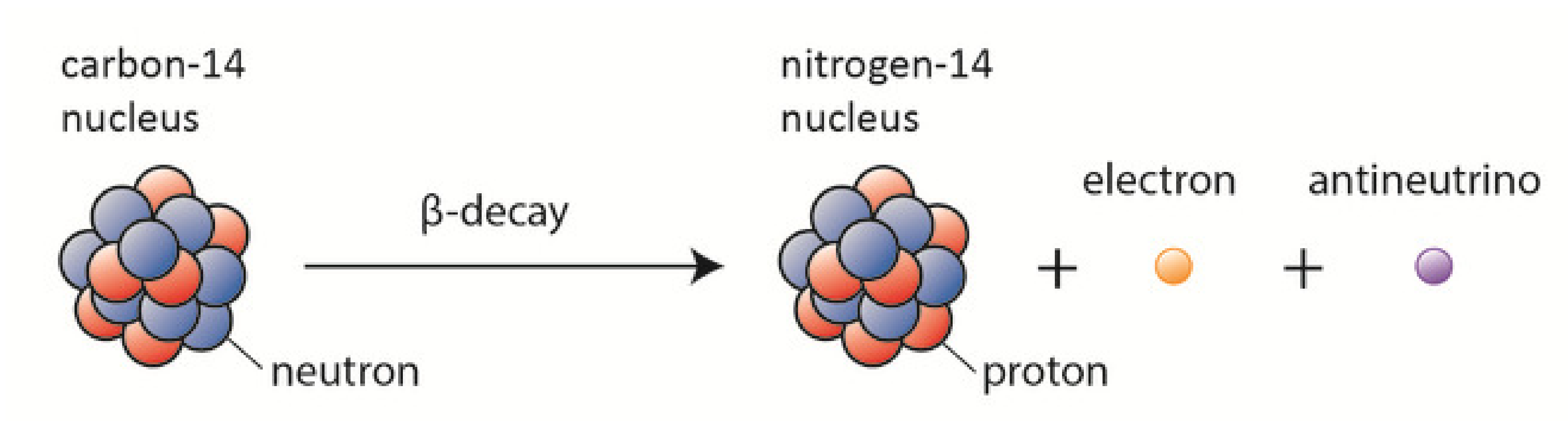
New WEAK interaction

(anti) neutrino: "little neutron"

https://en.wikipedia.org/wiki/Fermi%27s_interaction

1933: Fermi's Theory of Beta Rays

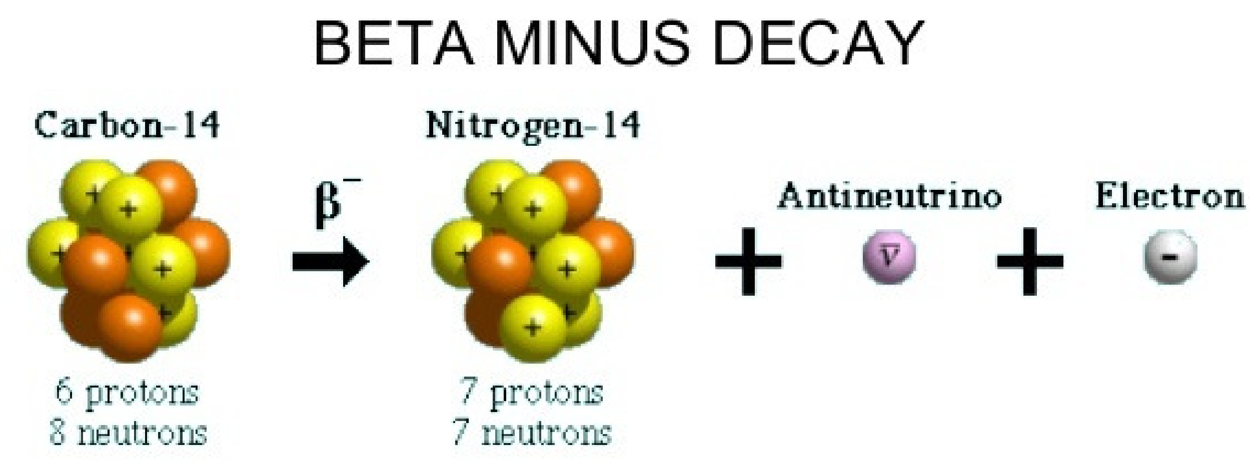
$$n \rightarrow p + e^{-} + \overline{\nu}_{e}$$



Transmutation of nuclei: Several processes are possible

#1

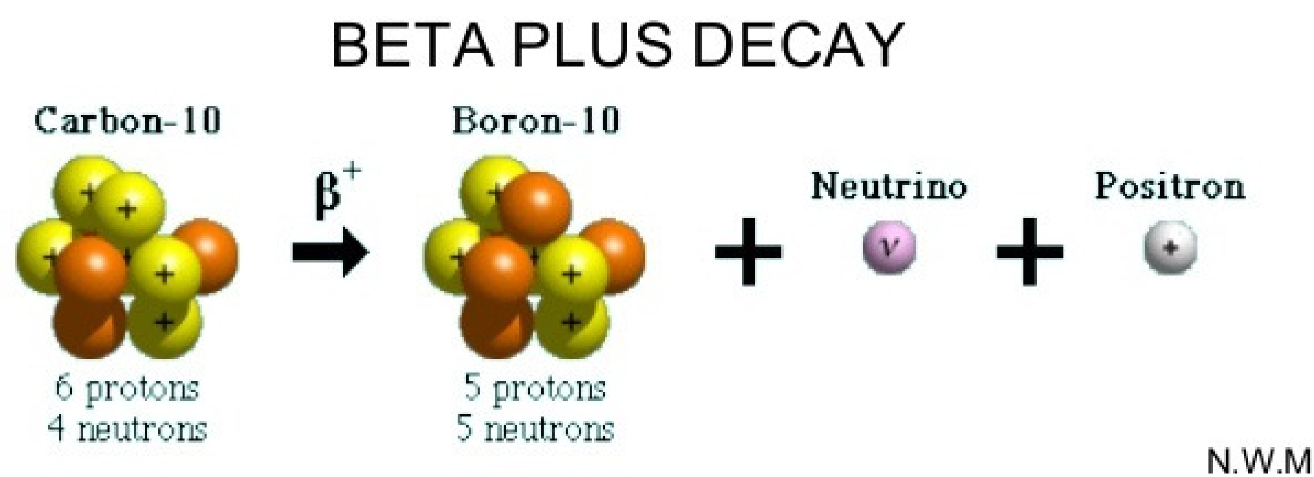
$$n \rightarrow p + e^{-} + \overline{\nu}_e$$



#2

$$p \rightarrow n + e^{+} + \nu_e$$

Positron emission



β^+ decay can only happen inside nuclei when the daughter nucleus has a greater binding energy (and therefore a lower total energy) than the mother nucleus.

http://www.slideshare.net/maheshsherkhane/nuclear-waste-management

Note on masses and allowed reactions

Mass can be measured in electron volts divided by c^2:
[$1\text{eV}/c^2 = 1.782662\times10^{-36}$ kg]

Remember energy vs. mass $E = mc^2$, note that c^2 is usually omitted

Examples: mass of proton is 1.67×10^{-27} kg = 938×10^{6}eV= 938 MeV

More accurately **proton mass is 938.272046(21) MeV/c^2**

neutron mass is 939.5654133(58) MeV/c^2

Difference is 1.293367 MeV/c^2

electron mass is 0.5109989461(31) MeV/c^2

$$m_n c^2 > m_p c^2 + m_e c^2 \text{ by } 0.782 \text{ MeV}$$

This means free neutron can decay $n \rightarrow p + e^- + \overline{\nu_e}$

Free (not bound in a nuclei) neutron lifetime is only 14.7 minutes!

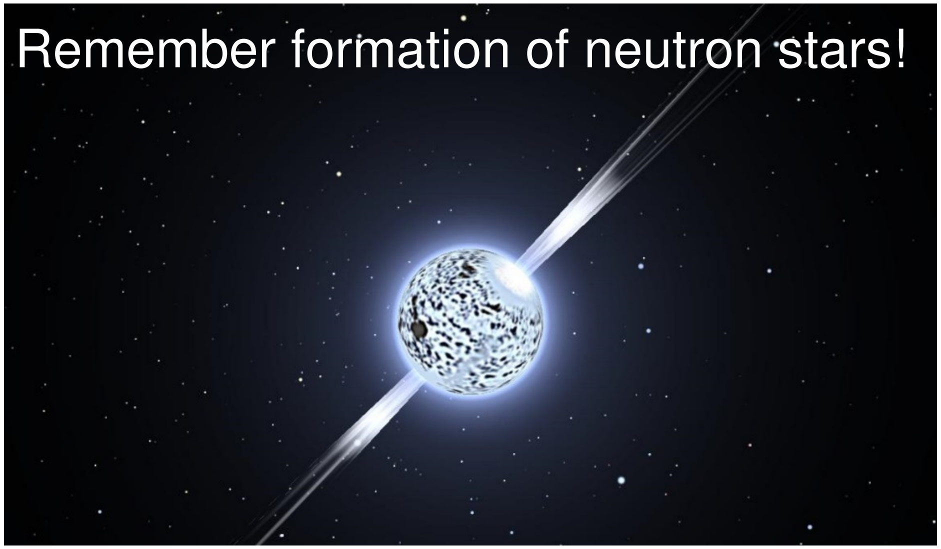
Free proton is stable – does not decay.

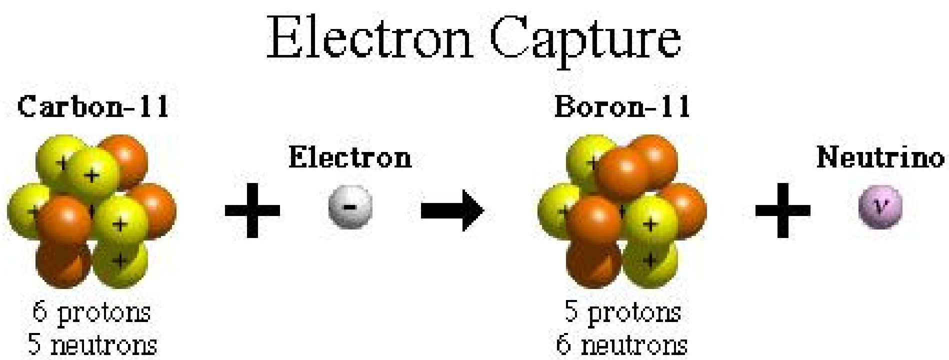
Transmutation of nuclei:

Electron capture (or K-capture)

#3

$$p + e^- \rightarrow n + \nu_e$$





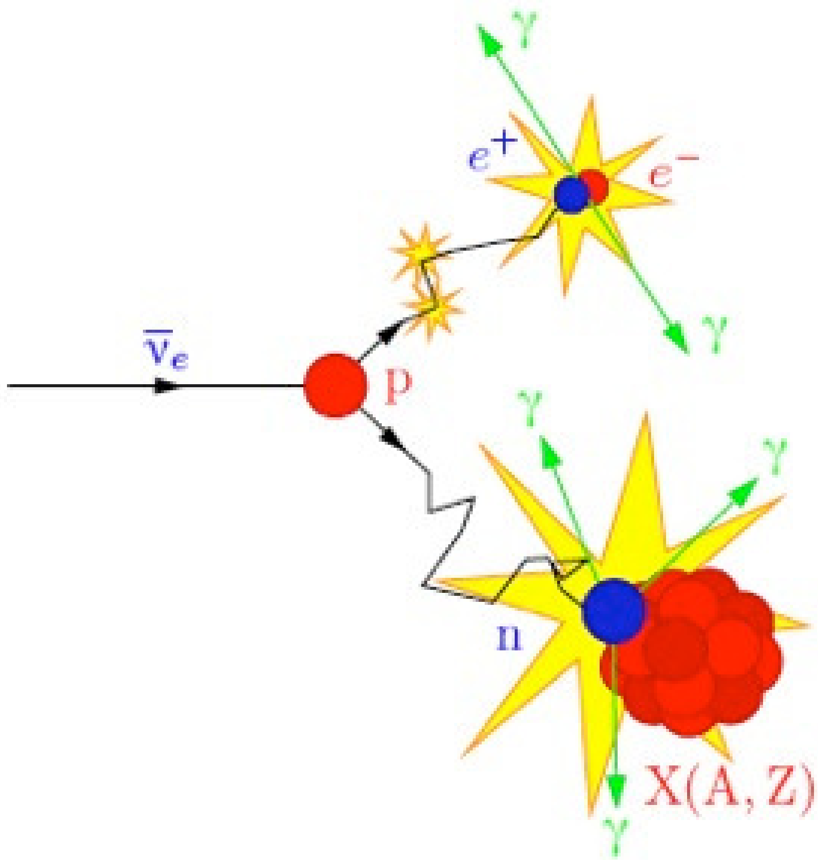
Again, need extra energy for this reaction to work.

$$m_n c^2 > m_p c^2 + m_e c^2 \text{ by } 0.782 \text{ MeV}$$

Transmutation of nuclei contd.
Very low probability reactions
This is how you can detect neutrinos!

#4

$$\overline{\nu}_e + p \rightarrow n + e^+$$



#5

$$\nu_e + {}^{37}\text{Cl} \mapsto {}^{37}\text{Ar} + e^-$$

17 protons
20 neutrons

18 protons
19 neutrons

$$\nu_e + n \rightarrow p + e^-$$

Summary

$$n \rightarrow p + e^- + \overline{\nu_e}$$

$$p \rightarrow n + e^+ + \nu_e$$

$$p + e^- \rightarrow n + \nu_e$$

$$\overline{\nu_e} + p \rightarrow n + e^+$$

e^+ is electron antiparticle (positron)

Summary

How can I remember any of this?

Charge is conserved – total is the same of the left and right

$$n \rightarrow p + e^- + \overline{\nu_e}$$

Charge 0 = 1 - 1 + 0 = 0

$$p \rightarrow n + e^+ + \nu_e$$

Charge 1 = 0 + 1 + 0 = 1

$$p + e^- \rightarrow n + \nu_e$$

Charge 1 -1 = 0 + 0

$$\overline{\nu_e} + p \rightarrow n + e^+$$

Charge 0 + 1 = 0 + 1

e^+ is electron antiparticle (positron)

Summary

How can I remember any of this?

Charge is conserved – total is the same of the left and right

Electron, neutrino and their antiparticle are leptons. **Lepton numbers are +1 for particles and -1 for antiparticles.** Lepton number is conserved here too.

$$n \rightarrow p + e^- + \overline{\nu}_e$$

Charge 0 = 1 - 1 + 0 = 0

$$n \rightarrow p + e^- + \overline{\nu}_e$$

Lepton number 0 = 0 +1 -1 = 0

$$p \rightarrow n + e^+ + \nu_e$$

Charge 1 = 0 + 1 + 0 = 1

$$p \rightarrow n + e^+ + \nu_e$$

Lepton number 0 = 0 -1 +1 = 0

$$p + e^- \rightarrow n + \nu_e$$

Charge 1 -1 = 0 + 0

$$p + e^- \rightarrow n + \nu_e$$

Lepton number 0 +1 = 0 +1

$$\overline{\nu}_e + p \rightarrow n + e^+$$

Charge 0 + 1 = 0 + 1

$$\overline{\nu}_e + p \rightarrow n + e^+$$

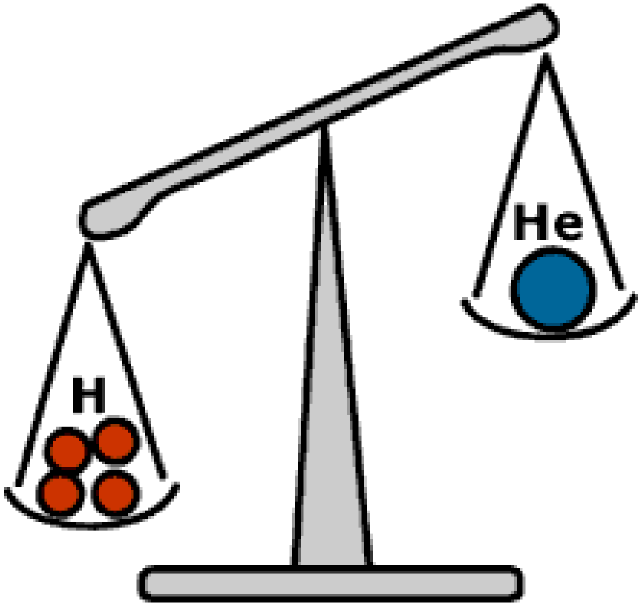
Lepton number -1 + 0 = 0 -1

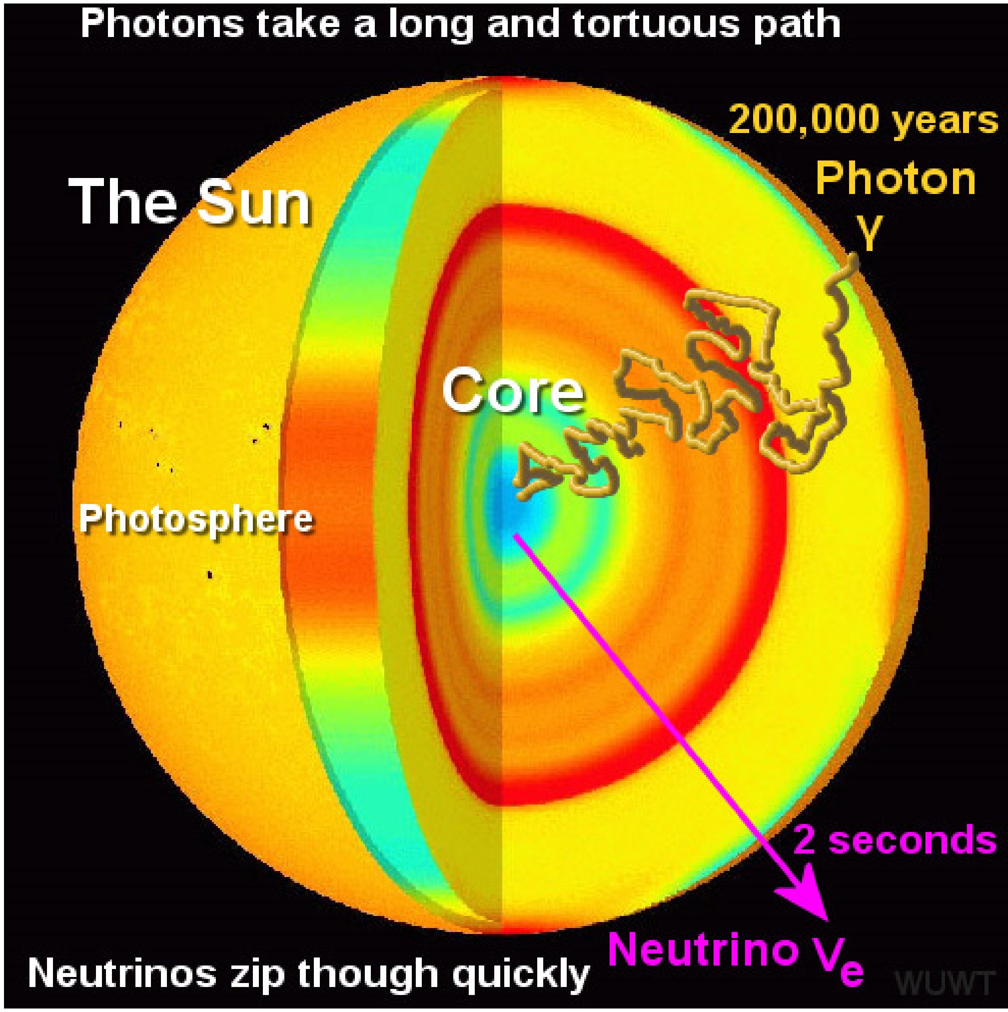
e^+ is electron antiparticle (positron)

p and n are not leptons – put zero

Back to the original question: Sun's energy source

Nuclear fusion converts H to He: energy is released



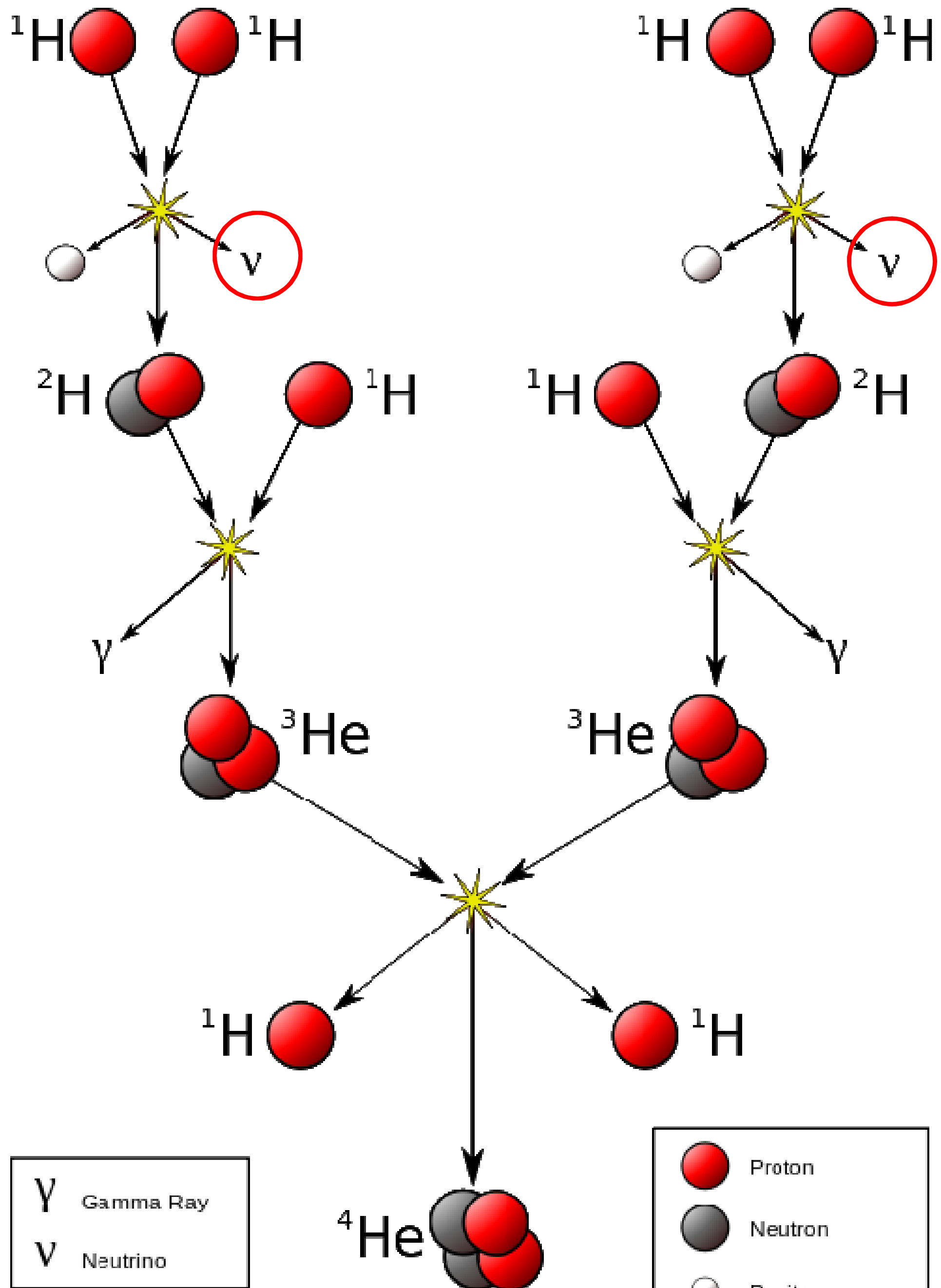


Looking at out list of reactions fusion should produce neutrinos!

If we can detect these neutrinos we can confirm what happens ***in the core*** of the Sun!

http://wattsupwiththat.com/2010/08/27/follow-up-on-the-solar-neutrinos-radioactive-decay-story/

Basic idea of how H is converted to He via fusion



$$p \rightarrow n + e^{+} + \nu_{e}$$

http://en.es-static.us/upl/2012/10/500px-FusionintheSun.png

1938: Problem with nuclear fusion in hotter stars

Hans Albrecht Bethe

1967 Nobel Prize in Physics

"for his contributions to the theory of nuclear reactions, especially his discoveries concerning the energy production in stars"

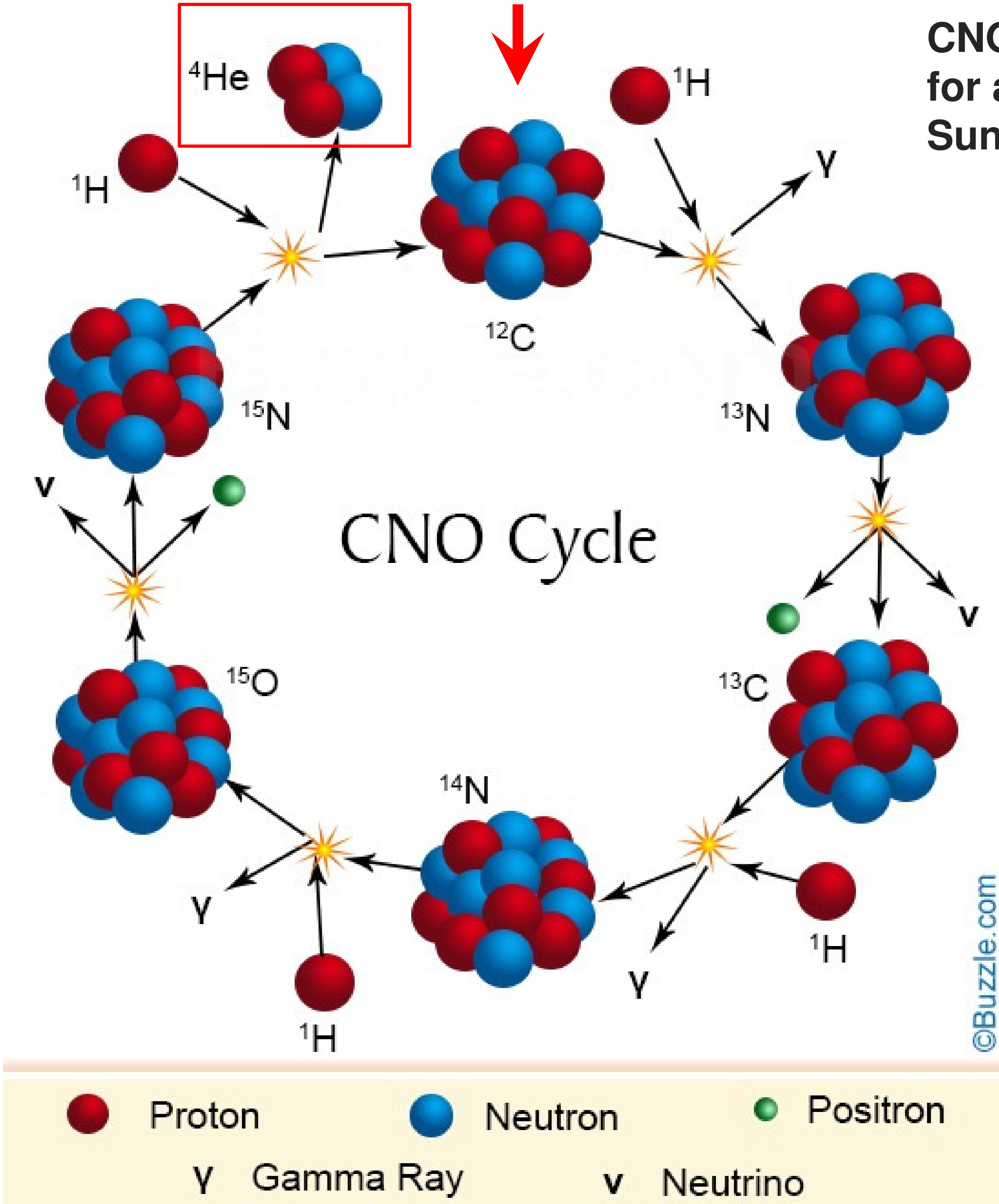
For the p-p chain reaction, energy output rises at $T^{3.5}$ with the stellar temperature.

For larger hotter starts the energy output rises as T^{17} !!!!!

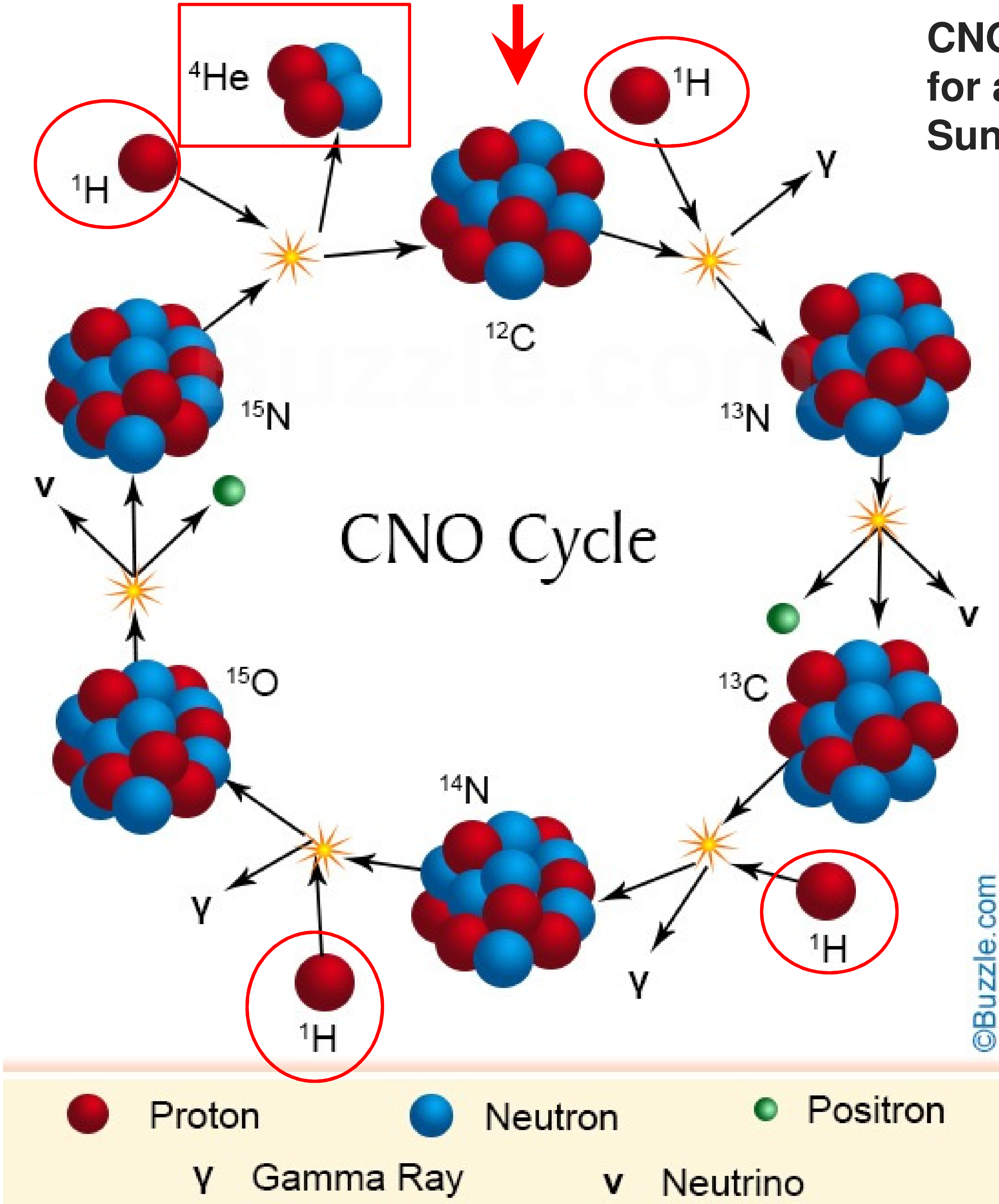
Need some completely different idea of how to make He out of H in stars!

CNO cycle – convert 4 proton into He with carbon nuclei as the catalysis

CNO cycle accounts for about 7% of the Sun's energy



CNO cycle accounts for about 7% of the Sun's energy



Detecting solar neutrinos

Main idea: $\nu_e + {}^{37}Cl \mapsto {}^{37}Ar + e^-$

	${}^{37}Cl$	${}^{37}Ar$
	17 protons	18 protons
	20 neutrons	19 neutrons

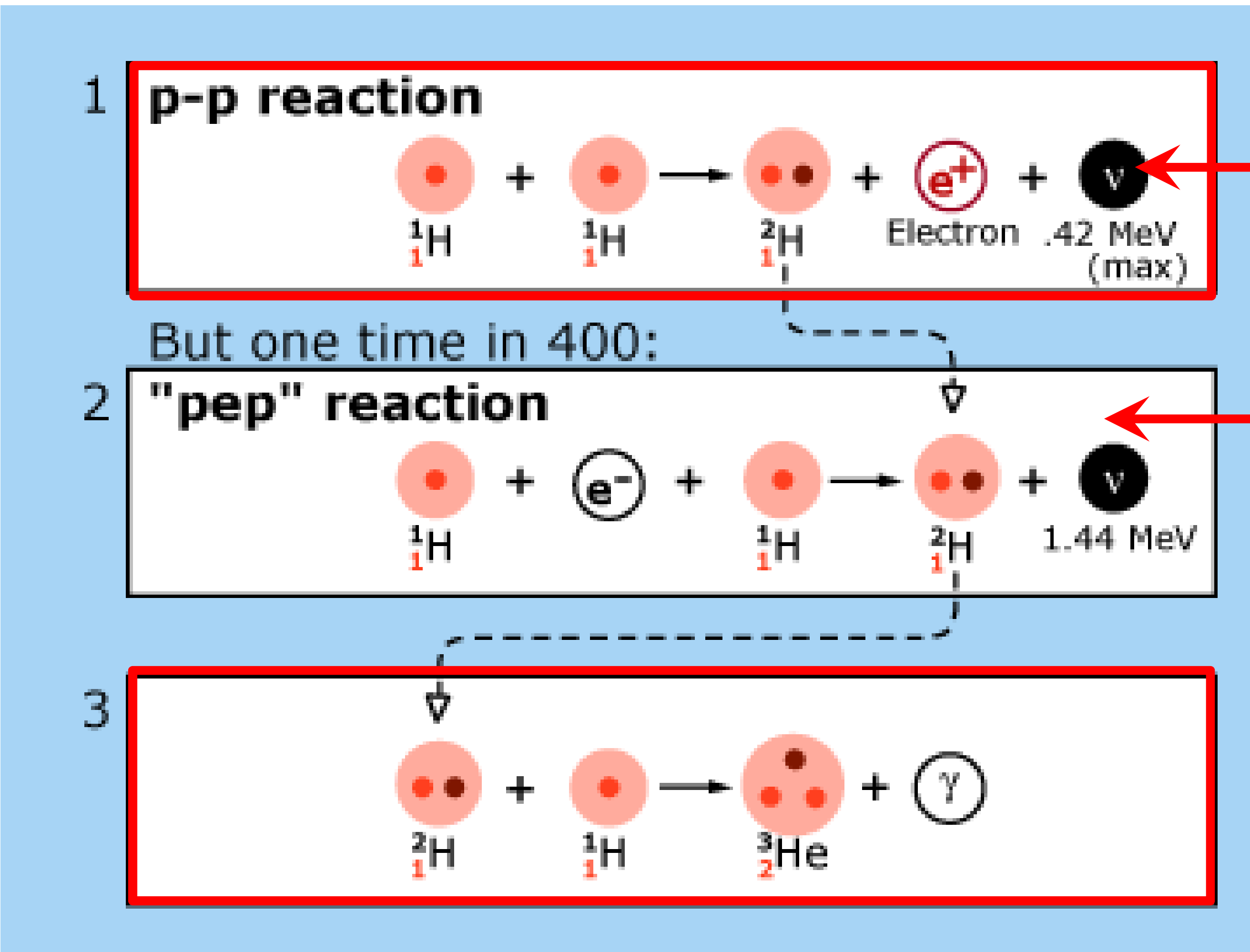
Problem: energy threshold for the capture reaction is 0.814 MeV, so need neutrinos with energies higher than 0.814 MeV.

Let's look at the energies of neutrino's coming from the sun.

Need neutrinos above 0.814 MeV

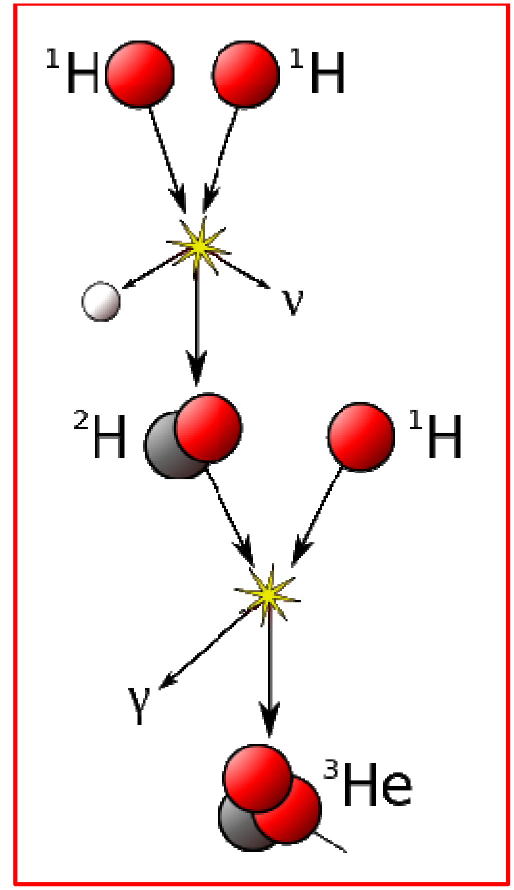
The p—p Chain Reaction

$$p \rightarrow n + e^{+} + \nu_e$$



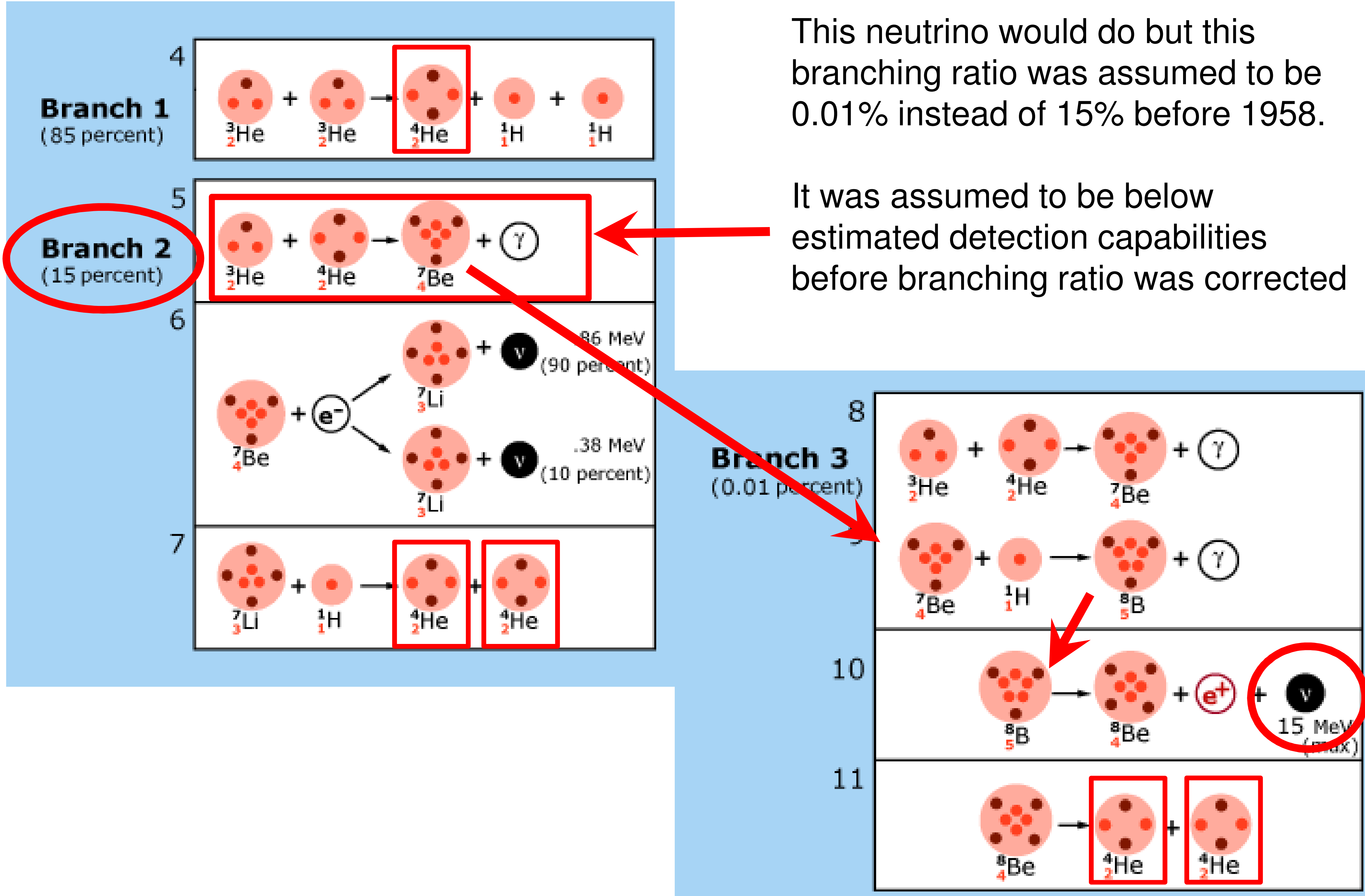
Too low energy

Too rare – not enough to detect



http://www.nobelprize.org/nobel_prizes/themes/physics/fusion/

The p—p Chain Reaction cont.

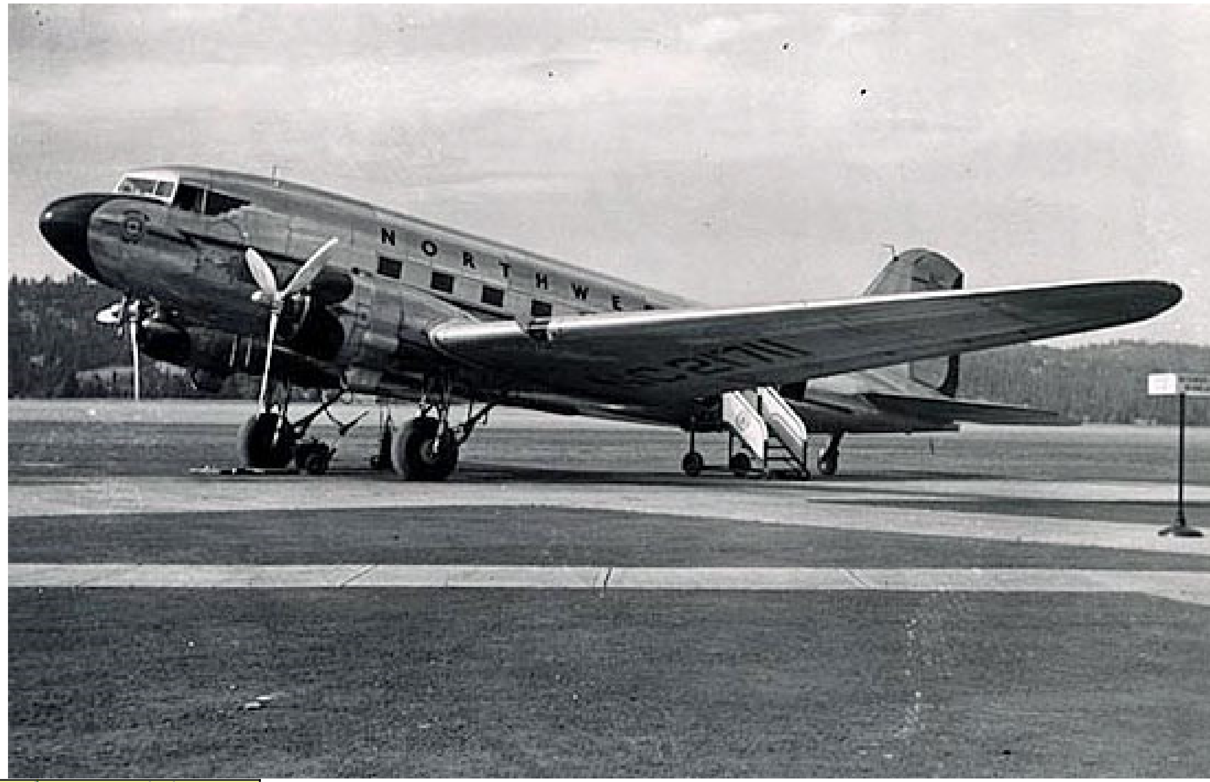


This neutrino would do but this branching ratio was assumed to be 0.01% instead of 15% before 1958.

It was assumed to be below estimated detection capabilities before branching ratio was corrected

Frederick Reines
Clyde Cowan

Stuck in Kansan with plane engine trouble
Decide to detect neutrinos



FR - "Let's do a really challenging problem"

FR "Let's work on neutrinos

CC - "GREAT IDEA!"

1953-1956

The Reines-Cowan Experiments

Detecting the Poltergeist

Goal: detect ANY neutrino (or antineutrino)

Why?
Because everyone said it was impossible!

$$\overline{\nu}_e + p \rightarrow n + e^+$$

Hanford Team 1953

http://library.lanl.gov/cgi-bin/getfile?00326606.pdf