“Neutrinos 101”

An introduction to neutrinos for the Mount San
Antonio College Astronomy Club.
Walnut, CA, 5/13/2022

Outline

- What is a neutrino - why was it “invented”?
- A little physics: conservation laws extended
    1. The chemistry analogy: How nuclear/neutrino reactions look a lot like chemical reactions.
    2. New quantum numbers
    3. The following topics use and illustrate the quantum numbers and reactions.
- How we get neutrinos from nuclear reactors and the discovery of neutrinos.
- How we get neutrinos from the sun
- How we get neutrinos from cosmic rays, and how those neutrinos seem to change as they travel.
- How we get neutrinos from supernovas
- Questions?

We'll do this next time.

What is a neutrino - why was it “invented”?

- 1930, Wolfgang Pauli was working on the puzzle of beta decay, neutrons splitting into protons and electrons

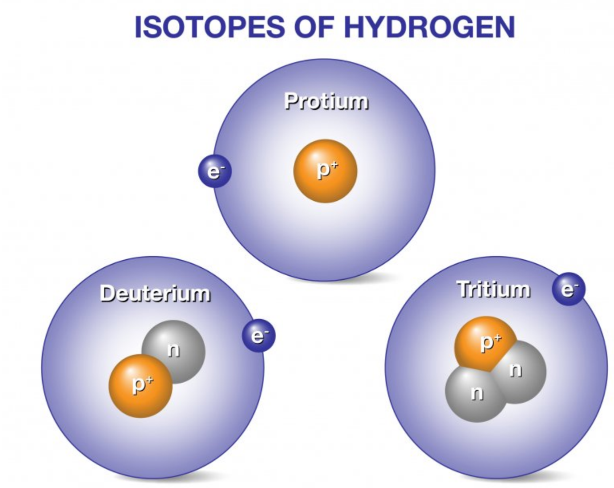
$$N \rightarrow P + e^-$$

- “Beta” particles, originally called “beta radiation” are actually electrons, which we write “e^- ”or “β^- ”.
- At that time solitary neutrons were not available to experimenters, so they were studying radioactive isotopes such as tritium (hydrogen with two extra neutrons).

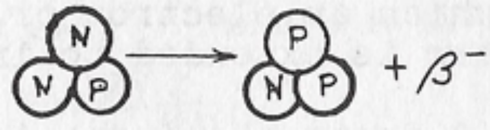
Wolfgang Pauli, who first hypothesized the neutrino

Review: what is tritium?

- “Regular” hydrogen, H, is a proton with an electron orbiting around it.
- Deuterium is hydrogen with one extra neutron. It is stable - not radioactive.
- Tritium is hydrogen with two extra neutrons. It is unstable, radioactive, with a half-life of 12.3 years.



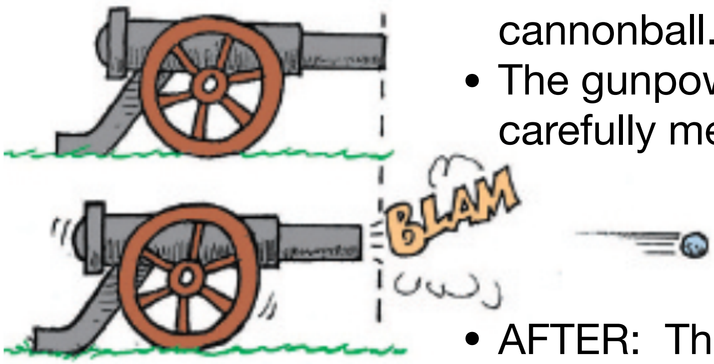
Beta decay of a tritium nucleus



- H-3 (tritium) decays into He-3 (helium) and an electron that speeds out.
- What should the energy of the electron (aka beta) particle be?
- That's determined by the nuclear potential energy available.
- The energy available can be measured using $E=mc^2$ (I should add a slide for that) but what's important is that it is a **definite amount of energy**.
- All tritium beta decay electrons should have exactly the same energy.
- But they don't!
- This drove physics crazy!

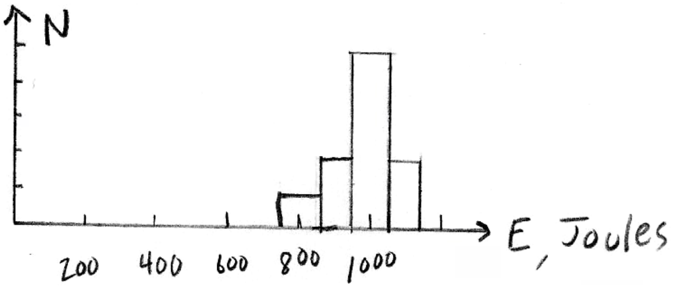
Cannon analogy for beta decay.

- BEFORE: The cannon is like the tritium nucleus.
- The cannon contains gunpowder and cannonball.
- The gunpowder has a **definite**, carefully measured amount of energy.



- AFTER: The cannon is like the helium-3 nucleus.
- The cannonball is like the electron.
- Every time you fire the cannon, the cannonball should have the SAME energy.

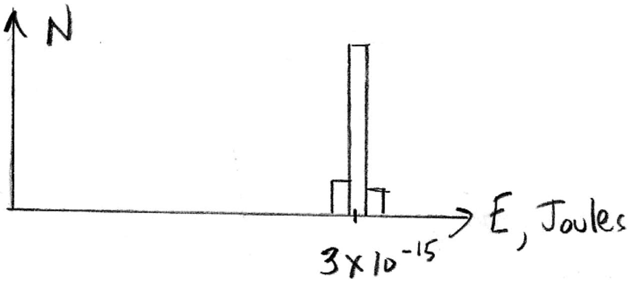
What they expected



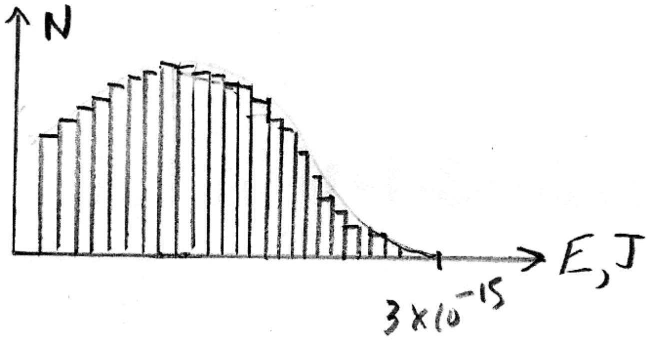
- If you fire a cannon 10 times, you get the same energy 10 times.
- Here's I'm showing the energies for a hypothetical antique cannon shot ten times.
- The vertical scale is the number of times the cannonball's kinetic energy was in a given range.
- It fired 5 out 10 times with *E* in the 950 to 1050 Joule range.
- (This type of diagram is called a histogram, or a frequency distribution.)

What they expected…

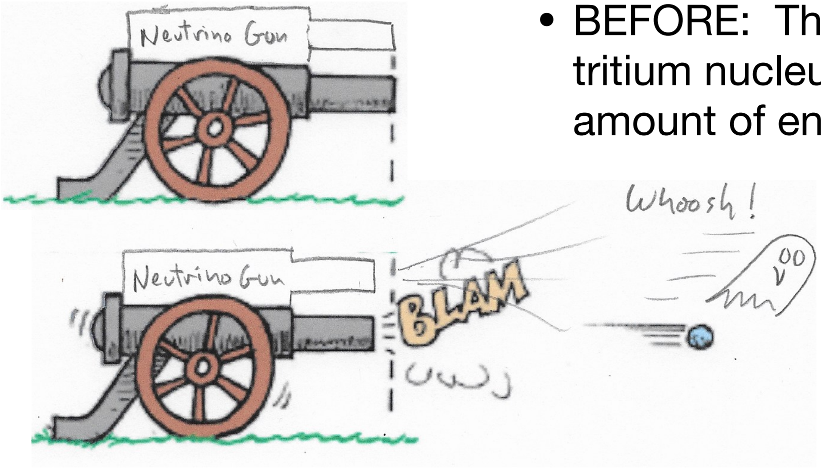
- Doing the experiments, they expected the betas (the electrons) to shoot out of the tritium nuclei with an energy *E* = 2.98 x 10 -15 Joules



- What they actually got is this:
- Only rarely did the electron get the full amount of energy.
- Was energy just lost? That would **break the law of conservation of energy**.
- W. Pauli hypothesized the energy was being "stolen" by an invisible particle.



Cannon analogy with neutrino

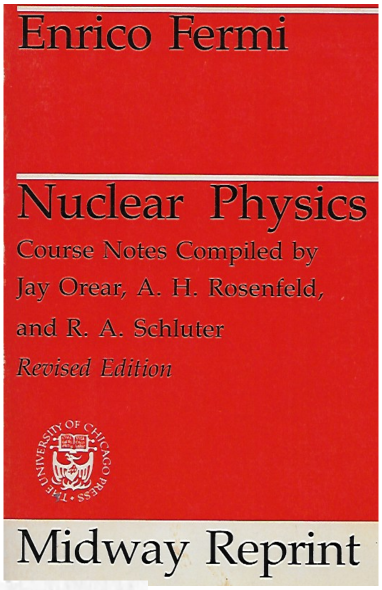


- BEFORE: The cannon is like the tritium nucleus with a definite amount of energy.
- AFTER: The cannon shoots the electron and a neutrino (the ghost).

- Together, they have a definite amount of energy, but the energy is **shared randomly**.
- Sometimes the electron gets more energy, sometimes the neutrino gets more.

Enrico Fermi takes the neutrino seriously

- Fermi, at the University of Chicago built the first nuclear reactor. He was a good theorist, a great experimentalist and a great teacher. (He taught *my* teacher, Ted Bowen!)
- Fermi named the ghost particle the neutrino which means “little neutral one.”
- I’m using Fermi’s notes from when he taught the nuclear physics course. Here is what he says is going on:



Enrico Fermi

Nuclear Physics

Course Notes Compiled by
Jay Orear, A. H. Rosenfeld,
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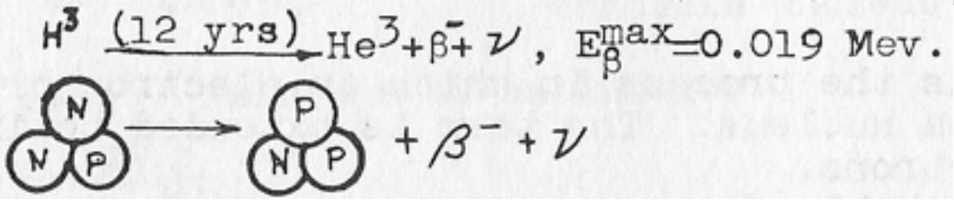
Revised Edition

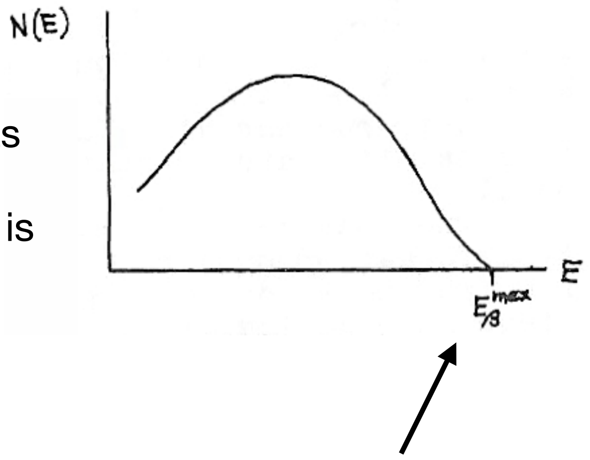
Midway Reprint



$H^3 \xrightarrow{(12\ \text{yrs})} He^3 + \beta^- + \nu$, $E_\beta^{max} = 0.019$ Mev.

Observed beta decay spectrum

- Fermi's graph show that the betas (the electrons), can have any energy up to E_β^{max} . That energy is calculated from the final nucleus mass minis the initial nucleus mass.
- For example the mass of He-3 minus the mass of H-3 (tritium).

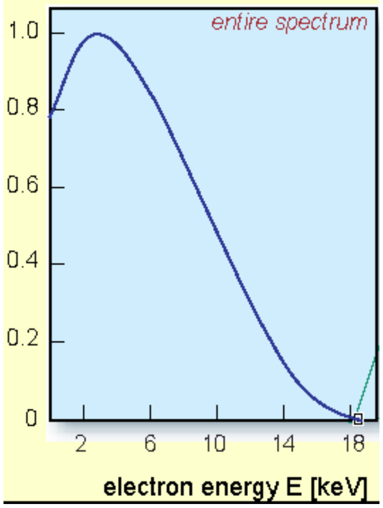


$$E_\beta^{\max} = (m_f - m_i)c^2$$

Observed beta decay spectrum

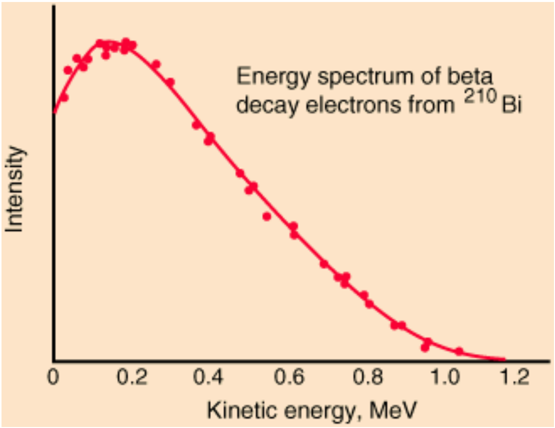
Tritium beta decay spectrum

$${}^{3}H \rightarrow {}^{3}He + e^- + \bar{\nu}$$



Bismuth-210 beta decay spectrum

$${}^{210}Bi \rightarrow {}^{210}Po + e^- + \bar{\nu}$$



Sources:
https://web.physics.utah.edu/~jui/5110/y2009m03d09/KATRIN.htm;.htm
http://hyperphysics.phy-astr.gsu.edu/hbase/Nuclear/beta2.html#c1

Neutrinos vs anti-neutrinos

- You might have noticed in the previous slide that I used a “bar” over the ν, the neutrino.
- The bar indicates “anti”. In modern (after the 1940’s) notation terminology we say that neutron, tritium, Bismuth-210 and so on decay into an electron and an anti-neutrino.
- Another form of beta decay actually emit “regular” neutrinos, illustrated by copper-64 decaying to nickel-64

$$^{64}Cu \rightarrow {}^{64}Cu + e^{+} + \nu$$

- Now we have beta decay creating an **anti-electron** and a “regular” neutrino!

Conservation rules

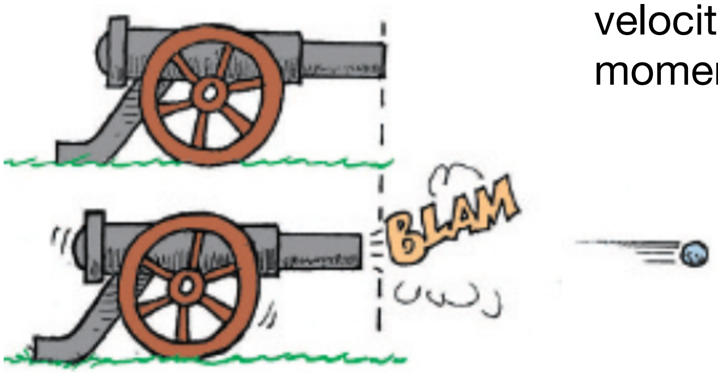
- What reactions are possible in nature? What’s impossible?
- The answer can be found by determining if it breaks any conservation laws.
  - Does it break a conservation law? If yes, it’s impossible.
  - If no, it’s possible.   (Though it might be improbable.)
- Conservation laws mean that certain quantities must stay the same before/after a reaction.
- Energy & matter before reaction **must equal** energy & matter after reaction.
- Electric charge before **must equal** electric charge after.
- Similar “must equal” rules apply to momentum, baryon number, lepton number and angular momentum.

Conservation rules

- **Conservation of matter**: What goes in must come out.
    1. Example - burning methane: $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$, the atoms in must be balanced by atoms out.
- **Conservation of energy**: Total energy going in must equal total energy coming out.
    2. Example: burning methane again: The chemicals on the left side have chemical potential energy. The right side has chemical and kinetic or thermal energy. So $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ + energy
- In nuclear physics conservation of matter and energy is "bundled" via $E=mc^2$. It is possible to convert matter to energy and energy to matter.
- (The $CH_4 + 2O_2$ weigh slightly more than the $CO_2 + 2H_2O$ because some mass has been converted to energy.)

Conservation rules…

- **Conservation of momentum**: Momentum is mass x velocity. The total momentum before a reaction must eual the total momentum after the reaction.
- Example: the cannon.
- BEFORE: nothing is moving velocities are zero so total momentum = zero.



- AFTER: the cannonball has velocity to the right. It has positive momentum. To get zero total momentum, something must move in the negative direction, to the left.
- It's the cannon, which recoils to the left

Conservation rules…

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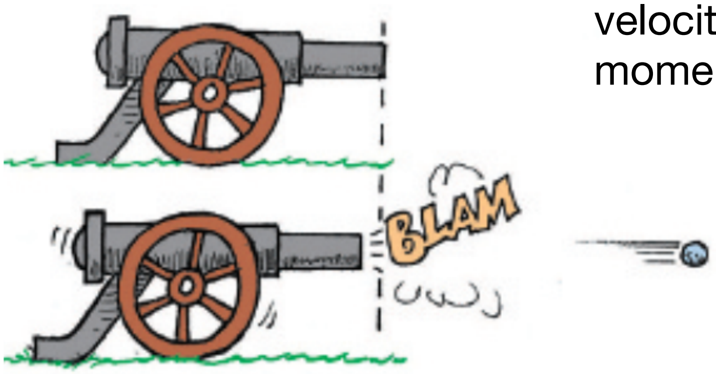

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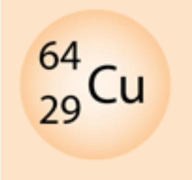
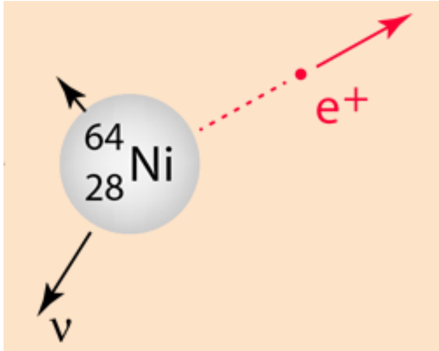
Conservation rules…

- **Conservation of momentum**:
- Example: the copper-64 beta decay

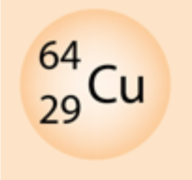




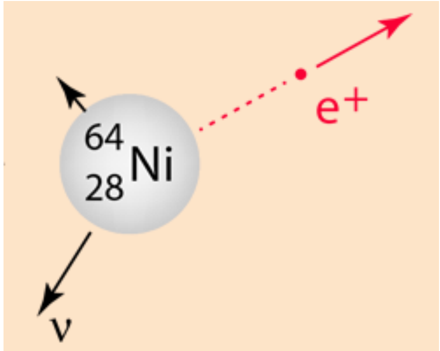
- BEFORE: nothing is moving velocities are zero so total momentum = zero.
- AFTER: positron (anti-electron) has momentum up and to the right. This is partly balanced by the neutrino momentum which is down and to the left.
- To completely balance the momentum, the Ni-64 move up and to the left.
- The total momentum is zero, same as before the reaction.

Conservation rules…

- **Conservation of matter & energy again**:
- Example: the copper-64 beta decay



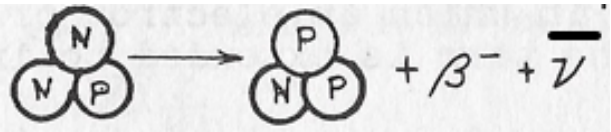
- BEFORE: the mass of Cu-64 is 63.929764 amu.



- AFTER: Total mass =
- = mass of Ni-64 + mass of electron + mass of neutrino
- = 61.928345 amu + 0.0005486 amu + 0 amu
- = 61.928894 amu
- This is 2.0009 amu less than before. The lost mass is in the kinetic energy (via $E=mc^2$)

Conservation rules… Charge number

- **Conservation of electric charge q**:
- The electron has a charge $q_{electron} = -1.602\mathrm{x}10^{\overset{\mathbf{-19}}{\cancel{-11}}}$ coulombs. This is an inconvenient number so we just say that the **charge number** of the electron is –1.
- Anti-electrons (positrons) and protons have q = +1
- Neutrons and neutrinos: q = 0
- Anti-protons : q = –1
- Example: beta decay of tritium

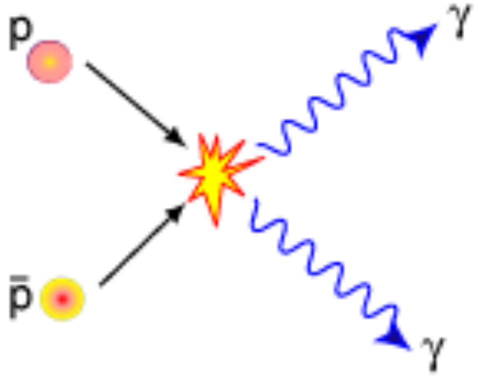


- BEFORE: q = +1

- AFTER: q = 2 + (–1) = 1
- The antineutrino has charge number = zero.

Conservation rules… q, charge number

- Example: proton and anti-proton annihilate.

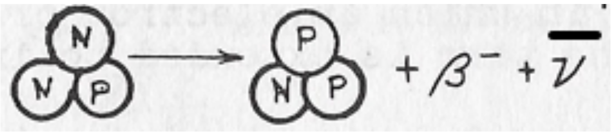


- BEFORE: q = 1 + (-1) = 0

- AFTER: q = 0
- The photons have charge number = zero.

Conservation rules… Baryon Number

- **Conservation of baryon number B**:
- Nucleons (neutrons and proton, anything with three quarks) are called baryons and they have a conserved property: baryon number.
- Electrons, neutrinos, photons: B=0
- Protons, neutrons: B=1
- Anti-protons, antineutrons: B= -1
- Example: beta decay of tritium

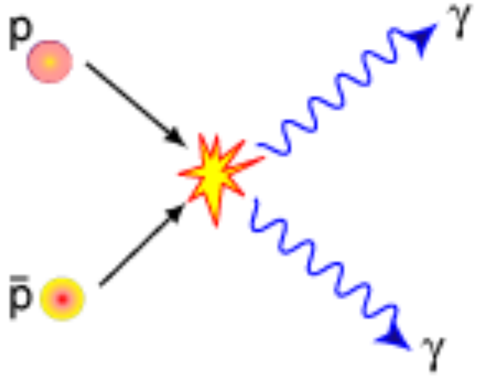


- BEFORE: B = 3

- AFTER: B = 3
- The electron and antineutrino have baryon number = zero.

Conservation rules… Baryon Number

- Example: proton and anti-proton annihilate.

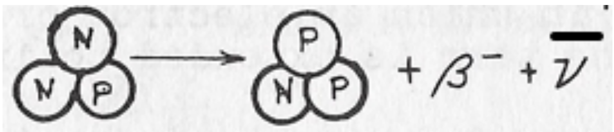


- BEFORE: B = 1 + (-1) = 0

- AFTER: B = 0
- The photons have baryon number = zero.

Conservation rules… Lepton Number

- **Conservation of lepton number L**:
- Electrons and neutrinos have a conserved property: lepton number.
- Electrons, neutrinos: L= 1
- Anti-electrons (positrons), anti-neutrinos: L= –1
- Protons, neutrons, photons: L= 0
- Example: beta decay of tritium

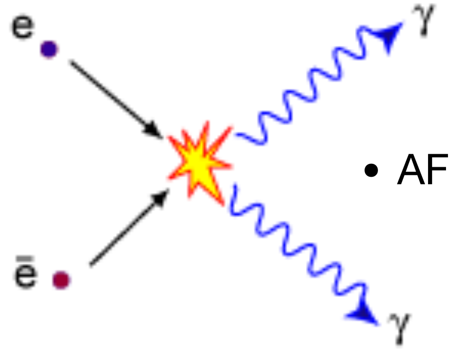


- BEFORE: L = 0

- AFTER: L = +1 + (–1) = 0
- The nucleus has lepton number = zero.

Conservation rules… Lepton Number

- Example: electron and positron annihilate



- BEFORE:
  $L = +1 + (-1) = 0$

- AFTER: $L = 0 + 0 = 0$

There are two ways to notate anti-electrons

(1) $\bar{e}$ (2) e^+

I will use both. (I know it's confusing, sorry.)

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angular

Conservation rules… momentum

- Although we won’t use it in this talk, reactions must conserve angular momentum.
- This is relevant in more detailed analyses of interactions where spin (typically + 1/2 or –1/2) and orbital and nuclear angular momentum determines the probabilities of reaction outcomes.

Summary of conserved numbers

Particle	Symbol	Charge # q	Baryon # B	Lepton # L	Mass, MeV
proton	p	+1	+1	0	938.272
anti-proton	$\bar{p}$	~~+1~~ **-1**	~~+1~~ **-1**	0	938.272
neutron	n	0	+1	0	939.965
anti-neutron	$\bar{n}$	0	~~+1~~ **-1**	0	939.965
electron	e^- or β	−1	0	+1	0.511
anti-electron	e^+ or β^+	+1	0	−1	0.511
neutrino	ν	0	0	+1	less than 0.0000008
anti-neutrino	$\bar{\nu}$	0	0	−1	less than 0.0000008
gamma	γ	**0**	**0**	**0**	**0**

Mass units

- Around the world, mass is measured is kilograms or grams.
- Doing chemistry, we often use atomic mass units.
  1. Examples
  2. H atom ≈ 1 amu. He ≈ 4 amu. C = 12 amu
- amu correspond roughly to the number of protons plus neutrons, however heavier nuclei deviate due to potential energy locked up in the necleus and the effect of $E=mc^2$.
- In nuclear physics, we measure mass and energy in units of MeV, mega-electron volts.
- The MeV is defined as the energy an electron would have if it came from a 1,000,000 volt battery or power supply.
- Conversion: 1 MeV = 1.602×10^{-13} joules
- Using $E=mc^2$, we also find that 1 MeV represents 1.78×10^{-30} kg. Using MeV is much more practical than using joules or kg.

Detect neutrinos?

- When Pauli proposed the neutrino (in 1930), and Fermi took the idea seriously it created a challenge: how do you detect this weakly interacting particle?
- How hard is it? In his notes, Fermi calculates that a neutrino can “cross the sun with little probability of being absorbed.”
- Another way to look at it, every second 100 billion neutrinos travel from the Sun and pass through your nose every second. Nobody notices.
- In other words you will need a lot of neutrinos and large, super-sensitive detectors to have a chance.

*** Neutrino Astrophysics by Bahcall, pg 14: pp flux=6×10^{10} cm^{-2} s^{-1}**

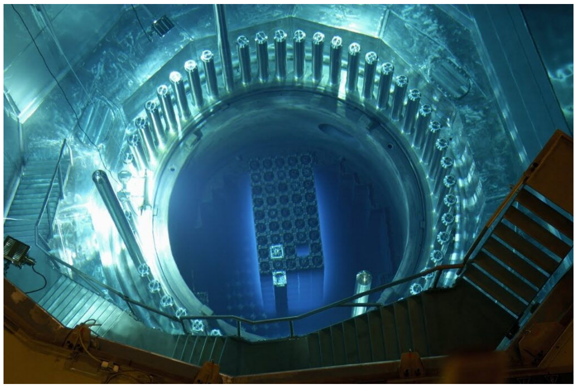
Neutrino Sources

- First you need a plentiful source of neutrinos. You need to be able to turn it on and off.
- Two possibilities
  1) A nuclear bomb
  2) A nuclear reactor
- Both produce large amounts of neutrons which then make anti-neutrinos via

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

~~This is called "inverse beta decay"~~

(Question: Are q, B and L conserved in this reaction?)



The Reines-Cowan Experiments

- In 1951 Clyde Cowan and Fred Reines (who was my boss at UCI) took on the challenge.
- Project Poltergeist set up large detectors underground, near huge reactors.
- First at Hanford, Washington
- Then at Savannah River, South Carolina

Hanford Team 1953

The Reines-Cowan Experiments…

- The experiments used the anti-neutrinos from

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

  reactions in the reactor then looked for

  $$\bar{\nu} + p \rightarrow n + e^+$$

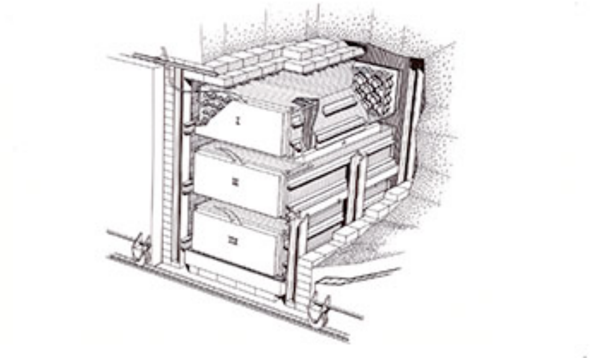
  This is "inverse beta decay"

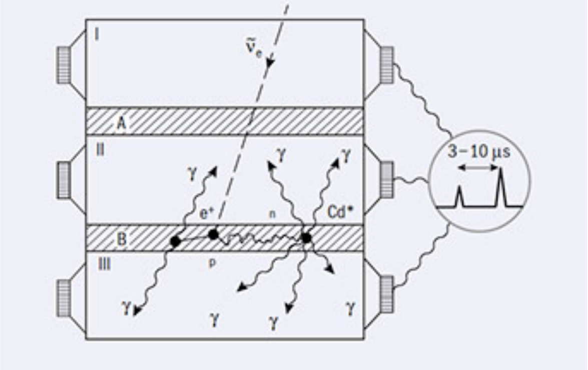
- The positron doesn't last long. It meets an electron and the reaction

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

  occurs.

The Reines-Cowan Experiments…





- The underground experiment had two water tanks “sandwiched” by three γ detectors - tanks of scintillator liquid that would make a flash when hit by a γ. Photomultiplier tubes at the ends picked up the flashes which recorded by oscilloscopes and photographic film.
- An anti-neutrinos would make a positron in the water which would meet an electron a annihilate.
- The e^+ e^- annihilation γ’s would go back-to-back (conservation of momentum!) and have exactly 0.511 MeV each (conservation of energy!)
- This is a good way to find the positrons created by neutrinos.

The Reines-Cowan Experiments…

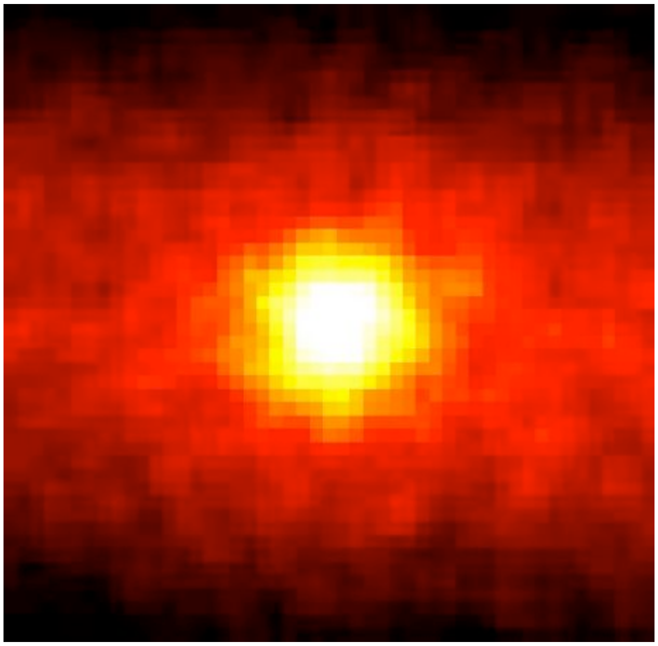
- This version of the experiment was pretty good, but there were too many “background” event from cosmic rays and the reactor.
- A big improvement came from dissolving cadmium chloride in the water and adding electronics to sense γ’s from the neutron being captured by a cadmium nucleus

$$n + {}^{108}Cd \rightarrow {}^{109}Cd * e \rightarrow {}^{109}Cd + \gamma$$

- So : Cowan and Reines knew thay had caught a neutrino when they saw the annihilation gammas followed a few microseconds later the γ from the excited cadmium nucleus.
- Fred Reines eventually received the Nobel prize for detecting the neutrino with this experiment. Sadly, Cowan died before the prize was awarded.

Neutrinos from the Sun

Neutrinos image of the Sun, taken by SuperKamiokande



500 days of data.
Picture covers 90x90 degrees of the sky.
~4.5 MeV threshold

https://apod.nasa.gov/apod/ap980605.html