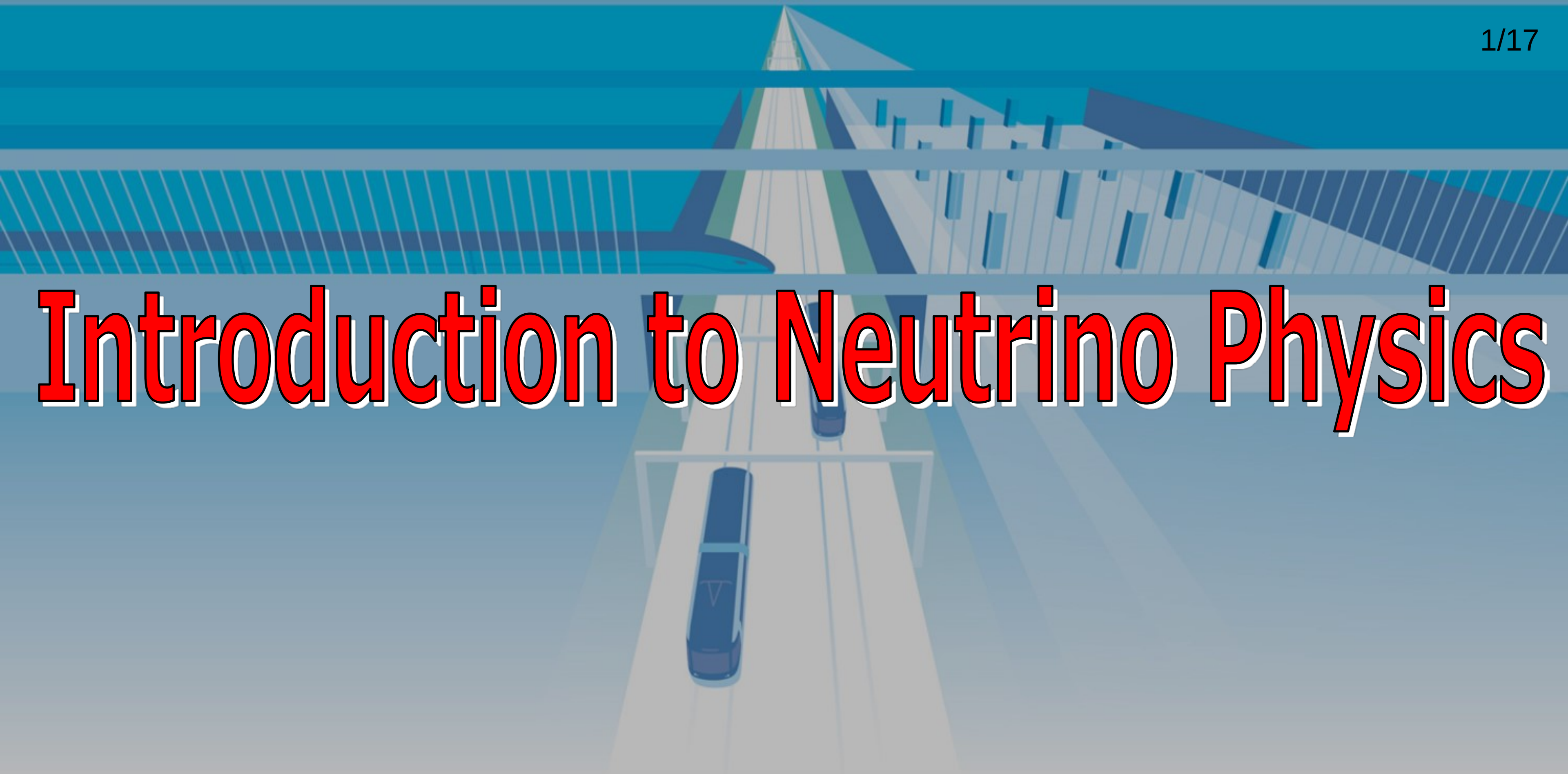
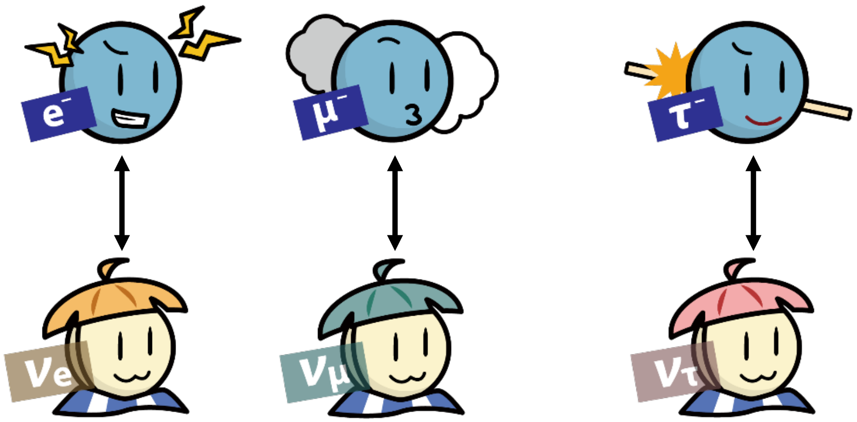


Introduction to Neutrino Physics

Hiroaki SUGIYAMA
(Toyama Prefectural Univ.)

What are Neutrinos

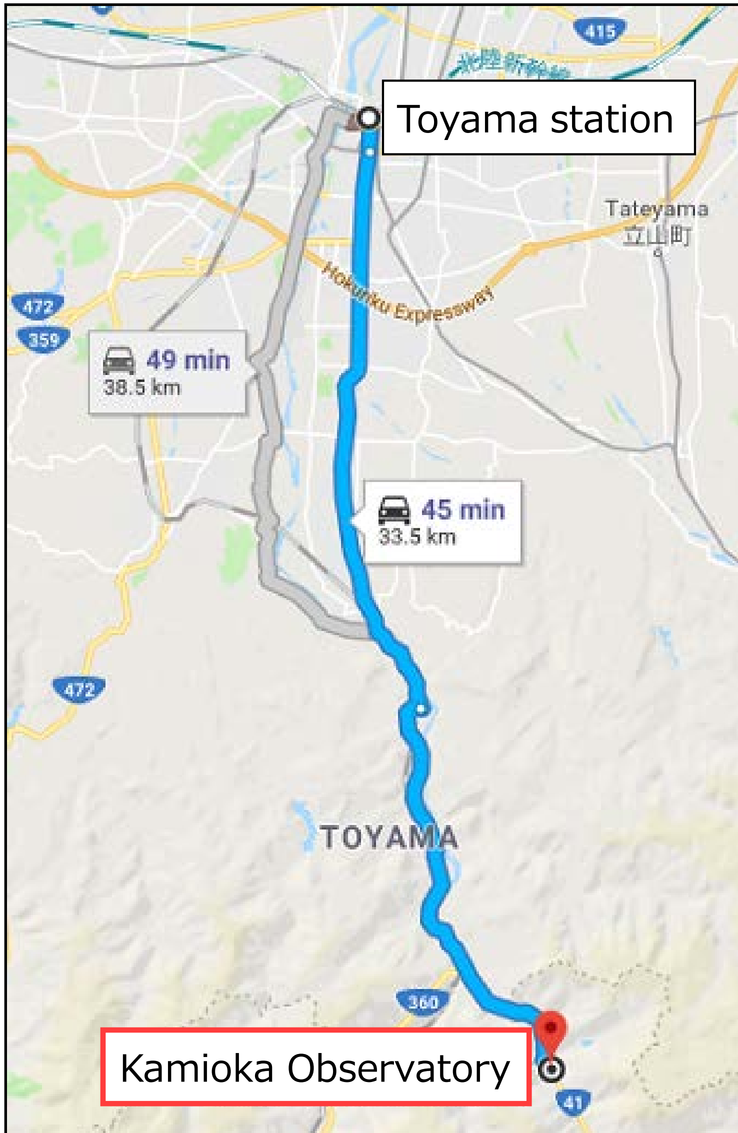
- Elementary particles
- **Electrically neutral**
- Spin 1/2 (Fermion that obeys the Fermi statistics)
- Three types (at the least)
  as partners of electron, muon, and tau-lepton



higgstan.com

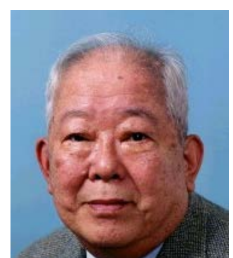
- **Very light** such that they had been regarded as massless particles for a long time
- Weakly interact

Neutrino and Toyama



- Easy (relatively) to go
  to **Kamioka Observatory**
  (in Gifu prefecture)
  from Toyama city

- Two Nobel prizes
  for **neutrino experiments**
  in Kamioka Observatry



 2002

Koshiba
(Kamiokande)

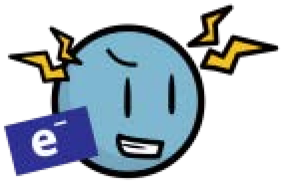
 2015

Kajita
(Super-Kamiokande)

Hello, Neutrino ! - Why is it Necessary ? -

Mystery on the "beta decay"

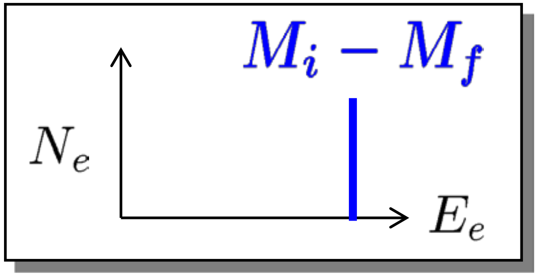
Initial atom → Decay → Final atom + Electron



Mass : M_i M_f m_e

Electron energy spectrum

Expectation :

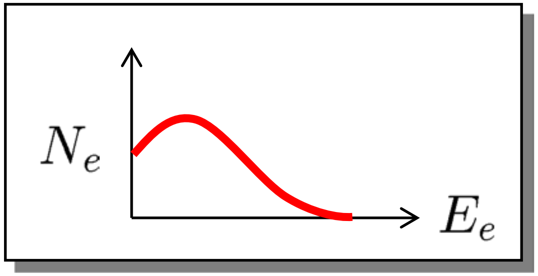


Mono-energetic

⇑

Energy conservation

Observation :



Continuous !

⇓

Breakdown of
the energy conservation ?

Pauli's letter for a workshop in 1930 (translated to English)

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, how because of the "wrong" statistics of the N and Li6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei **electrically neutral particles**, that **I wish to call neutrons**, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that **the sum of the energies of the neutron and the electron is constant**...*

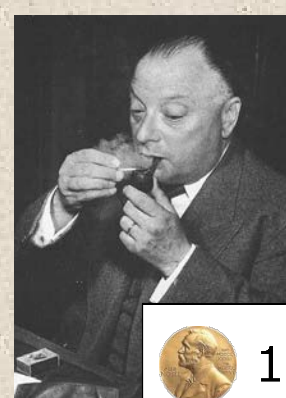
(neutrino)

$$E_\nu + E_e = M_i - M_f$$

Pauli’s letter for a workshop in 1930 (translated to English)

I agree that my remedy could seem incredible because one should have seen those neutrons very earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honoured predecessor, Mr. Debye, who told me recently in Bruxelles: "Oh, It's well better not to think to this at all, like new taxes". From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge. Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr. Back.

Your humble servant
W. Pauli



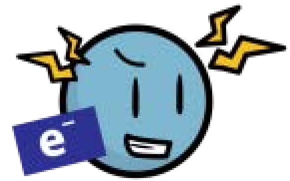
1945

Not for neutrino

Pauli's "neutron"

Neutrino hypothesis

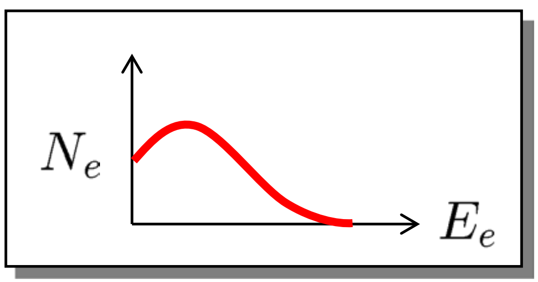
Initial atom → Decay → Final atom + Electron + (Anti-) **Neutrino**



Energy : E_e $\quad$ E_ν

Electron energy spectrum

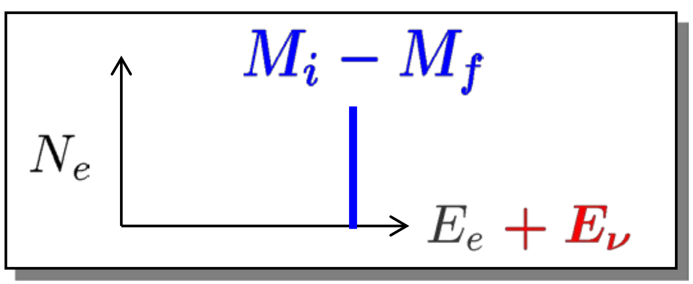
Observation :



Continuous

Consistent !

Explanation :



Energy cons.

Neutrino's godfather

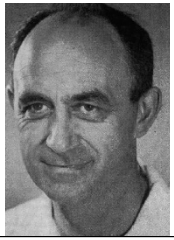
Pauli's "neutron" : Electrically **neutral**, spin 1/2, **very light**

↓

Discovery of a **heavy neutral particle** (the neutron)
by Chadwick in 1932


1935

↓




1938

<u>Fermi renamed</u> Pauli's "neutron"
(the godfather)

as the **neutrino** (= neutro + **ino**)

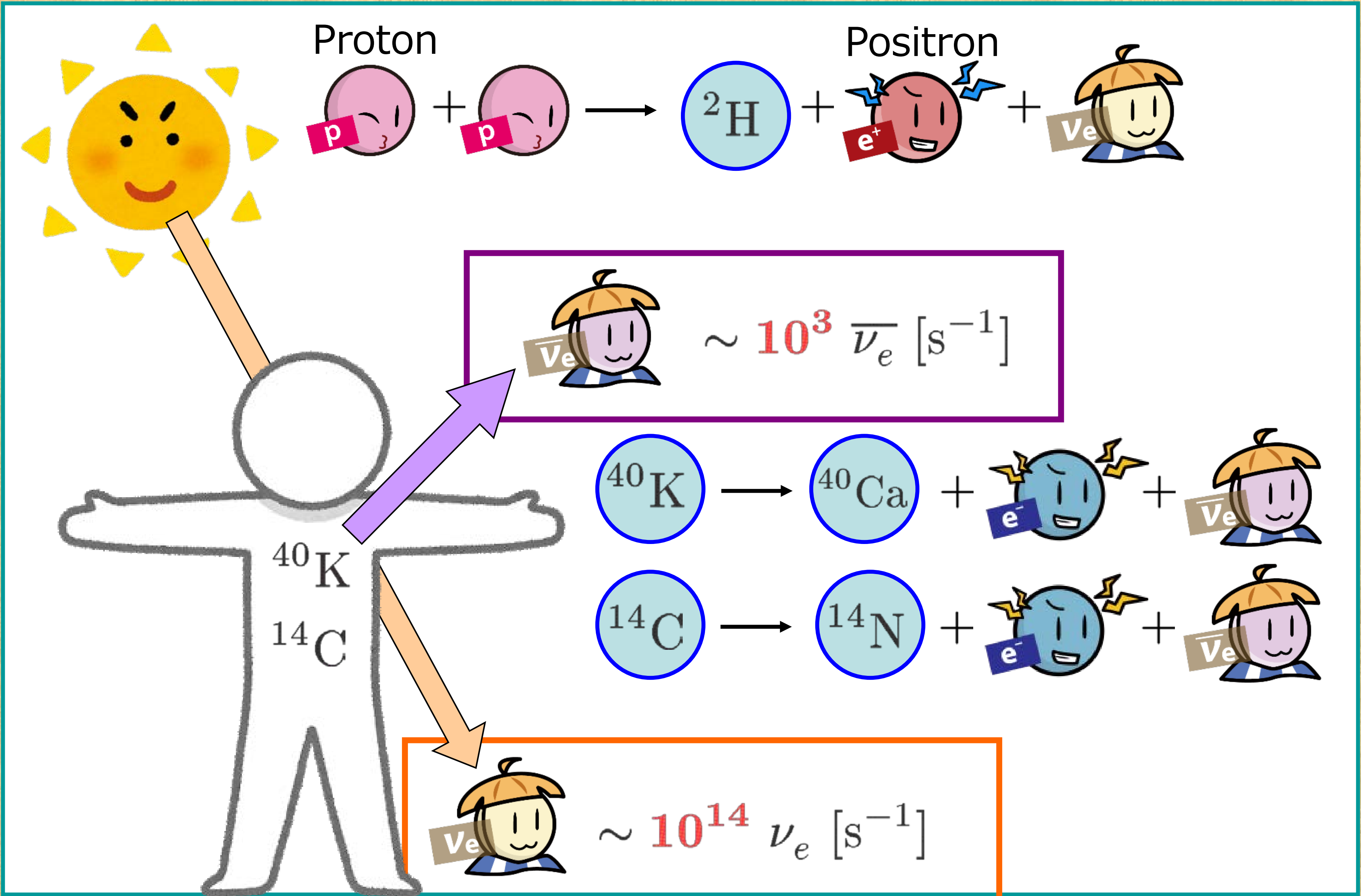
pan**ino** = pane + **ino**

banb**ino**

↓

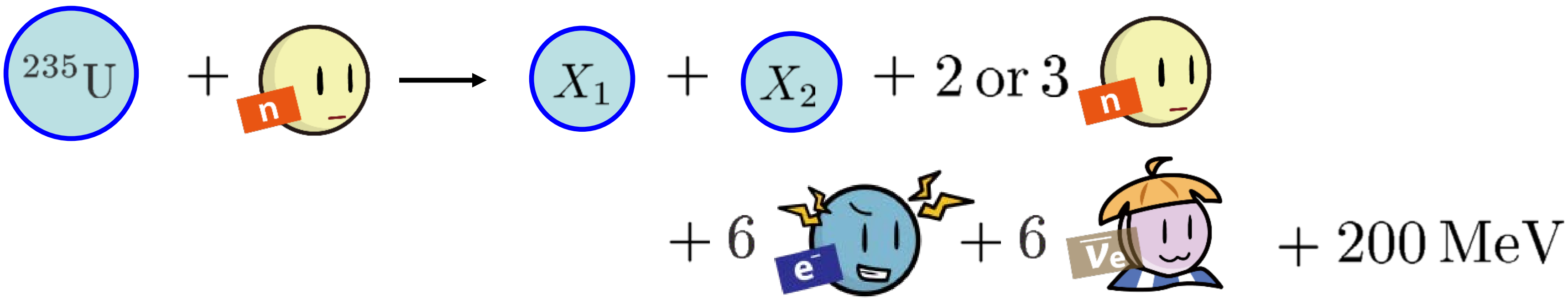
Fermi's theory of the beta decay (1934)

Neutrinos Around



Discovery of Neutrino

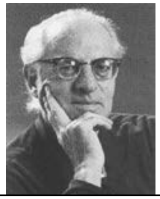
The **nuclear reactor** is a powerful source of (anti-) neutrinos



Electric power $\simeq 0.33 \times$ Thermal power

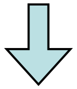
$$1\,[\mathrm{GW_{th}}] \Rightarrow \mathbf{1.6 \times 10^{20}}\ \overline{\nu_e}\ [\mathrm{s}^{-1}]$$

Reines and Cowan proposed an experiment to detect the reactor (anti-) neutrino



1995

Proposal : Phys. Rev. **90**, 492 (**24 Feb. 1953**)



only 4.5 months

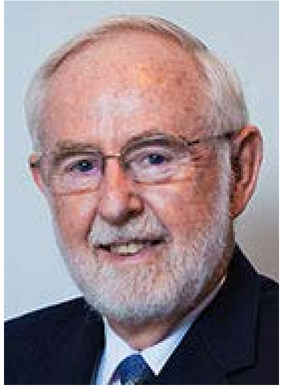
First result : Phys. Rev. **92**, 830 (**9 Jul. 1953**)

Improved result : Science **124**, 103 (**1956**)

Neutrino Oscillation

The Nobel Prize in Physics 2015

Takaaki Kajita



Arthur B. McDonard

"for the discovery of **neutrino oscillations**,
which shows that neutrinos have mass"

What is the neutrino oscillation ?

Neutrino oscillation

Neutrino oscillation : Oscillation of transition probability (Quantum theory)

Produced as a **mu**-neutrino

Energy : E

Distance : L

Observed as a **tau**-neutrino

Transition probability

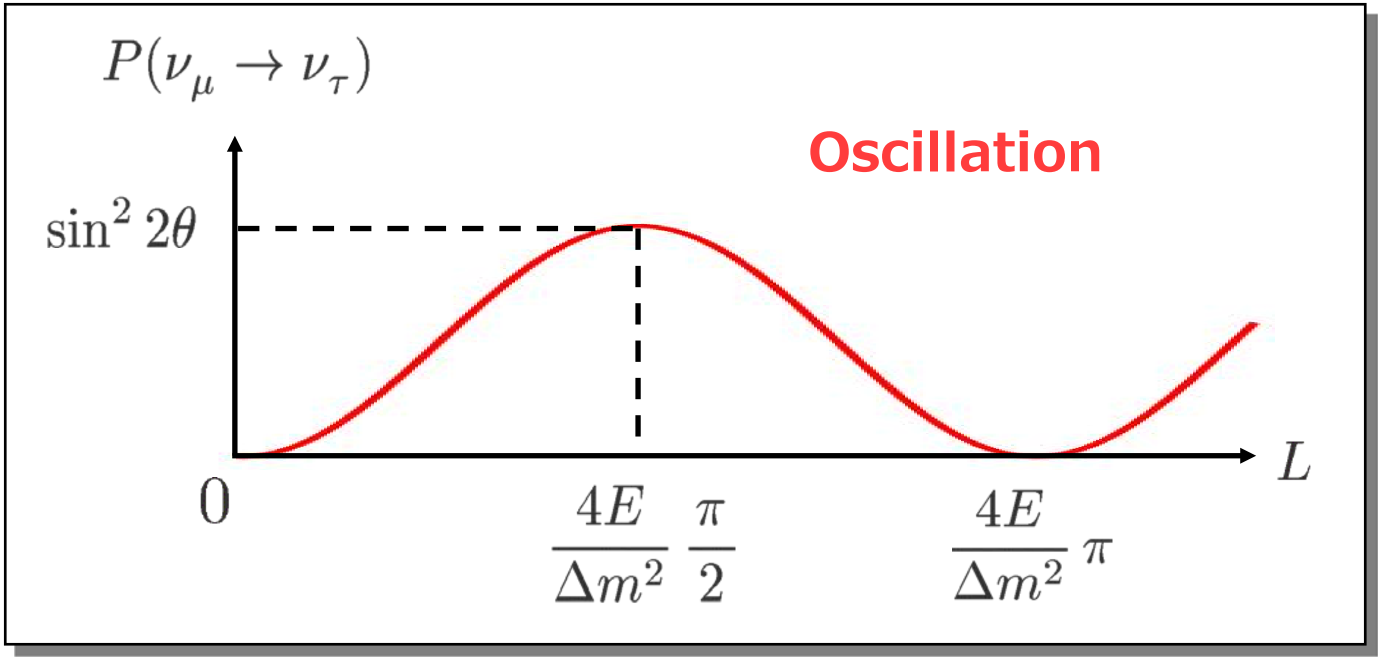
$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \ \sin^2\left(\frac{\Delta m^2}{4E} L\right)$$

$$\Delta m^2 = m_2^2 - m_1^2$$

Difference of squared masses of neutrinos

A parameter (mixing angle)

$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \ \sin^2\left(\frac{\Delta m^2}{4E} L\right)$$



Observation of oscillation

$$P(\nu_\mu \to \nu_\tau) \neq 0 \implies \Delta m^2 \neq 0$$

$$\implies m_1 \neq 0 \text{ and/or } m_2 \neq 0$$

Existence of neutrino mass though neutrinos have been regarded as massless

Neutrino Mass

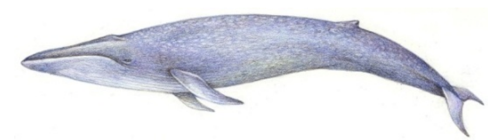
1 — 10^3 — 10^6 — 10^9 — 10^{12} [eV]

Neutrino
$m_\nu < 1\,\mathrm{eV}$

Electron
$m_e = 0.5\,\mathrm{MeV}$

Tau lepton
$m_\tau = 1.8\,\mathrm{GeV}$

Top quark
$m_t = 173\,\mathrm{GeV}$



Pictures : $1\,\mathrm{MeV}\ (= 1.8\times 10^{-30}\,\mathrm{kg})$ is regarded as $1\,\mathrm{kg}$

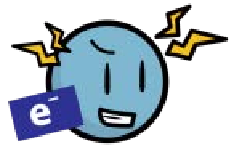
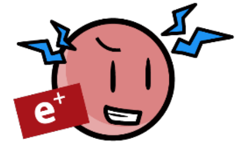
How to generate ?

Neutrino masses are much smaller than the other fermion masses

⇓

Generated in a unique way ? ・・・ **Open question**

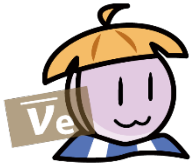
Anti-neutrino

	Electron	Positron (Anti-electron)
		
Electric charge :	-1	$+1$

$-1 \longleftrightarrow +1$ **Opposite**

	Neutrino	Anti-neutrino
		
Electric charge :	0	$0\,(=-0)$

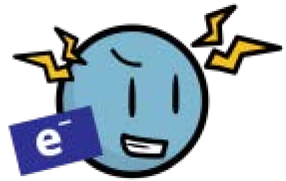
$0 \longleftrightarrow 0\,(=-0)$ **Same !**

 $=$  or  $\neq$  ? $\cdots$ **Open question**

Majorana fermion — Dirac fermion

Neutrinoless double beta decay

Double beta decay

Initial atom —Decay→ Final atom + 2 

+ 2 

Virtually annihilate

Neutrinoless Double beta decay

Initial atom —Decay→ Final atom + 2 

- Possible only with **Majorana neutrinos**

  ⇩

  Observed ⇒ Majorana neutrinos

- KamLAND-Zen in Kamioka Obs. searches for the decay

Summary

Neutrinos : Elementary particles, weakly interact, electrically **neutral**, very **light**

Open questions :

How are **tiny neutrino masses** generated ?

⟶ Probably, via neutrino-specific mechanism

⟶ **Theoretical studies** are necessary

Are neutrinos **Majorana fermions ?** $(\nu = \overline{\nu})$ Dirac fermions ? $(\nu \neq \overline{\nu})$

⟶ Origin of neutrino masses depends on the answer

Majorana fermions $\Rightarrow$ Neutrinos are really unique

⟶ Searches for **neutrinoless double beta decay**

e.g., KamLAND-Zen in Kamioka Observatry

ν **physics** guides us to **new physics**