

## **$\beta$ -Decay controversy. Neutrino hypothesis.**

1899 Discovery of  $\beta$ -rays (and  $\alpha$ -rays) by Rutherford

1920s Many elements were known to have  $\beta$ -decays:  $N_0(A, Z) \rightarrow N(A, Z+1) + e^-$ .

- Energy released was due to a small difference in nuclei masses  $E_0 = M_0 - M \sim$  a few MeV
- Measurements of electron energy spectra were controversial:
  - some saw fixed energy lines (same as for  $\alpha$ -particles emitted in  $\alpha$ -decays)
  - some saw wide continuous spectra that did not make much sense: two-body decay would imply a fixed energy line for electrons; however, one could argue that spread was due to energy losses by electrons before they were detected and due to experimental errors...
  - by late 1920s it became more and more evident that the spread in energy was real
  - **Bohr** suggested that the energy in microworld was conserved only on average, not on an event-by-event basis...

1930 **Pauli** suggested that the continuum spectra might be due to one more “invisible” light neutral particle (later to be named neutrino) involved in the  $\beta$ -decay. It could not be photons—they would be easily detected. It had to be something else and might be undetectable at all...

With three particles involved, electron would be able to take any momentum from zero to the maximum allowed, the balance being taken care of by the other light “invisible” particle...

However, the idea was not accepted very well<sup>1</sup>: at that time introducing new particles was a bad taste (same story was with prediction of positrons by Dirac).



1932 **Chadwick** discovered neutron...

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<sup>1</sup> E.g., by Bohr who was known not to take any new ideas lightly: he was an outspoken critic of Einstein’s light quanta (till 1924), discouraged Dirac in his search for new relativistic QM equations saying that the Klein-Gordon already had done it, opposed Pauli’s idea of an “invisible” particle, ridiculed Yukawa’s theory of meson, disparaged Feynman’s approach to QED...

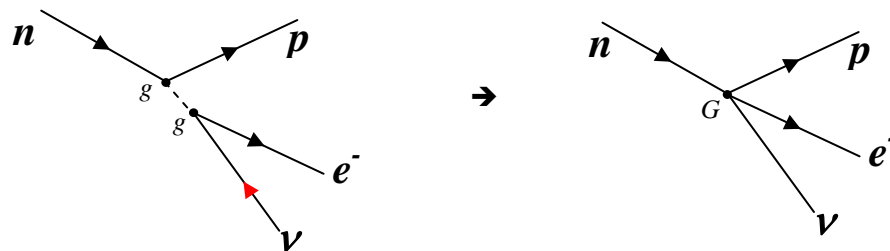
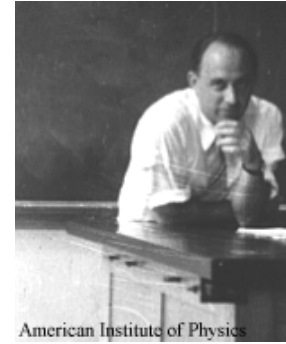
## $\beta$ -Decay: Fermi's model

1933 **Enrico Fermi** formulated his  $\beta$ -decay model:

- Existence of Pauli's "invisible" particle was accepted, the name *neutrino* (small neutron) was coined
- All  $\beta$ -decays were due to the same basic underlying process

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

- Neutrino was treated as  $1/2$ -spin particle (angular momentum conservation requires neutrino be a fermion) obeying the Dirac equation.
- Formalism was basically 100% paralleled to Dirac's equations for  $e/m$  interactions except for one major change: the intermediate propagator ( $e^2/q^2$  in case of Dirac's equations) was collapsed to a fixed constant  $G$ , now known as Fermi's constant  $G_F$ . Recalling Yukawa's formalism, this could be interpreted as the force due to exchange with a particle of a mass much larger than momenta transferred. The particle must have a charge to convert neutral neutron into a proton:



- The difference in lifetimes of various elements was basically due to differences in phase space available for the final state electron and neutrino (proton balances the momenta of electron and neutrino and does not contribute to the available phase space).
- The spectra of electrons were easily calculable from plain phase space considerations
- The value of the constant  $G_F = 1.166 \times 10^{-5} \text{ GeV}^{-2}$
- Other  $\beta$ -decay related processes were possible and calculable:
  - $\beta^+$ -decay:  $p \rightarrow n + e^+ + \nu$   
possible in certain nuclei only (proton is lighter than neutron), e.g.,  $^{30}\text{P} \rightarrow ^{30}\text{Si} + e^+ + \nu$   
→ discovered by Joliot and Curie in 1933
  - K-capture:  $p + e^- \rightarrow n + \nu$   
possible in certain nuclei only (proton and electron masses do not add up to neutron's mass)  
→ to be discovered by Luis Alvarez in 1938
  - Relate the neutron  $\beta$ -decays to the muon decays...  
→ to be discovered later...
  - neutrino absorption:  $\bar{\nu} + p \rightarrow n + e^+$   
calculation showed right away why neutrinos were "invisible" (see lecture 9):

$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2} p_{cm}^2$$

$$\sigma = \frac{G^2}{\pi} p_{cm}^2$$

⇒ show that the energy threshold  $E_0$  is 1.80 MeV (lab frame)

⇒ show that positrons momentum  $p_{cm}$

equals to energy of an antineutrino above threshold  $\Delta E$  (lab frame)

(assuming that antineutrino energy is  $\ll 1 \text{ GeV}$ )

$$\sim 10^{-48} \text{ m}^2 \text{ (at } \Delta E = 1 \text{ MeV)}$$

→ NEVERTHELESS, discovered by Cowan and Reines in 1956



Note: Fermi's paper was rejected by *Nature* on the grounds of being "too speculative". The paper was later published in scientific journals in Italy and Germany. Meanwhile, Fermi went to do experiments and the same year discovered artificial radioactivity induced by bombardment of nuclei with neutrons. In 1938 he was awarded the Nobel Prize "for his demonstrations of the existence of new radioactive elements produced by neutron irradiation, and for his related discovery of nuclear reactions brought about by slow neutrons".

## Experimental discovery of neutrino

1953 **Clyde Cowan and Fred Reines** set to observe neutrino interactions. Their first idea was to use the pulse of huge neutrino flux coming out from a nuclear explosion... The use of a nuclear reactor proved to be much more practical—they chose Savannah River Reactor in South Carolina. Given the illusive neutrino properties, the project was named *Poltergeist*.

- Uranium fission reactor 1000 MW, uranium fragments are reach with neutrons
- $n \rightarrow p + e + \bar{\nu}$  (energy of released neutrinos depends on the energy levels of decaying nuclei fragments)
- Anti-neutrino flux  $10^{13} \text{ cm}^{-2}\text{s}^{-1}$  (few meters from the reactor core)
- Two tanks of diluted cadmium chloride ( $\text{CdCl}_2$ ) in water sandwiched between
- Three tanks of liquid scintillator,  $183 \times 132 \times 56 \text{ cm}^3$  each.
- The apparatus surrounded with thick layer of earth and metal (scrap metal from an old battle ship) to shield it from other particles coming from the reactor and cosmic rays (only partially)

Chain of events:

- $\bar{\nu} + p \rightarrow n + e^+$
- *positron annihilates with electron:  $e^+ e^- \rightarrow 2\gamma$*
- *detect 0.51 MeV  $\gamma$ 's in two scintillator tanks in coincidence (time scale is a few ns)*
- *neutron slows down by colliding with hydrogen of water to very low energy (~thermal), it takes a few  $\mu\text{s}$*
- *thermal neutrons have enormous cross-section of capture by Cd,*
- *the capture is followed by disintegration of nucleus  $\rightarrow$  a number of gammas with total energy of 9 MeV*
- *look for the second pulse in two scintillator tanks in coincidence and delayed with respect by a few  $\mu\text{s}$  with respect to the previous flash*
- Counting rate of ~3 events per hour
- The first series of measurements: 200 hours, 567 events, ~200 estimated to be from background...
- Statistically sound excess!

Mass limit from direct mass measurements <2 eV

1995 **Reines** receives the Nobel Prize (Cowan deceased by that time).  
*One can only wonder why it took them so long...*



