The Experiment

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Inauguration of the EPS Historic Site

Atomki, Debrecen, 25 October, 2013

1 Unevenness in the progress of physics

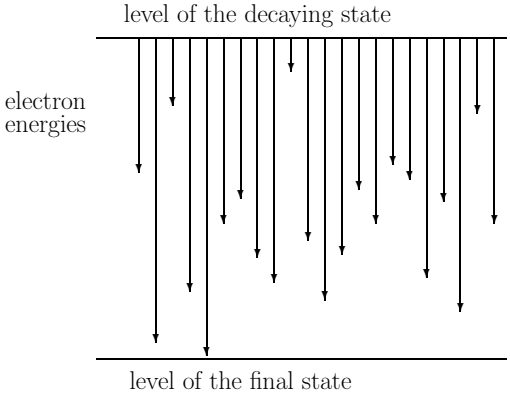
- Paradigm changes are sometimes painful.
- Example of the Higgs boson
  - proposed mid-60's
  - built in the Standard Model in mid-70's
  - last unverified element since mid-90's
  - verified 2010's
- Beta decay
  - known since $\sim$1900
  - the puzzle (violation of conservation theorems) recognized and the way out (the neutrino hypothesis) conjectured $\sim$1930
  - the neutrino hypothesis verified $\sim$1956

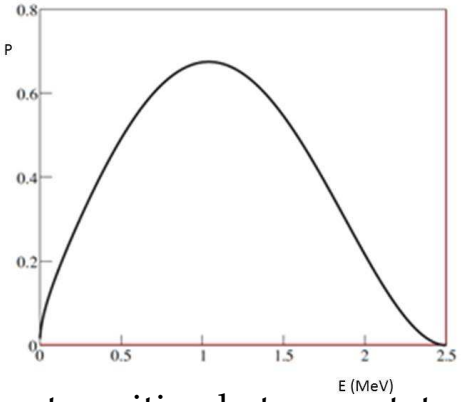
My duty: to show The Experiment in its historical perspective

Beta particles: electrons

The puzzle of the beta decay: violation of conservation theorems

1. Energy non-conservation



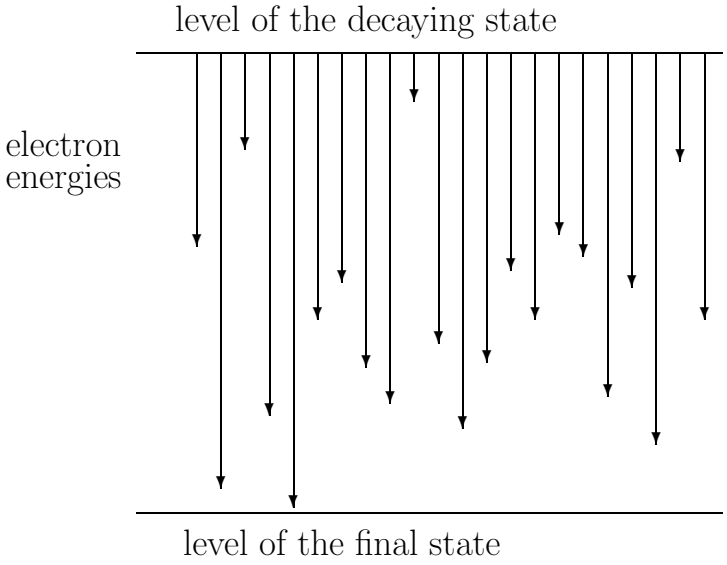


2. angular-momentum non-conservation: transition between states of integer spins by emission of a $\frac{1}{2}$-spin electron
3. Undertsanding obscured by
   - the unknown composition of nuclei (protons & electrons?)
   - doubts whether quantum mechanics is applicable to nuclei

2 Theory of beta decay

- 1930: Pauli's postulate of an elusive neutral spin-$\frac{1}{2}$ particle
  - to account for the missing energy
  - to restore angular-momentum conservation

Hypothesis by W. Pauli of a third particle: neutral, spin-$\frac{1}{2}$



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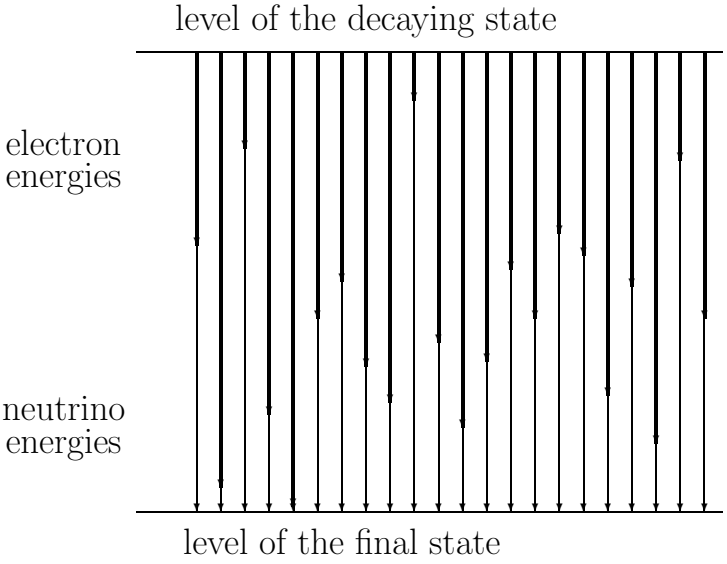


- 1932: discovery of the neutrons
- immediately: the nucleus must consist of protons and neutrons but no electrons
- 1934: Fermi: electrons and (anti)neutrinos must be created in the course of an elementary process:

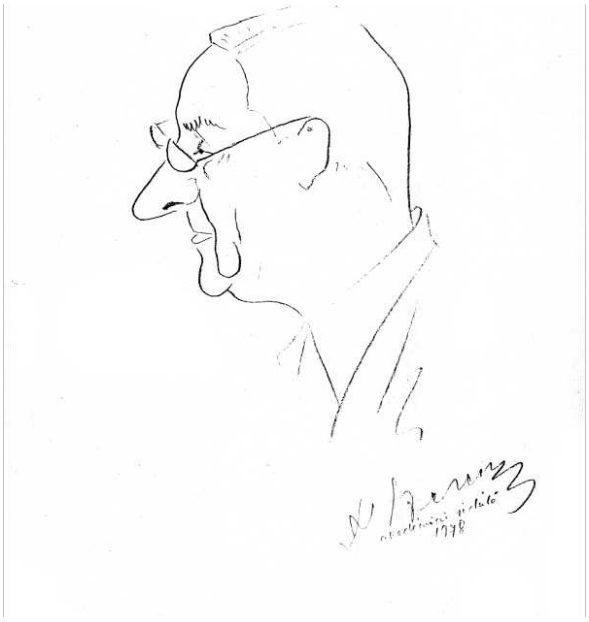
$$\mathrm{n} \longrightarrow \mathrm{p} + \mathrm{e}^{-} + \bar{\nu},$$

- The interaction is very weak, very short-ranged, and the (anti)neutrino must have zero or very small mass.
- A new fundamental interaction, later called the weak interaction
- It is omnipresent, but is observable only in transitions like beta-decay or its counterpart produced in proton-rich nuclei:

$$\mathrm{p} + \mathrm{energy} \longrightarrow \mathrm{n} + \mathrm{e}^{+} + \nu,$$

where ν is the neutrino.

3 The Debrecen experiment



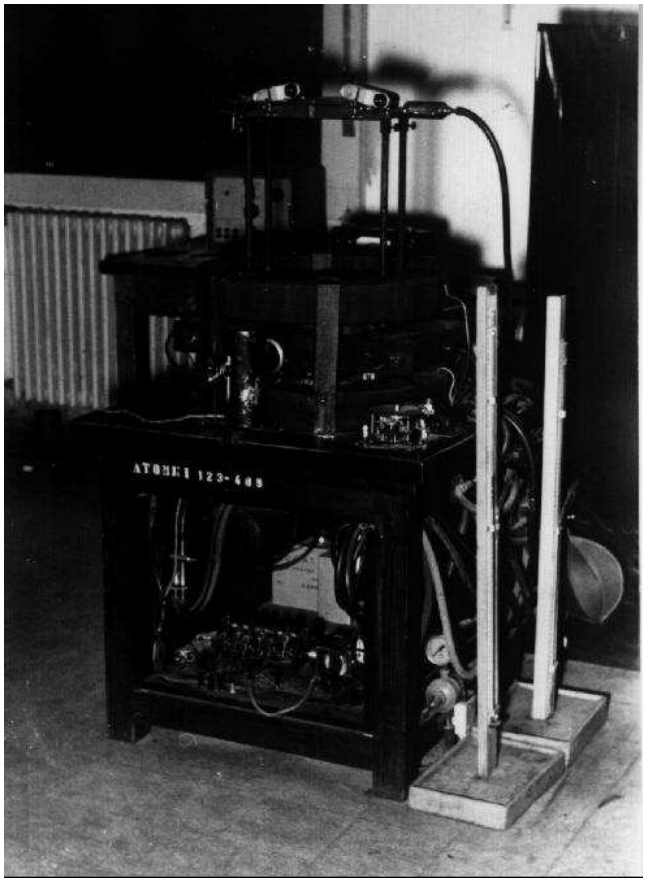
Professor Sándor (Alexander) Szalay, founder and first Director of this Institute

1951 Prof. Szalay's idea: beta decay in a cloud chamber (Wilson chamber)
let Gyula (Julius) Csikai and Gyula Hrehuss construct clould chambers

Prof. Szalay and young Mr. Csikai

Operation of the cloud chamber

- cylindrical box (diameter $\sim$30 cm) with vertical axis
- oversaturated vapour to visualize the tracks of charged particles
- oversaturation by adiabatic expansion of gas with saturated vapour
- transparent top
- powerful large-angle flash when stereo-snapshot from above
- vertical homogeneous magnetic field



Particulars of The Experiment

- The process studied:

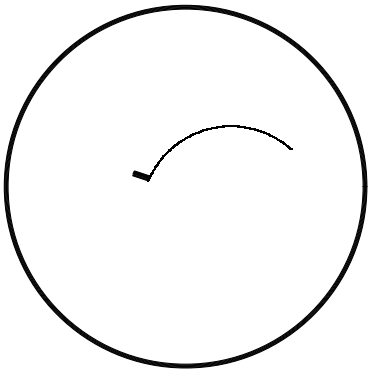
$$^{6}\mathrm{He} \longrightarrow ^{6}\mathrm{Li} + \mathrm{e}^{-} + \bar{\nu}\ (+3.6\ \mathrm{MeV})$$

- 3.6 MeV, is large and mass number $A = 6$ is small enough for the recoil to be visible.
- The half-life 0.8 s of ^{6}He is convenient for a periodic production of ^{6}He.
- Production of ^{6}He:

$$^{9}\mathrm{Be} + \mathrm{n} \longrightarrow ^{6}\mathrm{He} + \alpha$$

- Be supplied in a container of porous walls inside the chamber
- The neutron source shot to the vicinity of the chamber and then back behind a radiation shield
- The ^{6}He gas atoms released through the porous wall
- The expansion, flash and the exposition: 0.3 s after the shot

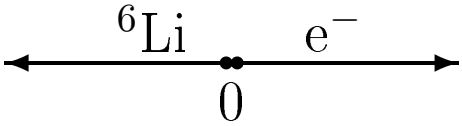
A photo should look like this:



- The long thin track is the track of the electron.
- The velocity of the electron can be calculated from the magnetic field strength, the electron mass and charge and the radius of the path.
- The short thick track is that of the recoiled nucleus.
- Most conspicuous feature: the two detected fragments emerge in an angle different from 180^o!

Before the decay the momentum of ^{6}He is zero. Thus, for a disintegration into two, momemtum conservation would strictly impose

$$m_{\mathrm{e}}\vec{v}_{\mathrm{e}} + m_{^6\mathrm{Li}}\vec{v}_{^6\mathrm{Li}} = 0, \text{ i.e., } m_{\mathrm{e}}\vec{v}_{\mathrm{e}} = -m_{^6\mathrm{Li}}\vec{v}_{^6\mathrm{Li}}.$$

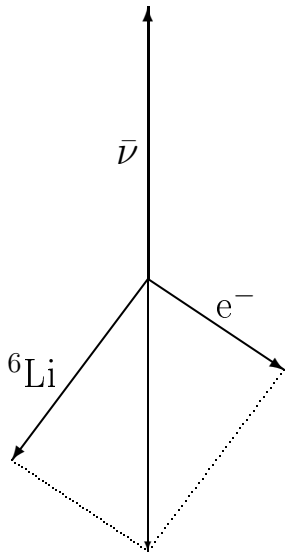


If there is a third particle emerging, the momentum conservation would look like

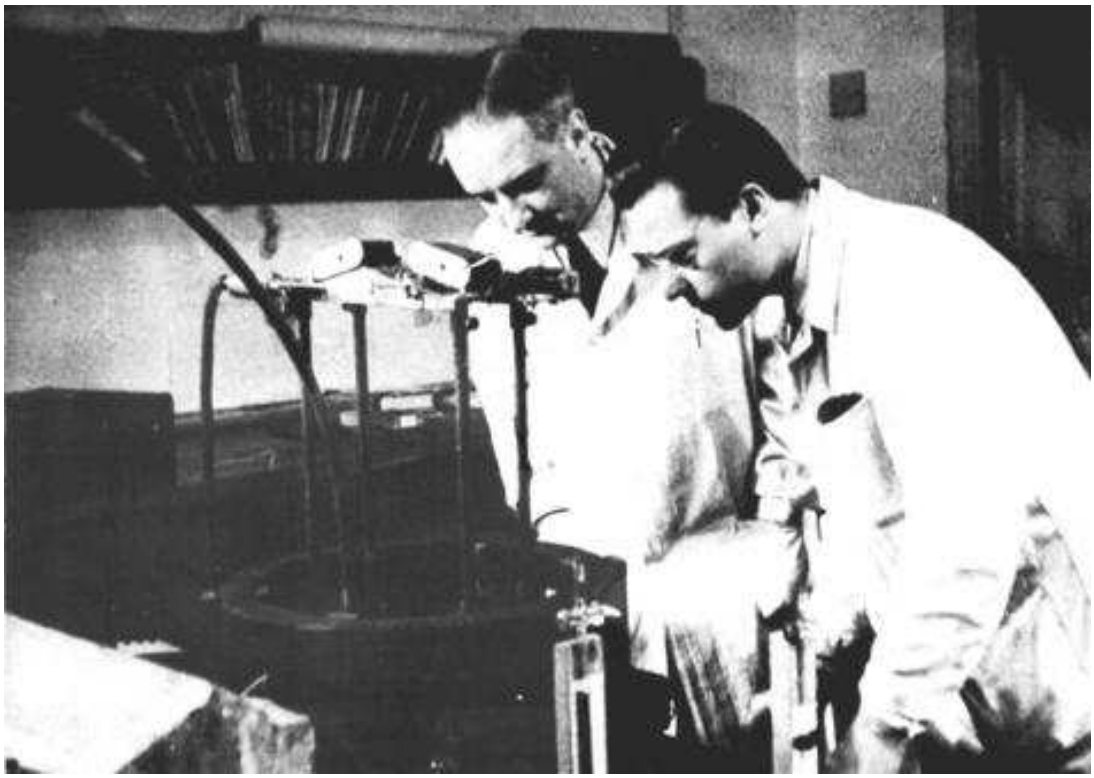
$$m_{\mathrm{e}}\vec{v}_{\mathrm{e}} + m_{^6\mathrm{Li}}\vec{v}_{^6\mathrm{Li}} + m_{\bar{\nu}}\vec{v}_{\bar{\nu}} = 0,$$

i.e.,

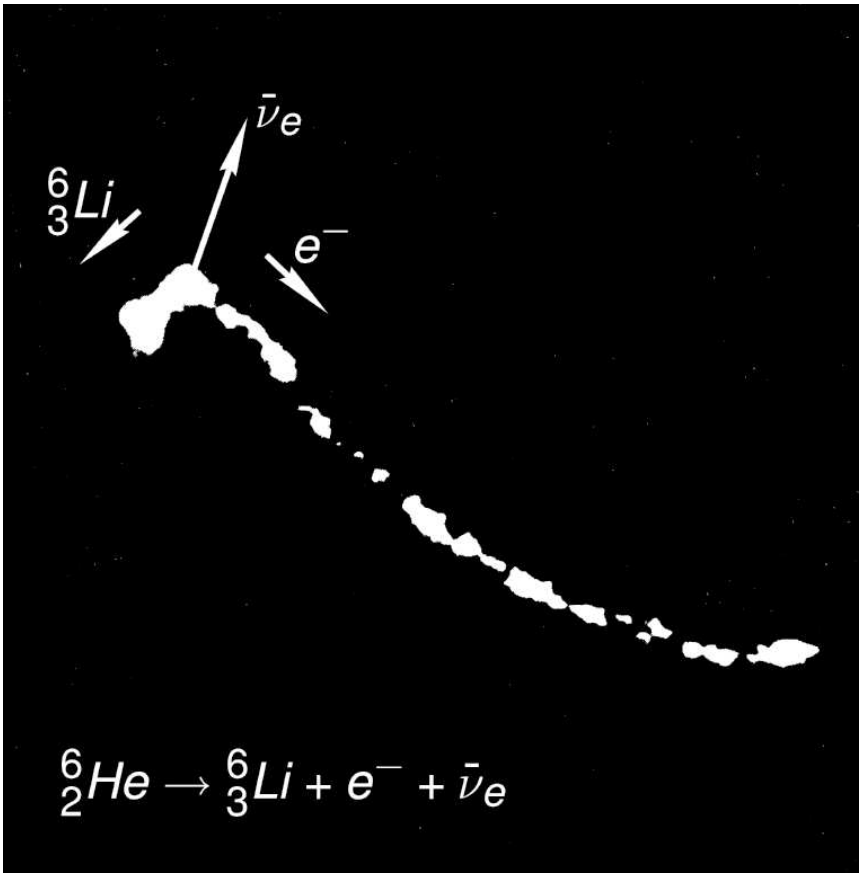
$$m_{\mathrm{e}}\vec{v}_{\mathrm{e}} + m_{^6\mathrm{Li}}\vec{v}_{^6\mathrm{Li}} = -m_{\bar{\nu}}\vec{v}_{\bar{\nu}}.$$

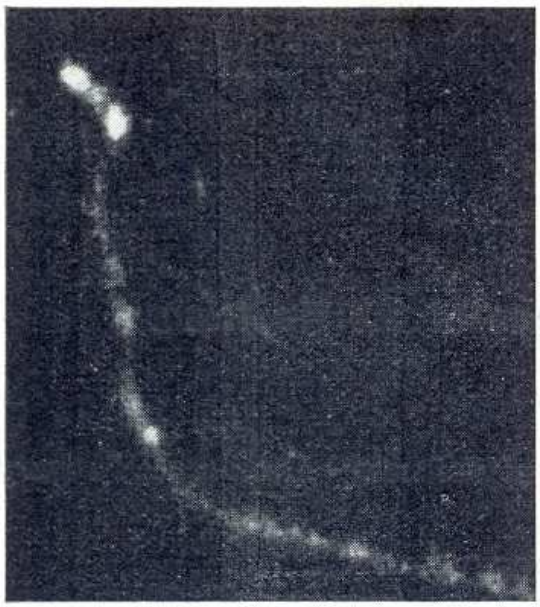


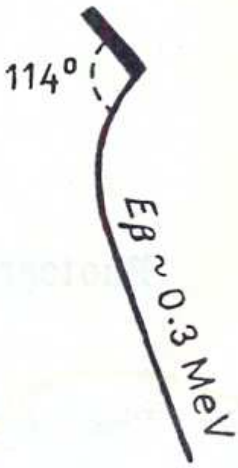
- With $\bar{\nu}$ undetected, it is observable, indirectly, through its missing momentum.
- In some of the snapshots the electron velocity is larger than the maximum that is possible in two-particle decay.

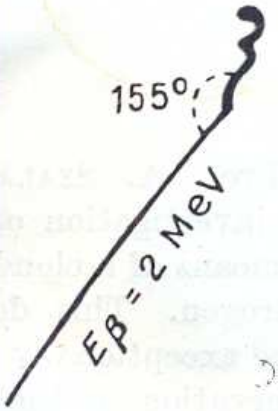


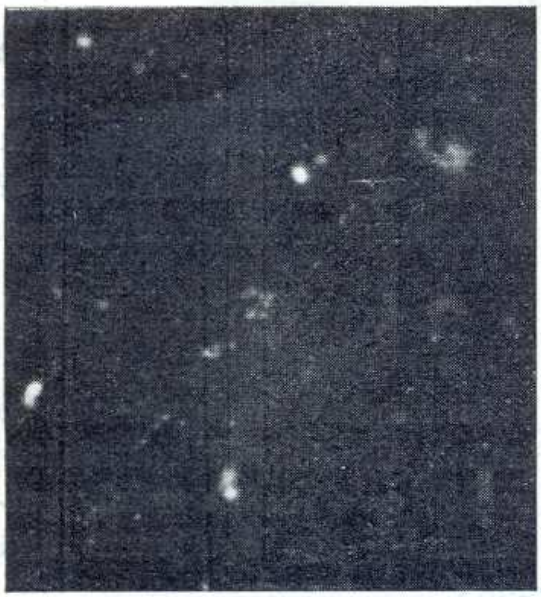
Prof. Szalay and young Mr. Csikai working on The Experiment
And some actual photos of the the decay:

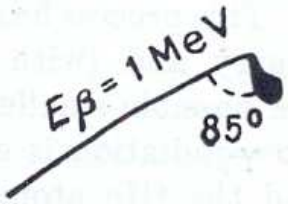

$\bar{\nu}_e$
^6_3Li
e^-
$^6_2He \rightarrow {}^6_3Li + e^- + \bar{\nu}_e$



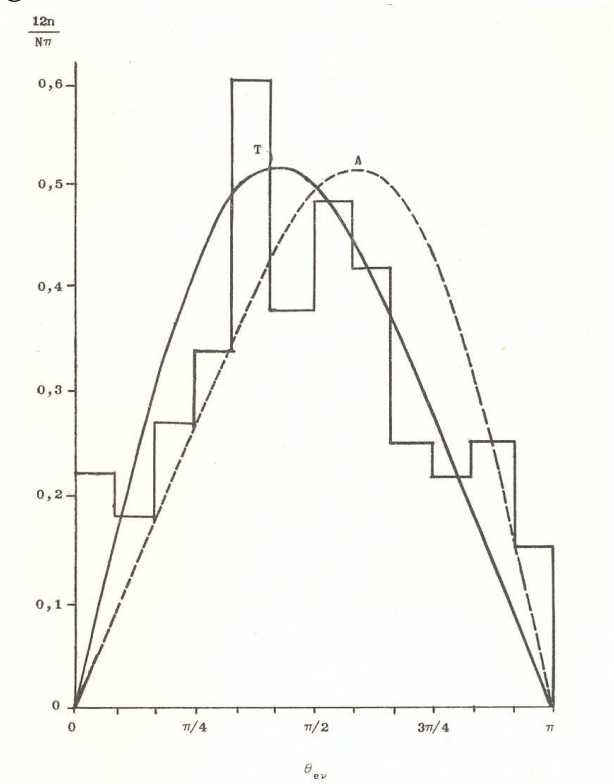

114°
Eβ ~ 0.3 MeV


155°
Eβ = 2 MeV




Eβ=1MeV
85°

Angular correlation



4 Chronology

- Csikai–Szalay experiments: autumn, 1956
- Direct detection of the neutrino, Reines & Cowan
  Experiments: 1953–56; published 20th July, 1956
  in a nuclear reactor, Los Alamos:

$$\bar{\nu} + \mathrm{p} \longrightarrow \mathrm{e}^{+} + \mathrm{n}$$

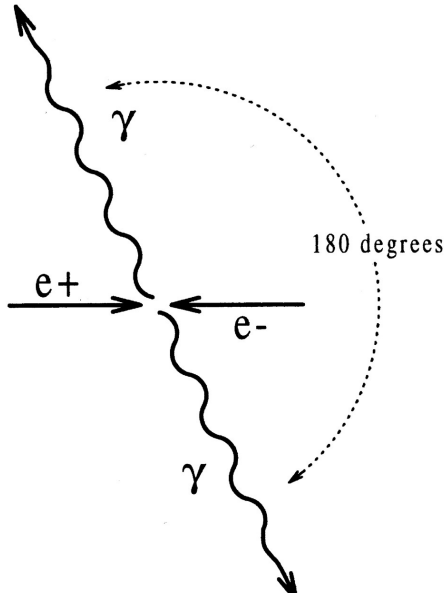
  The positrons detected through the pair of annihilation gamma rays:

$$\mathrm{e}^{+} + \mathrm{e}^{-} \longrightarrow \gamma + \gamma,$$

  neutrons identified through

$$\mathrm{n} + {}^{108}\mathrm{Cd} \longrightarrow {}^{109\mathrm{m}}\mathrm{Cd} \longrightarrow {}^{109}\mathrm{Cd} + \gamma$$

  Coincidence with time delay as expected.



Thus the Csikai–Szalay experiment can be regarded as a prompt confirmation of the existence of the neutrino.

5 Parallel story: parity violation

The proof of the existence of the neutrino restores the honour of the energy, momentum and angular momentum conservation.
1956, yet another revolution: beta decay violates the theorem of parity conservation.
Comments:

- Parity: behaviour of the wave function with respect to spatial reflection
- Beta decay does not obey the left-right symmetry: the spin of ν is left-handed, while the spin of $\bar{\nu}$ is right-handed $\Longrightarrow$ parity conservation is violated.
- Parity is not additive, thus no direct macroscopic consequence.
- All conservation theorems arise from symmetries.
- Since the energy, momentum and angular momentum conservation theorems always hold, they can be attributed to symmetries of space and time.
- Left-right symmetry is only violated by the weak interaction.
- The weak interaction also violates the particle-antiparticle and the time-reversal symmetries, but it seems to be symmetric with respect to the combination of all three: space reflection, time reflection and particle-antiparticle exchange.

6 Closing remarks

- Prof. Szalay's lectures in 1967–68
- No conspicuous displeasure for scoring second
- Strong censure of Niels Bohr for his willingness to give up energy conservation
- Utmost care should be excercised in reconciling new findings with well-established facts.
- Postulation of a new particle has proved useful ever since the explanation of beta decay.
- It is to be seen whether postulating a supersymmetric partner for each particle proves to be correct.
- A two-thousand-year-old opinion on conservation laws

Titus Lucretius Carus on the 'conservation theorems'
from ***De rerum natura***

Nunc age, res quoniam docui non posse creari
de nihilo neque item genitas ad nil revocari,
ne qua forte tamen coeptes diffidere dictis,
quod nequeunt oculis rerum primordia cerni,
accipe praeterea quae corpora tute necessest
confiteare esse in rebus nec posse videri.

And now, since I have taught that things cannot
Be born from nothing, nor the same, when born,
To nothing be recalled, doubt not my words,
Because our eyes no primal germs perceive;
For mark those bodies which, though known to be
In this our world, are yet invisible

Translated by William Ellery Leonard

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Nos, bizonyítottam, hogy nem jön létre a lévő
nem-létből, s ami van, nem tűnhet a semmibe újra,
mégis, mert netalán kételkednél abban a tényben,
hogy nem látni a tárgyban a legkisebb elemecskét,
felsorolok néhány természeti tárgyat, amelyről
megvallod magad is, hogy van, de szemünk sose látja.

Translated by Ágnes Nemes Nagy