Pauli’s new particle

In addition to the electron a neutral, light particle is created, which carries away the „missing energy“!

„Today I have done something, what one should not do in theoretical physics. I have something, what is not understood, explained by something, what can not be observed!”
Neutrino detection

• Detection of particles:

Interaction of particles with matter (detector)

• Interaction with matter depends on the particle:

Charged particles: Ionization of the matter

Photons: Energy transfer to charged particles
Neutrons: Nuclear reactions create charged particles

• Neutrinos interact only weakly:

Only one out of 100 billion neutrinos from a β-decay is discovered by the Earth.

*Calculated 1934: „Hopeless“*
Neutrinos from the Sun

4 Protons $\rightarrow$ Helium $+ 2e^+ + 2\nu + 26\text{MeV}$

- Known: total irradiated energy
- Known: Energy per fusion process

- Number of neutrinos produced $[\text{s}^{-1}]$!
  On Earth: 66 billion $\nu$ per $(\text{cm}^2 \cdot \text{s}^1)$

- **proton-proton-cycle**
  - pp-neutrino
    - $p+p \Rightarrow ^2\text{H} + e^+ + \nu_e (99\%)$
  - pep-neutrino
    - $p + e^+ + p \Rightarrow ^2\text{H} + \nu_e (1\%)$
  - $2\text{H} + p \Rightarrow ^3\text{He} + \gamma$
  - hep-neutrino
    - $^3\text{He} + ^3\text{He} \Rightarrow ^4\text{He} + 2p (86\%)$
    - $^3\text{He} + p \Rightarrow ^4\text{He} + \nu_e + e^- (<1\%)$
  - $^7\text{Be} + ^4\text{He} \Rightarrow ^8\text{Be} + \gamma (14\%)$
  - $^7\text{Be} + e^- \Rightarrow ^7\text{Li} + \nu_e$
  - $^7\text{Li} + p \Rightarrow 2^4\text{He} (99\%)$
  - $^7\text{Be} + p \Rightarrow ^8\text{B} + \gamma$
  - $^8\text{B} \Rightarrow ^8\text{Be} + e^+ + \nu_e$
  - $^8\text{Be} \Rightarrow 2^4\text{He} (1\%)$

- **Gallium, Chlorine, SuperK**

- **Neutrino Flux**

- **Neutrino Energy (MeV)**

- Solar neutrino energy spectrum
First measurement of the solar neutrinos

**Inverse beta-decay („neutrino-capture“)**

\[ \nu_e \rightarrow e^{-} + 37 \text{Cl} \]

- **600 tons Carbon tetrachloride**

- Homestake Sun neutrino-Observatory (1967–2002)

- 40 days neutrino irradiation …
  - Expected: 60 atoms $^{37}\text{Ar}$
The problem of the missing solar neutrinos

Homestake

Chlorine

Calculation of the solar neutrino flux from different source reactions

Raymond Davis Jr. 1914 – 2006

John Bahcall 1934 – 2005

“Neutrino transformation” the solution of the puzzle
# Neutrino oscillations

<table>
<thead>
<tr>
<th>electron $e$</th>
<th>myon $\mu$</th>
<th>tau $\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>e-neutrino</td>
<td>$\mu$-neutrino</td>
<td>$\tau$-neutrino</td>
</tr>
</tbody>
</table>

Idea: If neutrinos have a mass, then they can convert themselves into one another!

Assumption: Mixture of $\nu_e$ and $\nu_\mu$

Change of a neutrino-beam with the distance to the neutrino source:

1998: Discovery of the oscillations between myon- and tau-neutrinos using Super-Kamiokande (myon-neutrinos from the atmosphere)
Solar neutrino problem

Sun
Since 4.5 billion years fusion

66 billion neutrinos/s/cm^2

Since 1964: Detection with Homestake-experiment
Expected: 1.5 reactions/d
Observed: 0.5 reactions/d

Since 1986 Kamiokande: confirmation of Homestake

Kamiokande possible explanation: neutrino-oscillation

2002 SNO-experiment: checks neutrino-oscillation

Sun
Since 4.5 billion years fusion

prediction

2002 SNO-experiment: checks neutrino-oscillation

Masatoshi Koshiba

solar neutrino problem

solved!

R. Davis

Indian Institute of Technology Ropar
Hans-Jürgen Wollersheim - 2018
Examination of the oscillation-hypotheses for solar neutrinos

So far: Only electron-neutrinos detected

\[ 37\text{Cl} + \nu_e \rightarrow 37\text{Ar} + e^- \quad \text{Homestake} \]
\[ \nu_e + e^- \rightarrow \nu_e + e^- \quad \text{Kamiokande} \]
\[ (\nu_\mu + e^- \rightarrow \nu_\mu + e^- \quad \text{unlikely, undistinguishable}) \]

SNO: Detection of different neutrino-types using different reactions on D\textsubscript{2}O

Only electron-neutrino:

\[ \nu_e + d \rightarrow p + p + (e^-) \quad \text{detection} \]

With equal probability for all neutrinos:

\[ \nu_x + d \rightarrow p + (n) + \nu_x \quad \text{detection} \]
Neutrinos as astrophysical observer

- Nuclear reactors
- Sun
- Particle accelerator
- Supernovae (collapsing stars)
- Earth atmosphere (cosmic radiation)
- Astrophysical accelerator (soon?)
- Earth crust (natural radioactivity)
- Big bang of the universe (today 330 ν/cm³)