Part 1:
- What are neutrinos?
- Neutrino interactions, sources and detectors
- Neutrino oscillations
- Oscillations of atmospheric neutrinos
- Neutrino beams

Part 2:
- Solar neutrinos
- Oscillation of solar neutrinos
- KamLAND reactor neutrino experiment
- Future neutrino oscillation experiments
- The mass of the lightest neutrino
- $\beta$ and $\beta\beta$ decay
- Neutrino astronomy
Why are we doing Neutrino Physics?

Elementary Particle Physics:
- Mass?
- Matter - antimatter symmetry
- Physics beyond the Standard Model

Cosmology:
- early universe
- structure formation
- dark matter

Neutrino Physics

Astroparticle Physics:
- Solar Neutrinos
- Cosmic Radiation
- Supernovae
- Neutrino Telescopes

Applications:
- Monitoring of Nuclear Reactors
- Geo physics
- New Technologies
Wolfgang Pauli postulates the Neutrino (1930)

Energy spectrum of electrons from $\beta$-decay

$$n \rightarrow p + e^-$$

$$E_{\text{electron}} = m_n c^2 - m_p c^2$$

One expected this

But this was observed!

Solution: The Neutrino
1922 Assistant at Universität Hamburg
1924 Habilitation in Hamburg (Discovery of the Exclusion Principle)
Decay of the Neutron - Birth of a Neutrino

Transformation $d$-Quark $\rightarrow u$-Quark: Electroweak Interaction!

$\nu^+ \rightarrow -e$
First Detection of a Neutrino: 1956

- Neutrino source: Nuclear reactor
- Detection Method: $\bar{\nu}_e + p \rightarrow e^+ + n$
- Detector: Scintillator, PMT's

F. Reines 1995

Frederick REINES and Clyde COVAN
Box 1663, LOS ALAMOS, New Mexico

Thanks for waiting. Everything comes to him who knows how to wait.

Pauli
Neutrino History

- 1930: neutrino postulated by Pauli (massless, neutral)
- 1956: neutrino $\nu_e$ detected by Reines and Cowan (Nobel prize 1995)
- 1962: Discovery of $\nu_\mu$ at AGS in Brookhaven by Ledermann, Schwartz and Steinberger (Nobel prize 1988)
- 1975: neutrino $\nu_\tau$ postulated after $\tau$ lepton was discovered by M. Perl et al.
- 2000: First direct detection of $\nu_\tau$ by the DONUT experiment (Fermilab)

- ~1995: LEP measurement of $Z^0$ decay width:
  $\rightarrow$ 3 active neutrino flavors ($m_\nu < 80$ GeV):
  $N_\nu = 3.00 \pm 0.06$
  $\nu_e, \nu_\mu, \nu_\tau$
Fundamental Particles

Quarks:
- u
- c
- t
- d
- s
- b

Leptons:
- $v_e$
- $v_\mu$
- $v_\tau$
- e$^-$
- $\mu^-$
- $\tau^-$

Interactions by exchange of bosons:
- Graviton
- Photon
- Gluon
- W, Z
Neutrino Properties

- Neutral
- Fermions with Spin $\frac{1}{2}$
- In the Standard Model: massless, stable, always left handed!
- Today we know that neutrinos have mass $0.05 \text{ meV} < m_\nu < 2 \text{ eV}$
  Standard Model must be extended!
- Are Neutrinos and Anti-Neutrinos identical?
- many other properties are still unknown: sterile neutrinos?, CP-violation?, neutrino decay?, magnetic moment?...
How Neutrinos interact

- The weak interaction

\[
\begin{align*}
(u)_{L} & \quad (c)_{L} & \quad (t)_{L} \\
(d)_{L} & \quad (s)_{L} & \quad (b)_{L}
\end{align*}
\]

\[
\begin{align*}
(v_{e})_{L} & \quad (v_{\mu})_{L} & \quad (v_{\tau})_{L} \\
(e^{-})_{L} & \quad (\mu^{-})_{L} & \quad (\tau^{-})_{L}
\end{align*}
\]
**Charged Current**

- **Exchange of a W Boson:**

\[
\begin{align*}
\bar{v}_e &\rightarrow W^- & e^- \\
\nu_\mu &\rightarrow W^- & \mu^- \\
\pi^+ &\rightarrow W^+ & \nu_\mu
\end{align*}
\]

\[
\begin{array}{c}
\text{Charge Conservation:} \\
\text{Lepton Flavour Conservation:}
\end{array}
\]
Neutral Current

- Exchange of a $Z^0$ Boson:
Sources of Neutrinos

- Nuclear Reactors (Energy ~ MeV, Anti-\(\nu_e\))
  \(\beta\)-decay of neutron rich fission fragments
- Neutrino Beams (Energy ~ 1 - 100 GeV, \(\nu_\mu\)):
  from decaying pions
- Solar Neutrinos (Energy ~ MeV, \(\nu_e\)):
  from thermonuclear fusion reactions
- Atmospheric Neutrinos (Energy ~ 1 - 100 GeV):
  from decaying pions and muons (cosmic radiation)
- Neutrinos from Supernovae (Energy 10-30 MeV):
  emitted after gravitational collapse of a star
- Cosmic Neutrino Background (Energy \(10^{-4}\)eV = 1.9K)
Neutrino Detection

- Problem: Weak(!) Interaction cross sections are of order $10^{-40}\text{cm}^2$

- Huge detectors needed:
  - 10 ton scintillator (near nuclear reactors)
  - 1000 ton scintillator (200 km from nuclear reactors)
  - 2 kton Pb/emulsion (for $\nu_\tau$ detection)
  - 50 kton water (for solar, atmospheric, supernova $\nu$'s)
  - 1 Mton water (precision neutrino physics, CP-violation)
  - 1 km$^3$ water or ice (high energy neutrino astronomy)

- Detectors must be shielded against cosmic radiation:
  - deep underground (1000 – 5000 mwe)
  - deep underwater (2000 – 4000m)
Gran Sasso Underground Lab LNGS

Neutrino beam from CERN

Solar v’s
Neutrino Oscillations
Neutrino Oscillations were observed  
\(\rightarrow\) Neutrinos have mass!

\[ \nu_\mu \rightarrow \nu_\tau, (s) \]

Oscillation
\[ \Delta m^2 \approx 2 \cdot 10^{-3} \text{ eV}^2 \]

\[ \nu_e \rightarrow \nu_{\mu,\tau} \]

Oscillation
\[ \Delta m^2 \approx 8 \cdot 10^{-5} \text{ eV}^2 \]
Neutrino Oscillations are a consequence of neutrino mass and mixing.
Quark and Lepton Mixing:

Eigenstates of weak interaction ≠ Eigenstates of mass

**Neutrino - Mixing**

Mass eigenstates

\[
\sum_{1, 2, 3} \nu_v
\]

\[
\sum_{1, 2, 3} \nu_\mu
\]

\[
\sum_{1, 2, 3} \nu_\tau
\]

**Quark - Mixing**

\[
\begin{pmatrix}
    u \\
    d' \\
    c \\
    s' \\
    t \\
    b'
\end{pmatrix}
\]

\[
\sum_{d, s, b} \text{mass eigenstates}
\]

\[
\sum_{d, s, b} \text{mass eigenstates}
\]

\[
\sum_{d, s, b} \text{mass eigenstates}
\]
**Quark-Mixing**

**Cabbibo-Kobayashi-Maskawa (CKM) Matrix**

\[
\begin{pmatrix}
  u \\
  d' \\
  c \\
  s' \\
  t \\
  b'
\end{pmatrix}
= 
\begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\times
\begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix}
\]

- 3 mixing angles
- 1 phase: \( e^{i\delta} \)
- CP-violation

(BELLE, BABAR, CLEO, ...)

in precision measurement phase
Neutrino mass and mixing

3 massive neutrinos: $\nu_1, \nu_2, \nu_3$ with masses: $m_1, m_2, m_3$

Flavor-Eigenstates $\nu_e, \nu_\mu, \nu_\tau \neq$ Mass-Eigenstates

Neutrino mixing:

$$
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix} \cdot
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
$$

Example:

$$
|\nu_e\rangle = U_{e1} |\nu_1\rangle + U_{e2} |\nu_2\rangle + U_{e3} |\nu_3\rangle
$$
Neutrino Mixing for 2 Flavors

\[
\begin{pmatrix}
\nu_\mu \\
\nu_\tau \\
\end{pmatrix}
= 
\begin{pmatrix}
\cos \theta_{23} & \sin \theta_{23} \\
-\sin \theta_{23} & \cos \theta_{23}
\end{pmatrix}
\begin{pmatrix}
\nu_2 \\
\nu_3
\end{pmatrix}
\]

\[
|\nu_\mu\rangle = \cos \theta_{23} |\nu_2\rangle + \sin \theta_{23} |\nu_3\rangle
\]

The probability that \( \nu_\mu \) has mass \( m_2 \) is \( \cos^2 \theta_{23} \)

Today we know that \( \theta_{23} \approx 45^\circ \):

\[
|\nu_\mu\rangle = \frac{1}{2} (|\nu_2\rangle + |\nu_3\rangle) \quad |\nu_\tau\rangle = \frac{1}{2} (-|\nu_2\rangle + |\nu_3\rangle)
\]

e.g. probability that \( \nu_\mu \) has mass \( m_2 = 50\% \)
Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Matrix:

- 3 Mixing angles: $\theta_{12}$, $\theta_{23}$, $\theta_{13}$
- 1 Dirac-Phase (CP violating): $\delta$

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
=
\begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
\nu_e & 0 & s_{13}e^{-i\delta} \\
0 & \theta_{13}, \delta & 0 \\
-s_{13}e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
\nu_1 & \theta_{\text{sol}} & S_{12} & 0 \\
-c_{12} & c_{12} & 0 & 0 \\
0 & 0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]
Neutrino Oscillations

\[
\begin{pmatrix}
\nu_{\mu} \\
\nu_{\tau}
\end{pmatrix} =
\begin{pmatrix}
\cos \theta_{23} & \sin \theta_{23} \\
-\sin \theta_{23} & \cos \theta_{23}
\end{pmatrix}
\begin{pmatrix}
\nu_2 \\
\nu_3
\end{pmatrix}
\]

Flavor eigenstates \(v_{\mu}, v_{\tau}\)

Mass eigenstates \(v_2, v_3\)

with \(m_2, m_3\)

source creates flavor-eigenstates

propagation determined by mass-eigenstates

\[
\omega_{2,3} = E_{2,3} = \sqrt{p^2 + m_{2,3}^2}
\]

slightly different frequencies → phase difference changes

detector sees flavor-eigenstates
2 Flavor Neutrino Oscillations

Oscillation probability

\[ P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 (2\theta_{23}) \cdot \sin^2 \left( \frac{\pi}{L_{osz}} \cdot \frac{x}{L_{osz}} \right) \]

Survival probability

\[ P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 (2\theta_{23}) \cdot \sin^2 \left( \frac{\pi}{L_{osz}} \cdot \frac{x}{L_{osz}} \right) \]

Distance \( L_{osz} \) (in km)

\[ L_{osz} \text{ (in km)} = \frac{2.48 \cdot E \text{ (in GeV)}}{\Delta m^2 \text{ (in eV}^2)} \]

\[ \Delta m^2 = m_2^2 - m_3^2 \]
Historical Remark

- 1957-58: B. Pontecorvo proposed neutrino oscillations (because only $v_e$ was known, he thought of $v \leftrightarrow \text{anti-}v$)

- 1962 Maki, Nakagawa, Sakata described the 2 flavor mixing and discussed neutrino flavor transition

- 1967 full discussion of 2 flavor mixing, possibility of solar neutrino oscillations, question of sterile neutrinos by B. Pontecorvo
Primary cosmic ray

\[
\#(v_\mu) / \#(v_e) \approx 2
\]

atmospheric neutrinos
Oscillation of atmospheric neutrinos

Oscillation probability varies with zenith angle $\theta$

atmospheric neutrinos: $E_\nu$ in GeV range

$L \approx 20 \text{ km}$

$L \approx 13000 \text{ km}$

\[ P(\nu_\mu \rightarrow \nu_x) = \sin^2 2\theta_{atm} \sin^2 \left( \frac{1.27\Delta m_{atm}^2 [\text{eV}^2] L [\text{km}]}{E_\nu [\text{GeV}]} \right) \]
Super-Kamiokande

• solar neutrinos ($^8$B $\nu_e$ few MeV)
• atmospheric neutrinos ($\nu_\mu$, $\nu_e$ few GeV)
• K2K accelerator neutrinos ($\nu_\mu$ 1 GeV)
• start ~2009: T2K off-axis super neutrino beam
Super-Kamiokande

50kt H$_2$O

12000 PMTs

electron event

myon event
**e - µ Separation in SK:**

The Cerenkov radiation from a muon produced by a muon neutrino event yields a well defined circular ring in the photomultiplier detector bank.

The Cerenkov radiation from the electron shower produced by an electron neutrino event produces multiple cones and therefore a diffuse ring in the detector array.
SuperK - atmospheric neutrinos

e-like events

µ-like events

$\nu_e$  $\mu$

$\nu_e$  $\mu$

- without oscillation
- oscillation (best fit)
- data

DESY Summer School 2006
Caren Hagner, Universität Hamburg
Atmospheric neutrinos:
Analysis neutrino oscillation (full SK-I data set)

1.5 x 10^{-3} \text{ eV}^2 < \Delta m^2 < 3.4 \times 10^{-3} \text{ eV}^2
\sin^2 2\theta > 0.92 \text{ at 90\% CL}

Best Fit:
\sin^2 2\theta = 1.02
\Delta m^2 = 2.1 \times 10^{-3} \text{ eV}^2
\chi^2 = 174.9/177 \text{ dof}
\chi^2 = 465/179 \text{ dof for no osc}

Confirmed by MACRO, SOUDAN

E. Kearns, Neutrino2004
Super-Kamiokande: Accident 2001

Accident Nov 21, 2001:
~7000 of 12000 PMT's imploded in chain reaction
After Repairs for SK-2
Summary Atmospheric Neutrino Oscillation

- The disappearance of atmospheric neutrinos $\nu_\mu$ is explained by the vacuum neutrino oscillation
  \[ \nu_\mu \rightarrow \nu_\tau \]
  \[ \Delta m^2_{23} = 2.5 \cdot 10^{-3} \text{ eV}^2 \]
  \[ \theta_{23} \sim 45^\circ \]

- Such oscillation should also be observable with a $\nu_\mu$ beam ($\approx 1 \text{ GeV}$) at a distance of 250 km
  (also possible: 3 GeV and 750 km)
  Disappearance of $\nu_\mu$

- Another important test:
  Detect the $\nu_\tau$ which should appear!
How to make Neutrino beams

Beam composition (typical example):

- dominantly $v_\mu$
- contamination from $\bar{v}_\mu$ ($\approx 6\%$), $v_e$ ($\approx 0.7\%$), $\bar{v}_e$ ($\approx 0.2\%$)
- $v_\tau \leq 10^{-6}$
**K2K accelerator experiment**

**Near Detector**
- KEK
- 1 ton

**Far Detector**
- Super-K
- 50 kton

**νμ, ⟨Eν⟩ = 1.3 GeV**

**Goal:** $1.0 \times 10^{20}$ POT

- = 200 neutrino events in SK

**Data (06/1999 – 02/2004):**
- $8.9 \cdot 10^{19}$ POT

**events in “Far Detector”**
- : expected without oscillation:
  - $108$
  - $150.9^{+11.6}_{-10.0}$

**Probability for no oscillation:** <0.01%

**Neutrino oscillation confirmed with 3.9σ!**

\[ L_{ozz} (in \ km) = \frac{2.48 \cdot E (in \ GeV)}{\Delta m^2 (in \ eV^2)} \]
First hint for typical deformation of energy spectrum

- $N_{SK}^{obs} = 108$
- $N_{SK}^{exp \ (best \ fit)} = 104.8$

$\sin^2 2\theta = 1.00$
$\Delta m^2 [eV^2] = 2.73 \times 10^{-3}$

without oscillation
best fit oscillation
Today: Two Long Baseline Experiments

- MINOS (running since 2005)
  Neutrino beam (NuMI) from Fermilab to Soudan Mine
  \( L = 735 \text{ km}, \ E = 3.5 \text{ GeV} \)
  Goal: reach better precision on \( \Delta m_{23}^2, \theta_{23} \)

- OPERA (starting, CNGS beam since last week!)
  Neutrino beam (CNGS) from Cern to Gran Sasso Lab
  \( L = 732 \text{ km}, \ E = 17 \text{ GeV} \)
  Goal: direct detection of \( \nu_T \)
The MINOS Experiment

A large detector at Soudan

A smaller detector at Fermilab

Measure the beam and neutrino energy spectrum near the source

> See how it differs far away

( Jeff Nelson @ Neutrino2006 )
Example of a disappearance measurement

Look for a deficit of $\nu_\mu$ events at a distance...

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 \sin^2 2\theta \sin^2 \left(1.267 \Delta m^2 L / E\right)$$

Many events!

Energy resolution!

$v_\mu$ spectrum

Monte Carlo

Spectral ratio

Monte Carlo

0.0033 eV$^2$

NC subtracted
The NuMI beamline

Water-cooled segmented graphite target
- 47 2.0 cm segments; total length of 95.4 cm

2 parabolic horns carrying
- Up to 200 kA current provides up to 3T fields
- Target can be positioned up to 2.5m upstream of the first horn to change beam energy

( Jeff Nelson @ Neutrino2006 )
MINOS Detectors

Near Detector

1 kton, 4×5×15m
282 steel,
153 scintillator planes

Far Detector

5.4 ktons, 8×8×30m
484 steel/scintillator planes
Event Topologies

$\nu_\mu$ CC Event

- long $\mu$ track + hadronic activity

NC Event

- short event, often diffuse

$\nu_e$ CC Event

- short event, typical EM shower profile

Monte Carlo
MINOS best-fit spectrum for 1.27x10^{20} POT

$$|\Delta m^2_{32}| = 2.72^{+0.38}_{-0.25} \text{ (stat)} \times 10^{-3} \text{ eV}^2$$

$$\sin^2 2\theta_{23} = 1.00^{+0.13}_{-0.13} \text{ (stat)}$$
MINOS confirms SuperKamiokande

MINOS will improve precision on $\Delta m^2$ in next years!
Neutrino beam ($\nu_\mu$) from CERN to Gran Sasso Underground Lab (Italy)

$\nu_\tau$ Appearance!

$\nu_\mu \rightarrow \nu_\tau$ ?

CERN

Geneva

Mont-Blanc

Monte-Emilius

Piemonte

Alessandria

Emilia

Marches

Toscana

Firenze

Arezzo

Umbria Laboratory of Gran Sasso

LNGS

732 km
Detection of a Tau-Neutrino:

Typical Topology of a $\tau$-decay: "Kink" within mm from Vertex

**Aktive Target:**
200,000 Lead-Emulsion-bricks = ca. 1,800 t

$\tau^-$-decay:

- $\tau^- \rightarrow \mu^- + \bar{\nu}_\mu + \nu_\tau$ 18%
- $\tau^- \rightarrow e^- + \bar{\nu}_e + \nu_\tau$ 18%
- $\tau^- \rightarrow \pi^- (n\pi^0) + \nu_\tau$ 48%
- $\tau^- \rightarrow \pi^- \pi^- \pi^+ (n\pi^0) + \nu_\tau$ 15%

Detection of a Tau-Neutrino:

\[ \nu_{\tau} \rightarrow \nu_{\tau} + \nu_{\mu} + \nu_{\pi} \]

\[ \tau^- \rightarrow \mu^- + \bar{\nu}_\mu + \nu_\tau \]

\[ \tau^- \rightarrow e^- + \bar{\nu}_e + \nu_\tau \]

\[ \tau^- \rightarrow \pi^- (n\pi^0) + \nu_\tau \]

\[ \tau^- \rightarrow \pi^- \pi^- \pi^+ (n\pi^0) + \nu_\tau \]
Structure of the OPERA Experiment

31 target planes / supermodule (in total: 206336 bricks, 1766 tons)

Proposal: July 2000, installation at LNGS started in May 2003
First observation of CNGS beam neutrinos: August 18th, 2006
**OPERA Sensitivity**

**OPERA: 6200 \( \nu_\mu \) CC+NC /year**

**19 \( \nu_\tau \) CC/year (for \( \Delta m^2 = 2 \cdot 10^{-3} \text{ eV}^2 \))**

<table>
<thead>
<tr>
<th>( \nu_\tau ) in OPERA</th>
<th>( \Delta m^2 = 1.9 \times 10^{-3} \text{ eV}^2 )</th>
<th>( \Delta m^2 = 2.4 \times 10^{-3} \text{ eV}^2 )</th>
<th>( \Delta m^2 = 3.0 \times 10^3 \text{ eV}^2 )</th>
<th>BKGD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6.6</td>
<td>10.5</td>
<td>16.4</td>
<td>0.7</td>
</tr>
</tbody>
</table>

exposure: 5 years @ 4.5 \( \times 10^{19} \) pot / year
Neutrino beams worldwide:

- **CNGS beam**: started last week! \( E_\nu = 17 \text{ GeV}, \ P = 0.3 \text{ MW} \)
- **K2K beam (Japan)**: terminated \( E_\nu = 1.3 \text{ GeV}, \ P = 0.005 \text{ MW} \)
- **NuMI beam (USA)**: since 2005 \( E_\nu = 3.5 \text{ GeV}, \ P = 0.4 \text{ MW} \)
- **T2K Superbeam (Japan)**: 2009 \( E_\nu = 0.7 \text{ GeV}, \ P = 0.75-4 \text{ MW} \)
**CC event in the first magnet**

*Horizontal projection*

Event Number 119110

μ-track

*Vertical projection*

(forgive about the red-line fit)

OPERA collaboration
Neutrino Physics Part 2
Solar Neutrinos

\[ 4p \rightarrow \text{He}^4 + 2e^+ + 2\nu_e + 26.7 \text{ MeV} \]
neutrino production in the sun

\[ p + p \rightarrow ^3\text{H} + e^+ + \nu_e \]
99.8%

\[ p + ^2\text{H} \rightarrow ^3\text{He} + \gamma \]
85%

\[ ^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + 2p \]

\[ ^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma \]
15%

\[ ^7\text{Be} + e^- \rightarrow ^7\text{Li} + \nu_e \]

\[ ^7\text{Li} + p \rightarrow 2^4\text{He} \]

\[ p + p + e^- \rightarrow ^2\text{H} + \nu_e \]
0.2%

\[ p + ^2\text{H} \rightarrow ^3\text{He} + \gamma \]

\[ ^3\text{He} + p \rightarrow ^4\text{He} + e^+ + \nu_e \]
10^{-8}

\[ ^3\text{He} + p \rightarrow ^4\text{He} + e^+ + \nu_e \]

\[ ^7\text{Be} + p \rightarrow ^8\text{B} + \gamma \]
0.016%

\[ ^8\text{B} \rightarrow ^8\text{Be}^* + e^+ + \nu_e \]

pp- I

pp- II

pp- III
Energy Production in Stars

H. A. Bethe
Cornell University, Ithaca, New York
(Received September 7, 1939)

It is shown that the most important source of energy in ordinary stars is the reactions of carbon and nitrogen with protons. These reactions form a cycle in which the original nucleus is reproduced, viz., C + H = N, N + H = O, O + H = C + He.

The carbon-nitrogen reactions are unique in their cycling character. For all nuclei lighter than carbon, reaction with protons will lead to the emission of an α-particle so that the original nucleus is permanently destroyed. For all nuclei heavier than helium, only radiative capture of the protons occurs, also destroying the original nucleus. Oxygen and fluorine reactions mostly lead back to nitrogen. Besides, these heavier nuclei react much more slowly than C and N and are therefore unimportant for the energy production.

The agreement of the carbon-nitrogen reactions with observational data is excellent. In order to give the correct energy evolution in the sun, the central temperature of the sun would have to be 18.5 million degrees while the amount of heavy matter, and therefore the cycle, does not change with time.

The first main result is that, under present conditions, no elements heavier than helium can be built up by any appreciable extent. Therefore we must assume that the heavier elements were built up before the stars reached their present state of temperature and density. No attempt will be made at speculations about this previous state of stellar matter.

The energy production of stars is then due entirely to the combination of four protons and two electrons into an α-particle. This simplifies the discussion of stellar evolution inasmuch as the solution of the Bethe-Haldane equations gives 19. For the brightest stars Y Cephei the corresponding figures are 30 and 32. This good agreement holds for all bright stars of the main sequence, but, of course, not for giants.

For fainter stars, with lower central temperatures, the reaction H + H = D + e+ and the reactions following it, are believed to be mainly responsible for the energy production. (10)

It is shown further (§6) that no elements heavier than He can be built up in ordinary stars. This is due to the fact, mentioned above, that all elements up to boron are intimately bound by proton bombardment, i.e., rather than built up by a colliding and captured. The instability of the heavier elements leads the formation of heavier elements still further. The production of neutrons in stars is likewise negligible. The heavier elements found in stars must therefore have existed already when the star was formed.

Finally, the suggested mechanism of energy production is used to draw conclusions about astrophysical problems, such as the mass-luminosity relation (§10), the stability against temperature changes (§11), and stellar evolution (§12).

§1. INTRODUCTION

The progress of nuclear physics in the last few years makes it possible to decide rather definitely which processes can and which cannot occur in the interior of stars. Such decisions will be attempted in the present paper, the discussion being restricted primarily to main sequence stars. The results will be at variance with some current hypotheses.

The first main result is that, under present conditions, no elements heavier than helium can be built up by any appreciable extent. Therefore we must assume that the heavier elements were built up before the stars reached their present state of temperature and density. No attempt will be made at speculations about this previous state of stellar matter.

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Finally, the suggested mechanism of energy production is used to draw conclusions about astrophysical problems, such as the mass-luminosity relation (§10), the stability against temperature changes (§11), and stellar evolution (§12).

The combination of four protons and two electrons can occur essentially only in two ways. The first mechanism starts with the combination of two protons to form a deuteron with positron emission, viz.

\[
H + H = D + e^+.
\]  

(1)

The deuteron is then transformed into He² by further capture of protons; these captures occur very rapidly compared with process (1). The second mechanism uses carbon and nitrogen as catalysts, according to the chain reaction

\[
C^{12} + H = N^{13} + \gamma, \quad N^{13} = C^{13} + e^+ \\
C^{13} + H = N^{14} + \gamma, \quad N^{14} + H = O^{15} + \gamma, \quad O^{15} = N^{15} + e^+ \\
N^{15} + H = C^{12} + He^4.
\]  

(2)
The principal energy source for main-sequence stars like the sun is believed to be the fusion, in the deep interior of the star, of four protons to form an alpha particle. The fusion reactions are thought to be initiated by the sequence $^4\text{He}(p, e^-p)^4\text{H}(p, \gamma)^4\text{He}$ and terminated by the following sequences: (i) $^4\text{He}(p, e^-n)^3\text{He}(p, \gamma)^4\text{He}$; (ii) $^4\text{He}(p, e^-p)^3\text{H}(p, \gamma)^3\text{He}$; and (iii) $^3\text{He}(p, e^-p)^3\text{H}(p, \gamma)^4\text{He}$. No direct evidence for the existence of nuclear reactions in the interiors of stars has yet been obtained because the mean free path for photons emitted in the center of a star is typically less than $10^{-12}$ of the radius of the star. Only neutrinos, with their extremely small interaction cross sections, can enable us to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars.

The most promising method for detecting solar neutrinos is based upon the endothermic reaction $^{37}$Cl($^8$B, $^8$Be)$^{37}$Ar, which was first discussed as a possible means of detecting neutrinos by Pontecorvo and Alvarez. In this note, we predict the number of absorptions of the star. Only neutrinos, with their extremely small interaction cross sections, can enable us to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars. 

The prospect of observing solar neutrinos by means of the inverse beta process $^{37}$Cl($^8$e$^-$,$\nu_e$)$^{37}$Ar, which led us to place the apparatus previously described in a mine, is a new method for determining the striking sensitivity of the method to a degree capable of measuring the solar neutrino flux calculated by Bahcall in the preceding paper. 

The apparatus consists of two 500-gallon tanks of perchloroethylene, C$_2$Cl$_4$, equipped with agitators and an auxiliary system for purging with helium. It is located in a limestone mine 3300 feet below the surface (1850 meters of water equivalent shielding, m.w.e.). Initially, the tanks were swept completely free of air argon by purging the tanks with a stream of helium gas. $^{39}$Ar carrier (0.10 cm$^3$) was introduced and the tanks exposed for periods of four months or more to allow the 35-day $^{39}$Ar activity to reach nearly the saturation value. Carrier argon along with any $^{39}$Ar pro-
Neutrino Production versus Radius

- $^8\text{B}$
- $^7\text{Be}$
- pp
- hep
First generation of experiments

Homestake $^{37}\text{Cl}$

Gallex $^{71}\text{Ga}$

SAGE $^{71}\text{Ga}$

Kamiokande + SuperK

$\text{H}_2\text{O}$ Cerenkov

Raymond Davis Jr.

disappearance of $v_e$

solar neutrino puzzle
CC experiments only sensitive to $\nu_e$ proposed by Pontecorvo in 1946

\[
Interaction\ Rate\ (R) = N_{\text{target}} \cdot \sum_i \sigma_i(E) \cdot \frac{d\Phi_i(E)}{dE} P(\nu_e \rightarrow \nu_e) dE
\]

\[
\sigma_i \sim 10^{-46}\ cm^2;\ \Phi_i \sim 6 \times 10^{10}\ [s\ cm^{-2}]^{-1}
\]

1 Solar Neutrino Unit [SNU] = 1 $\nu$ interaction/sec each $10^{36}$ target atoms.

$N_{\text{target}} = 10^{29}$-$10^{30}$ nuclei, namely $O(10-100)$ tons of target to have $O(1)$ $\nu$ interaction/day
Solar Neutrinos: “pioneering experiment”

Nobelprize 2002

Raymond Davis Jr., Homestake Experiment

Since ~1970

$\nu_e + ^{37}\text{Cl} \rightarrow ^{37}\text{Ar} + e^-$

$E_\nu > 814$ keV

$R_{\text{exp}} = 0.34 \times \text{SSM}$
Prof. J.N. Bahcall
The Institute for Advanced Study
School of Natural Science
Princeton, New Jersey 08540, USA

Dear Prof. Bahcall,

Thank you very much for your letter and the abstract of the new Davis investigation the numerical results of which I did not know. It starts to be really interesting! It would be nice if all this will end with something unexpected from the point of view of particle physics. Unfortunately, it will not be easy to demonstrate this, even if nature works that way.

I will attend the Balaton meeting on neutrinos and looking forward to see you there.

Yours sincerely,

B. Pontecorvo
\[ \nu_e + ^{71}\text{Ga} \rightarrow ^{71}\text{Ge} + \text{e}^- \]  
\[ E_\nu > 233 \text{ keV} \]
GALLEX Results

expected without oscillation

Combined result

Caren Hagner, Universität Hamburg
The Solar Neutrino Puzzle

Helioseismology confirms solar models

Energy dependent deficit

Data/SSM(BP98)

Non-standard neutrino properties!
Status of solar neutrino oscillation
spring 2000
• $^8$B solar neutrinos
• first measurement of total flux: $v_e + v_\mu + v_\tau$
Creighton Mine (Nickel)
Sudbury, Canada

Depth 2070m

1000t D$_2$O
9500 PMTs
Neutrino detection in SNO

**CC** \( v_e + d \rightarrow p + p + e^- \)

**ES** \( v_e + e^- \rightarrow v_e + e^- \)

**NC** \( v_x + d \rightarrow p + n + v_x \)
Neutron detection in SNO

**Phase I (D₂O)**
Nov. 99 - May 01
- n captures on $^2\text{H}(n, \gamma)^3\text{H}$
- $\sigma = 0.0005$ b
- Observe 6.25 MeV $\gamma$
- PMT array readout
- Good CC

**Phase II (salt)**
July 01 - Sep. 03
- 2 t NaCl. n captures on $^{35}\text{Cl}(n, \gamma)^{36}\text{Cl}$
- $\sigma = 44$ b
- Observe multiple $\gamma$'s
- PMT array readout
- Enhanced NC

\[ ^2\text{H} + n \rightarrow 6.25 \text{ MeV} \rightarrow ^3\text{H} \]

\[ ^{35}\text{Cl} + n \rightarrow 8.6 \text{ MeV} \rightarrow ^{36}\text{Cl} \]
Neutron detection in SNO

**Phase I (D\textsubscript{2}O)**
Nov. 99 - May 01
- n captures on \( ^2\text{H}(n, \gamma)^3\text{H} \)
- \( \sigma = 0.0005 \text{ b} \)
- Observe 6.25 MeV \( \gamma \)
- PMT array readout
- Good CC

**Phase II (salt)**
July 01 - Sep. 03
- 2 t NaCl. n captures on \( ^{35}\text{Cl}(n, \gamma)^{36}\text{Cl} \)
- \( \sigma = 44 \text{ b} \)
- Observe multiple \( \gamma \)'s
- PMT array readout
- Enhanced NC

**Phase III (\(^3\text{He}\))**
Summer 04 - Dec. 06
- 40 proportional counters
  - \(^3\text{He}(n, p)^3\text{H} \)
  - \( \sigma = 5330 \text{ b} \)
- Observe \( p \) and \(^3\text{H}\)
- PC independent readout
- Event by Event Det.

\[ ^2\text{H} + n \rightarrow 6.25 \text{ MeV} \]
\[ ^{35}\text{Cl} + n \rightarrow 8.6 \text{ MeV} \]
\[ ^3\text{H} \]
\[ ^{36}\text{Cl} \]
SNO Result (salt-phase)
(PRL 92, 181301, 2004)

\[
\phi(\text{^8B})_{\text{meas}} = (0.88 \pm 0.04 \text{ (exp)} \pm 0.23 \text{ (th)}) \phi(\text{^8B})_{\text{SSM}}
\]

- 1/3 of solar $v_e$ arrive as $v_e$ on Earth
- 2/3 of solar $v_e$ arrive as $v_\mu$ or $v_\tau$.
- Measured total flux = Predicted flux
  (Standard Solar Model)
Oscillation analysis of all solar neutrino experiments

\[ \chi^2_{\text{min}} = 70.207 \text{ at (3.98e-01, 6.46e-05)} \]

\[ b_8 = 1.040 \text{ hep} = 1.000 \]

\[ \tan^2 \theta \]

\[ \Delta m^2 (eV^2) \]

SNO pure D\textsubscript{2}O d/n spectra
+ SNO salt CC & NC & ES fluxes
+ SK-I zenith spectra + Cl + Ga\textsuperscript{8}B free

BP00

LMA

SMA

LOW

VAC

Active
Includes
SKsp(D/N)
KAMLAND
Reactor neutrino experiment
to confirm
solar neutrino oscillation
KAMLAND

reactor neutrinos = $\bar{\nu}_e$

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

prompt signal $E_{\nu} - 0.77\text{MeV}$

delayed signal $n + p \rightarrow d + \gamma(2.2\text{MeV})$
Average distance of reactors from KamLAND: 175km

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</table>
Test of solar Neutrino-Oscillations with Reactor Neutrinos

Average distance of japanese nuclear reactors from KamLAND detector:
175km

\[
L_{\text{osz}}^{\text{vac}} [\text{m}] = \frac{2.48 \cdot E_\nu [\text{MeV}]}{\Delta m^2 [\text{eV}^2]} \]

E (Reactor \(\nu\)) \(\approx\) 4MeV
\(\Delta m^2\) (solar \(\nu\)) = 8 \cdot 10^{-5}\text{eV}^2

\[
L_{\text{osz}} \approx \frac{2.5 \cdot 4}{8 \cdot 10^{-5}} \text{m} = 125\text{km}
\]

Test possible!
Caren Hagner, Universität Hamburg

KamLAND Ergebnis (hep-ex/0406035)

First evidence of deformation in energy spectrum for reactor neutrinos

Best Fit:

\[ \Delta m_{12}^2 = 8.3 \times 10^{-5} \text{ eV}^2 \]

\[ \sin^2 2\theta_{12} = 0.83 \]
\[ \tan^2 \theta_{12} = 0.40^{+0.10}_{-0.07}, \quad \Delta m^2_{12} = 7.9^{+0.6}_{-0.5} \times 10^{-5} \text{ eV}^2 \quad (1\sigma) \]

\( \theta_{12} \approx 33^\circ \pm 5^\circ \)

\( \theta_{12} + \theta_c = 45^\circ? \)
Progress of Precision of Oscillation Parameters for $v_e \rightarrow v_\mu$
Summary

- Neutrino Oscillations have been observed with solar, atmospheric, reactor and accelerator neutrinos.
- Neutrinos have mass! The absolute neutrino mass has not yet been measured, allowed range: $0.05 \text{ eV} < m_\nu < 2 \text{ eV}$
- Neutrino mixing exists and is very different from quark mixing. Why?
- The third mixing angle must be measured
- Is there CP-violation for neutrinos?
- Is the neutrino a Majorana particle? Search for neutrinoless Double-Beta Decay (Evidence?)

Many interesting results expected in next years
Many questions still waiting to be solved by you!