The World of Neutrinos

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Symposium on Neutrinos and INO
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The world of neutrinos

1. Their sources
2. Their interactions
3. Their puzzling nature
4. Their detection
The world of neutrinos

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Neutrinos from the Sun

- Nuclear fusion reactions: (many steps but effectively)
  \[ 4 \, ^1H + 2e^- \rightarrow ^4\text{He} + \text{light} \]
Neutrinos from the Sun

Nuclear fusion reactions: (many steps but effectively)

\[ 4 \, ^1_1H + 2e^- \rightarrow ^4_2He + \text{light} + 2\nu_e \]

- Neutrinos needed to conserve energy, momentum, angular momentum

Davis-Koshiba Nobel prize 2002
Neutrinos from the Sun

Nuclear fusion reactions: (many steps but effectively)
\[ 4 \, ^1H + 2e^- \rightarrow ^{4}\text{He} + \text{light} + 2\nu_e \]

Neutrinos needed to conserve energy, momentum, angular momentum

Davis-Koshiba Nobel prize 2002

\[ \sim 10^{14} \text{ neutrinos pass through each of us every second !!} \]
Neutrinos from the Earth

- From radioactive decays of $^{235}\text{U}$, $^{232}\text{Th}$, $^{40}\text{K}$, etc.
- Larger flux from the Earth’s crust
Neutrinos from cosmic rays (atmospheric neutrinos)

- Cosmic rays (mainly protons) interact with atmosphere to produce pions ($\pi^{\pm}$)
  - $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

- These are the ones INO will explore
Neutrinos from astrophysical events

<table>
<thead>
<tr>
<th>Neutrinos as messengers from the sky</th>
</tr>
</thead>
<tbody>
<tr>
<td>No bending in magnetic fields ⇒ point back to the source</td>
</tr>
<tr>
<td>Minimal obstruction / scattering ⇒ can arrive directly from regions from where light cannot come.</td>
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</tbody>
</table>

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<tr>
<th>Interesting astrophysical sources</th>
</tr>
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<tbody>
<tr>
<td><strong>Core-collapse supernovae</strong>*:</td>
</tr>
<tr>
<td>$10^{65}$ neutrinos emitted within 10 sec</td>
</tr>
<tr>
<td><strong>Active galactic nuclei</strong>**:</td>
</tr>
<tr>
<td>the most powerful, long-lived objects in the universe</td>
</tr>
<tr>
<td>Gamma ray bursts</td>
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</table>

*We saw these neutrinos in 1987
**We may have seen these neutrinos last year!!
Neutrinos from the big bang

- Cosmic microwave background: 400 photons/ cm$^3$
  Temperature: $\sim 3$ K
- Cosmic neutrino background: 300 neutrinos / cm$^3$
  Temperature: $\sim 2$ K

The “relic” neutrinos
- The second-most abundant particles in the universe
- Detection still far in future
  (unless someone has a brilliant idea)
Neutrinos from artificial sources

- Reactor neutrinos ($\bar{\nu}_e$)
- Accelerator neutrinos
Neutrinos everywhere

<table>
<thead>
<tr>
<th>Where do Neutrinos Appear in Nature?</th>
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<tr>
<td><strong>Earth Crust</strong> (Natural Radioactivity)</td>
</tr>
<tr>
<td>✔️ Nuclear Reactors</td>
</tr>
<tr>
<td>✔️ Particle Accelerators</td>
</tr>
<tr>
<td>✔️ Earth Atmosphere (Cosmic Rays)</td>
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Georg Raffelt, Max-Planck-Institut für Physik, München, Germany

Neutrino Physics & Astrophysics, 17-21 Sept 2008, Beijing, China
Neutrinos at all energies
The world of neutrinos

1. Their sources
2. Their interactions
3. Their puzzling nature
4. Their detection
About hundred trillion through our body per second
But we do not notice them!

Even during night!
Neutrinos during night = Neutrinos during day

Reach us directly from the core of the Sun
Light from the Sun’s core cannot reach us directly
Interesting trivia about solar neutrinos

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But we do not notice them!

Even during night!
Neutrinos during night = Neutrinos during day

Reach us directly from the core of the Sun
Light from the Sun’s core cannot reach us directly

Why these strange features?
Three questions, the same answer

- Why did the *roti* char?
- Why did the betel leaves (*paan*) rot?
- Why could the horse not run?
Three questions, the same answer

- Why did the *roti* char?
- Why did the betel leaves (*paan*) rot?
- Why could the horse not run?

Because they were not moved!
Three questions about neutrinos

- Why do we not notice neutrinos passing through us?
- Why do neutrinos from the Sun reach us during night?
- Why can we see “inside” the sun with neutrinos?
Three questions about neutrinos

- Why do we not notice neutrinos passing through us?
- Why do neutrinos from the Sun reach us during night?
- Why can we see “inside” the sun with neutrinos?

Because neutrinos interact extremely weakly!
The most weakly interacting particles

Stopping radiation with lead shielding

- Stopping $\alpha, \beta, \gamma$ radiation: 50 cm

Why do we not notice neutrinos passing through us?
Neutrinos pass through our bodies without interacting.

Why do neutrinos from the Sun reach us during night?
Neutrinos pass through the Earth without interacting.

Why can we see "inside" the sun with neutrinos?
Neutrinos pass through the Sun without interacting.

How do we see the neutrinos then?
The most weakly interacting particles

Stopping radiation with lead shielding

- Stopping $\alpha, \beta, \gamma$ radiation: 50 cm
- Stopping neutrinos from the Sun: light years of lead!
The most weakly interacting particles

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### Answers to the three questions
- Why do we not notice neutrinos passing through us?
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- Why do neutrinos from the Sun reach us during night?
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The most weakly interacting particles

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Answers to the three questions
- Why do we not notice neutrinos passing through us? Neutrinos pass through our bodies without interacting
- Why do neutrinos from the Sun reach us during night? Neutrinos pass through the Earth without interacting
- Why can we see “inside” the Sun with neutrinos? Neutrinos pass through the Sun without interacting

How do we see the neutrinos then?
SuperKamiokande: 50 000 000 litres of water

Neutrinos passing through SK per day: \(10^{25}\)

Neutrino interactions in SK per day: 5-10

Recipe for observing neutrinos

- Build very large detectors
- Go deep underground to get rid of background
- Wait for a very long time
SuperKamiokande: 50 000 000 litres of water

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Recipe for observing neutrinos
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## How does the Sun look in neutrinos?

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<td><img src="image" alt="Sun in photons" /></td>
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<td>Angular size $\sim 1^\circ$</td>
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<th>Sun in neutrinos: nuclear fusion 8 minutes ago</th>
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<td><img src="image" alt="Sun in neutrinos" /></td>
</tr>
<tr>
<td>Angular size $\sim 20^\circ$</td>
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Three kinds of neutrinos: $\nu_e$, $\nu_\mu$, $\nu_\tau$

- Negatively charged leptons produced $\Rightarrow$ neutrinos
- Positively charged leptons produced $\Rightarrow$ antineutrinos
The Standard Model of Particle Physics

- 3 neutrinos: $\nu_e, \nu_\mu, \nu_\tau$
- chargeless
- spin 1/2
- almost massless (at least a million times lighter than electrons)
- only weak interactions
The role of neutrino interactions in our being here

Creation of atoms

- Our best guess for the creation of Matter-antimatter asymmetry in the universe needs charge-parity (CP) violation in neutrinos (Leptogenesis)
The role of neutrino interactions in our being here

**Creation of atoms**
- Our best guess for the creation of Matter-antimatter asymmetry in the universe needs charge-parity (CP) violation in neutrinos (Leptogenesis)

**Creation of the solar system**
- Existence of heavy elements implies that the material came from the explosion of a core-collapse supernova
- Core-collapse supernovae explode due to the neutrinos pushing the shock wave
The role of neutrino interactions in our being here

Creation of atoms
- Our best guess for the creation of Matter-antimatter asymmetry in the universe needs charge-parity (CP) violation in neutrinos (Leptogenesis)

Creation of the solar system
- Existence of heavy elements implies that the material came from the explosion of a core-collapse supernova
- Core-collapse supernovae explode due to the neutrinos pushing the shock wave

Burning of the Sun
- Nuclear fusion reactions need neutrinos to help conserve energy, momentum and angular momentum
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The beta decay puzzle: $\sim 1930$

- Nuclear beta decay: $X \rightarrow Y + e^-$
- Conservation of energy and momentum $\Rightarrow$ Electrons have a fixed energy.
- But:

![Diagram showing the energy-momentum distribution of electrons in beta decay]

- Energy-momentum conservation in grave danger !!
The beta decay puzzle: \( \sim 1930 \)

- **Nuclear beta decay:** \( X \rightarrow Y + e^- \)
- **Conservation of energy and momentum** \( \Rightarrow \) **Electrons have a fixed energy.**
- **But:**

  ![Graph](image)

- **Energy-momentum conservation in grave danger!!**

- **A reluctant solution (Pauli):** postulate a new particle
"But don't you see, Wolfgang- if the particle is too weakly interacting to detect, we can't just take it on faith that you've discovered it."

Discovery of electron neutrino: 1956

The million-dollar particle

- Reactor neutrinos: $\bar{\nu}_e + p \rightarrow n + e^+$
- $e^+ + e^- \rightarrow \gamma + \gamma$ (0.5 MeV each)
- $n + ^{108}\text{Cd} \rightarrow ^{109}\text{Cd}^* \rightarrow ^{109}\text{Cd} + \gamma$ (delayed)

Reines-Cowan: Nobel prize 1995
The “Who ordered muon neutrino?” puzzle: 1962

Muon neutrino: an unexpected discovery

- Neutrinos from pion decay: $\pi^- \rightarrow \mu^- + \bar{\nu}$
- $\bar{\nu} + N \rightarrow N' + e^+$ ??
- Electrons/positrons expected
The “Who ordered muon neutrino?” puzzle: 1962

Muon neutrino: an unexpected discovery

- Neutrinos from pion decay: $\pi^- \rightarrow \mu^- + \bar{\nu}$
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Actual experiment:

- Always a muon observed, never an electron/positron

This must be a new particle, not $\bar{\nu}_e$, but $\bar{\nu}_\mu$

Steinberger-Schwartz-Lederman: Nobel prize 1988
The long-term puzzles ⇒ neutrino oscillations

Solar neutrino puzzle: 1960s – 2002
- Only about half the expected $\nu_e$ observed!

- Half the $\nu_\mu$ lost in the Earth!

Reactor neutrino experiments
- Breaking news of 2012-13: 10% of reactor $\bar{\nu}_e$ are lost!
The long-term puzzles ⇒ neutrino oscillations

**Solar neutrino puzzle: 1960s – 2002**
- Only about half the expected $\nu_e$ observed!
- Possible solution: $\nu_e$ change to $\nu_\mu/\nu_\tau$

**Atmospheric neutrino puzzle: 1980s – 1998**
- Half the $\nu_\mu$ lost in the Earth!
- Possible solution: $\nu_\mu$ change to $\nu_\tau$

**Reactor neutrino experiments**
- Breaking news of 2012-13: 10% of reactor $\bar{\nu}_e$ are lost!
- Possible solution: $\bar{\nu}_e$ change to $\bar{\nu}_\mu/\bar{\nu}_\tau$
Three questions, the same answer

- Why did half the $\nu_e$ from the sun become $\nu_\mu/\nu_\tau$?
- Why did half the $\nu_\mu$ from the atmosphere become $\nu_\tau$?
- Why did 10% $\bar{\nu}_e$ from the reactors become $\bar{\nu}_\mu/\bar{\nu}_\tau$?
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- Why did half the \( \nu_e \) from the sun become \( \nu_\mu/\nu_\tau \)?
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- Why did 10\% \( \bar{\nu}_e \) from the reactors become \( \bar{\nu}_\mu/\bar{\nu}_\tau \)?

Because neutrinos have different masses and they mix!

Quantum Mechanics
What is meant by neutrino mixing?

$\nu_e, \nu_\mu, \nu_\tau$ do not have fixed masses!!

For example, $\nu_e-\nu_\mu$ mixing:

\[ \nu_2 = \nu_e \sin \theta + \nu_\mu \cos \theta \]
\[ \nu_1 = \nu_e \cos \theta + \nu_\mu \sin \theta \]

$\cos^2 \theta \quad \sin^2 \theta$
Still open puzzles about neutrino masses

Mixing of $\nu_e, \nu_\mu, \nu_\tau \Rightarrow \nu_1, \nu_2, \nu_3$ (mass eigenstates)
Still open puzzles about neutrino masses

Mixing of $\nu_e, \nu_\mu, \nu_\tau \Rightarrow \nu_1, \nu_2, \nu_3$ (mass eigenstates)

- Mass ordering: Normal or Inverted?
- What are the absolute neutrino masses?
- Can neutrinos be their own antiparticles?
- Is there leptonic CP violation?
- Are there more than 3 neutrinos?
Superluminal neutrinos?
The neutrinos do not travel faster than light

Relativity
The world of neutrinos

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Some neutrino detectors with different materials

**Water:** SuperKamiokande

**Heavy water:** SNO

**Scintillator:** Kamland

**Iron:** MINOS
Below the antarctic ice: Gigaton IceCube

Sensitivity to $E \gtrsim 100$ GeV

- Neutrinos from AGNs/GRBs, late SN neutrinos
- Luminosity of SN neutrino burst
Future large detectors

- Three types of large multi-purpose underground detectors with astrophysical program

  Water Cherenkov ($\approx 0.5 \rightarrow 1$ Mton)
  MEMPHYS

  Liquid Scintillator ($\rightarrow 50$ kton)
  LENA

  Liquid Argon ($\approx 10 \rightarrow 100$ kton)
  GLACIER

Sensitivity to MeV – 100 GeV neutrinos

- Measuring the energy of the sun in neutrinos
- Supernova neutrino detection
- Detecting neutrinos produced at accelerators thousands of km away (long baseline experiments)
Detection of UHE neutrinos: cosmic ray showers

- Neutrinos with $E \gtrsim 10^{17}$ eV can induce giant air showers (probability $\lesssim 10^{-4}$)
- Deep down-going muon showers
- Deep-going $\nu_\tau$ interacting in the mountains
- Up-going Earth-skimming $\nu_\tau$ shower
Coming soon to a mountain near you: INO

India-based Neutrino Observatory

- In a tunnel below a peak (Bodi West Hills, near Madurai)
- 1 km rock coverage from all sides
- 50 kiloton of magnetized iron (50 000 000 kg)
- Can distinguish neutrinos from antineutrinos
- Determining mass hierarchy from atmospheric neutrinos
Future results to look forward to

Neutrino masses and mixing

- Determination of masses and mixing parameters from data
- Neutrino mass ordering: Normal or Inverted?
- Are neutrinos their own antiparticles (Majorana)?
- Signals of physics beyond the Standard Model
- Models for small $\nu$ masses and the mixing pattern
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**Astrophysics and cosmology**
- Understanding of supernova explosions
- Nucleosynthesis of heavy elements inside stars
- Nature of astrophysical phenomena like AGNs
- Creation of the matter-antimatter asymmetry
- Mapping the sky in neutrinos (like we do in photons)
BACKUP SLIDES
Nuclear reactions inside the Sun

Hydrogen burning: Proton-Proton Chains

\[ p + p \rightarrow ^2H + e^+ + \nu_e \quad < 0.420 \text{ MeV} \]
\[ p + e^- + p \rightarrow ^2H + \nu_e \quad 1.442 \text{ MeV} \]

\[ ^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + 2p \]
\[ ^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma \]
\[ ^3\text{He} + p \rightarrow ^4\text{He} + e^+ + \nu_e \quad < 18.8 \text{ MeV} \]
\[ ^7\text{Be} + e^- \rightarrow ^7\text{Li} + \nu_e \quad 0.862 \text{ MeV} \]
\[ ^7\text{Be} + e^- \rightarrow ^7\text{Li} + \nu_e \quad 0.384 \text{ MeV} \]
\[ ^7\text{Be} + p \rightarrow ^8\text{B} + \gamma \quad 8\text{B} \rightarrow ^8\text{Be}^* + e^+ + \nu_e \quad < 15 \text{ MeV} \]

PPi, PPII, PPIII
Neutrinos from exploding stars

**Gravity ⇒**

**Strong nuclear force ⇒**

**Weak nuclear force (Neutrino push) ⇒**

**Electromagnetism (Hydrodynamics) ⇒**

(Crab nebula, SN seen in 1054)
What supernova neutrinos can tell us

On neutrino masses and mixing
- Identify neutrino mass ordering: normal or inverted

On supernova astrophysics
- Locate a supernova hours before the light arrives
- Track the shock wave through neutrinos while it is still inside the mantle (Not possible with light)

Inverse supernova neutrino problem
Observe the neutrino spectra, deduce neutrino mixing parameters, primary neutrino spectra, shock wave propagation
Mapping the universe

Gamma ray
Near infrared

X-ray
Infrared

Visible

Radio waves

CMB from Planck

Neutrinos entering this domain, slowly but surely...

We should be adding more colors to the universe...