A New View of our Universe from a Hole in the Ground

David Sinclair
Carleton and Triumf
A new view of our universe from a hole in the ground

Or

How to get in from the rain

David Sinclair
Carleton and TRIUMF
What are we looking for

- There are many particles in our universe which are not very familiar to us but we would like to study them.
- We know about protons and neutrons and electrons.
- There are 10,000,000,000 times as many ‘neutrinos’ in our universe than electrons or protons.
- There should be other exotic particles about.
- How do we see them in the ‘rain’ of cosmic rays?
What is a Neutrino?

- One of the ‘fundamental’ particles of nature
- First evidence in nuclear $\beta$ decay
- Among the most abundant particles in the Universe (10 Billion times as common as electrons, protons or neutrons)
What is $\beta$ Decay?

- Within the nucleus
  
  Neutron $\rightarrow$ Proton + electron

  Or

  Proton $\rightarrow$ Neutron + positron

Example $^{14}\text{C} \rightarrow ^{14}\text{N} + \text{e}^-$
β-Decay – Our first look at Weak Interaction

- First studied in early 1900’s
- Appears to violate fundamental laws of Physics
β-Decay and Energy Conservation

Appears to violate Energy Conservation
\[ ^6\text{He} \rightarrow ^6\text{Li} + e^- \]

Appears to violate
Momentum Conservation
Wolfgang Pauli Proposes Neutrino

- 1930 – Neutral particle could carry off missing energy and momentum
- Shortly after Chadwick discovers neutron
- Neutrons have the wrong properties
Enrico Fermi Provides Quantitative Theory of $\beta$ Decay

- Good agreement with energy spectra obtained
- Neutrino concept essential
- Name Neutrino (Little Neutral one) Introduced
Neutrinos can React but Chance TINY

- 1934 – Fermi and Peierls calculate reaction rates
- Reactions are opposite of decay
- If 10,000,000,000 neutrinos strike the earth, all but one pass through!

\[ \nu_e + n \rightarrow e^- + p \]

Rudolf Peierls
Some basic facts on Neutrinos

- Mass must be very small ($<1/100,000 \, m_e$)
- No Charge
- Only weak interactions
- Produced any time a neutron changes to a proton or proton to neutron
- Symbol $\nu$
Nuclear Reactors are neutrino sources

- In a reactor uranium fissions to form lighter fragments
- Fragments are very neutron rich
- Neutrons decay to protons to form more stable nuclei giving neutrinos
Neutrinos Finally Found

- Reines and Cowan (1957)
- Detected neutrinos from a reactor
- Efforts at Chalk River by John Robson ended due to reactor problem

Fred Reines
Lost Under Way

Berlin, Germany - A ship was lost under way in the Baltic Sea.

The ship was carrying 200 passengers and 100 crew members.

The cause of the loss is under investigation.

News Item

Leak in Atomic Furnace Halts Search for Neutrons

Chalk River, Ont. - An atomic furnace has leaked.

The furnace was being used to search for neutrons.

The leak has halted the search.

News Item

Gas Masks for Everybody

Ontario Civil Defense Aims

The province of Ontario has decided to equip all citizens with gas masks.

The decision was made due to the increasing threat of nuclear war.

News Item

The Water's Fine

Two members of the Montreal Polar Bear Club have survived the icy waters of Lake St. Louis.

They were able to swim back to safety after being thrown into the lake.

News Item

Northern Ontario's Largest Newspaper

The Sudbury Daily Star

Tomorrow's Weather

Cloudy, mild, snow showers.
More properties of Neutrinos

- Comes in 3 types ($\nu_e$, $\nu_\mu$, $\nu_\tau$) forming families with charged electron, muon and tau. Collectively called Leptons
- Each has a distinct antiparticle
- There appears to be a set of conservation laws – Lepton number conservation
  - E.g. Number of electron family particles is constant
Examples of Lepton Conservation

\[ n \rightarrow p + e^- + \nu_e \]

\[ p \rightarrow n + e^+ + \nu_e \]

\[ \mu^+ \rightarrow e^+ + \nu_e + \nu_\mu \]

\[ \nu_e + n \rightarrow p + e^- \]
Lepton Conservation Forbids

\[ \nu_\mu + n \rightarrow p + e^- \]

\[ \mu \rightarrow e + \gamma \]

These are never observed
Lets banish the rain and think about the Sun
What makes the Sun Shine?

- Can it be chemical burning?
- No! The Sun would burn up in ~1000 years
- Can it be gravity
- No! It would last longer but not nearly long enough
- We think the sunshine is powered by ‘nuclear burning’
Energy From the Sun

- 1925 Eddington showed energy source must be nuclear
- 1934 Hans Bethe produces detailed model

Hans Bethe
Nuclear Reactions in the Sun
Solar Energy and Neutrinos

- For every $^4\text{He}$ formed, 2 protons change into 2 neutrons.
- For every $^4\text{He}$ formed, 2 neutrinos produced.
- We know how much energy we get by making $^4\text{He}$ and how much energy reaches the earth from the Sun.
- $100,000,000,000$ neutrinos/cm$^2$/second hit Earth.
- Measuring neutrinos should allow a study of energy production in Sun.
First Search for Solar Neutrinos

Ray Davis looked for neutrinos using a tank of dry-cleaning fluid deep underground. Based on a suggestion of Pontecorvo at Chalk River

Look for process

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

\(^{37}Ar\) is removed from tank every month

Look for decay of \(Ar\) back to \(Cl\)

Production rate is 1 atom per week
Ray Davis and his Chlorine based Detector Deep underground
Results of the Chlorine Experiment

- First data - 1968
- Production of Argon is $\frac{1}{4}$ expected rate
  - Experiment may be wrong
  - Model of Sun may be wrong
  - Model of neutrino may be wrong

- Solar Neutrino Problem is Born
Pontecorvo Questions Neutrino

- Perhaps neutrinos ‘oscillate’
- That is, a neutrino created as electron type might change to muon type and back again

Bruno Pontecorvo
Physics Community Reaction

- Oscillation not generally accepted
- Physicists could understand a small mixing
- Solar Neutrino Problem required complete mixing of 3 neutrino types
Mikheyev and Smirnov to the Rescue

- Neutrino mixing can be greatly enhanced in matter
- Even small mixing can explain solar neutrino problem
- Seems so elegant nature has to use this
New Experiments add to Mystery

- Two gallium experiments built (Italy and Russia)
  - See $\frac{1}{2}$ expected rate
  - Sensitive to low energies

- Water detector built (Japan)
  - Sees $<\frac{1}{2}$ expected rate

- No agreement with Solar models

John Bahcall
Guru of Solar Models
It’s Not Just the Sun
Dark Matter

- There appears to be much more mass in the universe than we can account for.
- Neutrinos are the most abundant particle in the Universe
- If neutrinos have mass could they be the Dark Matter?
- Dark matter determines fate of the Universe
It’s Not Just the Sun

Dark Matter

- Rotation of matter in galaxies shows too much mass
- Gravitational lensing shows too much mass
- Big Bang theory gives total mass of neutrons and protons is ~4% of total
- If lightest neutrinos account for solar neutrino problem then heaviest has right mass (See-Saw Model) for Dark Matter
It’s Not Just the Sun

Supernovae

- A Supernova occurs at the end of the life of massive stars (>8 $M_\odot$)
- Core Collapses to produce a neutron star
Crab Nebula – a Supernova Remnant from 1057
It’s Not Just the Sun

Supernovae

- Neutrinos carry off 99% of the energy of the supernova in a few seconds
- This burst outshines the visible universe
- Why does the supernova explode?
- Neutrinos could drive the explosion but best models fail to explode
- Neutrino oscillations would help if the mass is large enough
Sudbury Neutrino Observatory

- A Project started in 1984 to solve the Solar Neutrino Problem
- Proposed by Herb Chen (U.C. Irvine)
- Heart of experiment is 1000 tonnes of heavy water used to detect neutrinos from Sun
Neutrino Detection in Heavy Water

- Heavy water is $\text{D}_2\text{O}$ – D is Deuterium
- Deuterium nucleus is weakly bound proton and neutron

\[
\nu_e + d \rightarrow p + p + e^- \quad \text{(CC)}
\]
\[
\nu_x + e^- \rightarrow \nu_x + e^- \quad \text{(ES)}
\]
\[
\nu_x + d \rightarrow n + p + \nu_x \quad \text{(NC)}
\]

$x$ means any neutrino type
Cherenkov Detectors

- Electrons produced in reactions move close to speed of light (Light in water moves slower)
- Sets up shock similar to supersonic boom
- Takes form of flash of light
- About as bright as a candle on the moon
The SNO Detector

- 1000 Tonnes of D$_2$O
- 12 M Acrylic vessel
- 10,000 phototubes
- 8000 Tonnes of pure light water
- 2000 m deep in Mine
- World’s largest deep cavern
- All materials very pure
Excavating the Cavity

SNO is as large as a 10 story building

Largest cavity excavated at this depth
Constructing the Acrylic Vessel

This is the largest All acrylic structure built
Partially completed detector acrylic vessel and Geodesic structure used to hold phototubes
Detector partially filled
Top of Detector
Heavy Water Train leaves for the Mine
Heavy water enters the Cage
A part of the Heavy Water Purification System
Typical Neutrino Reaction in SNO

- Ring represents hit phototubes
- Number of hits gives energy
- Timing gives location
- Pattern gives direction
Background is Everything

- Expect about 10 neutrino events per day
- Go Deep to avoid cosmic rays
- All materials must be chosen with care to avoid radioactivity
- Build detector in clean conditions to avoid dust
- Extensive analysis to get rid of instrumental backgrounds
SNO Energy Spectrum
Data plotted as function of Direction to Sun

Events per 0.05 wide bin

CC
NC + bkgd neutrons
Bkgd

ES
Graphical Presentation of SNO RESULT

\( \phi_{\mu\tau} (10^6 \text{ cm}^{-2} \text{ s}^{-1}) \)

\( \phi_{\mu\tau} \)

\( \phi_{\text{ES}} \)

\( \phi_{\text{CC}} \)

\( \phi_{\text{NC}} \)

\( \phi_{\text{SNO}} \)

\( \phi_{\text{SSM}} \)

\( \phi_e (10^6 \text{ cm}^{-2} \text{ s}^{-1}) \)
The Basic SNO Result

- Flux of Electron type Neutrinos
  \[1.76 \pm 0.11 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}\]
- Flux of All Neutrinos
  \[5.09 \pm 0.66 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}\]
- High Energy Only

These numbers are different
Direct Evidence for Neutrino Oscillation
What Does it Mean for The Sun?

- Standard Solar Model is Accurate
- Prediction $5.05 \times 10^6$
- SNO Measures $5.09 \times 10^6$
- Flux varies as $T^{25}$
- Central temperature fixed to <1%
- (Central temperature ~ 15,000,000 K)
What Does it Mean for Neutrino Oscillations?

- Neutrinos Oscillate
- Neutrinos have Mass
- Neutrinos have large mixing
What Does it Mean for Dark Matter

- Neutrinos are too light to make up Dark Matter (May contribute a few % like normal matter)
- We need another particle – Search underway!
- Recently Dark Energy found
- Maybe whole picture is wrong!
What Does it Mean for Supernovae

- Neutrino Masses too light for Resonant Oscillation to be effective
- New High Performance Computers (like HPCVL) allow 3d modelling
- With effects of turbulence Supernovae explode (still driven by neutrinos!)
What Does it Mean for Big Bang?

- Universe seems to be made of matter not anti matter
- Unexpected large mixing of neutrinos could allow this in the Big Bang
- Will require huge experimental effort to explore this
Where Do We Go Next

- Build new laboratory to
  - Look at low energy neutrinos from Sun
  - Look for Dark Matter
  - Look for new neutrino properties
  - Look for supernovae
Picasso – Search for Dark Matter using Superheated Droplets (SNOLAB will have 5 different experiments looking for Dark Matter)
Final Thoughts

- There are many unsolved problems in ‘astroparticle physics’
  - What is Dark matter?
  - Why is the universe made of matter?
  - What really happens in a Supernova

- To study these we need to get out of the ‘rain’ of cosmic rays to allow very sensitive measurements

- Looking at the universe from a hole in the ground gives us a new laboratory to explore these fundamental questions