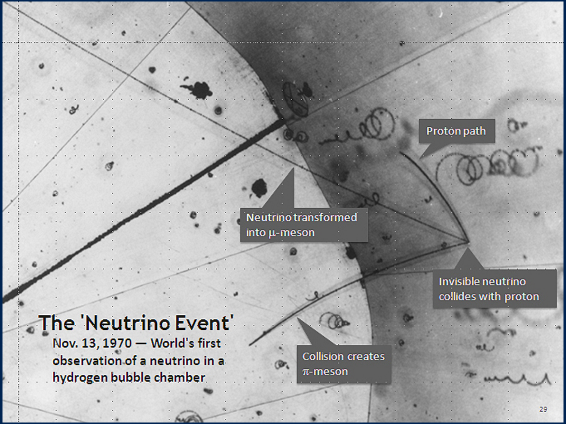
Neutrinos: Past present and future

EIEIOO Workshop

May 8, 2024

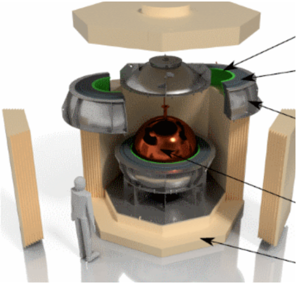
R. Martin
Queen's University



Queen's UNIVERSITY

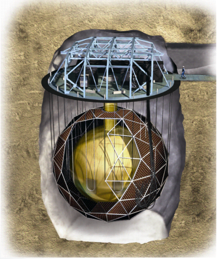
The GeRMLab - a bit about myself

My research interests are focused on neutrino physics, searches for dark matter, and physics education. I participate in the LEGEND, SNO+ and NEWS-G experiments.



NEWS-G (gas SPC)

LEGEND (HPGe)

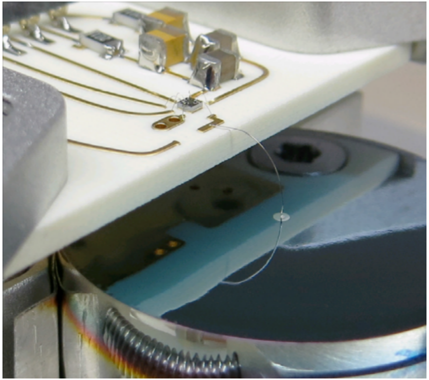


SNO+ (LS)

The GeRMLab - a bit about myself

My research interests are focused on neutrino physics, searches for dark matter, and physics education. I participate in the LEGEND, SNO+ and NEWS-G experiments.

Ge rmanium - we work with germanium particle detectors!

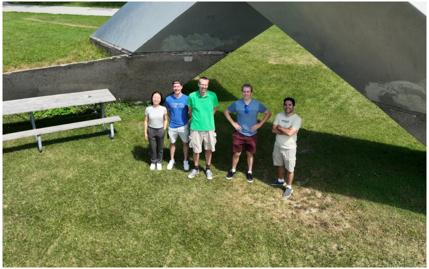


A germanium detector with a prototype ASIC.

The GeRMLab - a bit about myself

My research interests are focused on neutrino physics, searches for dark matter, and physics education. I participate in the LEGEND, SNO+ and NEWS-G experiments.

- **Ge** rmanium - we work with germanium particle detectors!
- **RM** Ryan Martin - that's me!

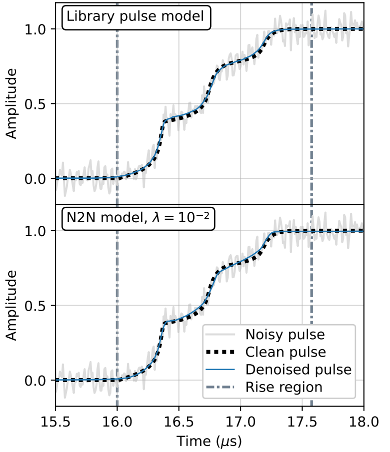


The GeRMLab, seen from above.

The GeRMLab - a bit about myself

My research interests are focused on neutrino physics, searches for dark matter, and physics education. I participate in the LEGEND, SNO+ and NEWS-G experiments.

- **Ge** rmanium - we work with germanium particle detectors!
- **RM** Ryan Martin - that's me!
- **ML** Machine Learning - we do a lot of machine learning, focused on developing techniques of broad use in particle astrophsyics!

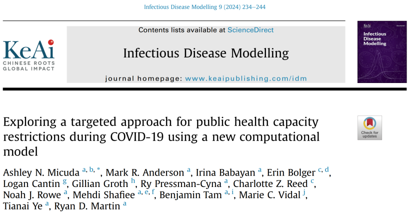


*Machine learning to remove electronic noise, M. Anderson et. al, EPJC **82.12** (2022)*

The GeRMLab - a bit about myself

My research interests are focused on neutrino physics, searches for dark matter, and physics education. I participate in the LEGEND, SNO+ and NEWS-G experiments.

- **Ge** rmanium - we work with germanium particle detectors!
- **RM** Ryan Martin - that's me!
- **ML** Machine Learning - we do a lot of machine learning, focused on developing techniques of broad use in particle astrophsyics!
- **GeRM** We maintain a code for COVID-19 modelling.


Infectious Disease Modelling 9 (2024) 234–244

Contents lists available at ScienceDirect

KeAi CHINESE ROOTS GLOBAL IMPACT

Infectious Disease Modelling

journal homepage: www.keaipublishing.com/idm

Exploring a targeted approach for public health capacity restrictions during COVID-19 using a new computational model

Ashley N. Micuda [a, b, *], Mark R. Anderson [a], Irina Babayan [a], Erin Bolger [c, d], Logan Cantin [g], Gillian Groth [h], Ry Pressman-Cyna [a], Charlotte Z. Reed [c], Noah J. Rowe [a], Mehdi Shafiee [a, e, f], Benjamin Tam [a, i], Marie C. Vidal [j], Tianai Ye [a], Ryan D. Martin [a]

We published an article in a medical journal! Led by undergraduates!

The GeRMLab - a bit about myself

My research interests are focused on neutrino physics, searches for dark matter, and physics education. I participate in the LEGEND, SNO+ and NEWS-G experiments.

Ge rmanium - we work with germanium particle detectors!

RM Ryan Martin - that's me!

ML Machine Learning - we do a lot of machine learning, focused on developing techniques of broad use in particle astrophsyics!

GeRM We maintain a code for COVID-19 modelling.

Lab We even have an actual lab! Maybe one day you'd like to join?! ;-)

Our lab at Queen's University.

Outline

History of neutrinos

Who invented them?
Who discovered them?

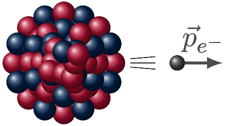
The continuous β-decay spectrum

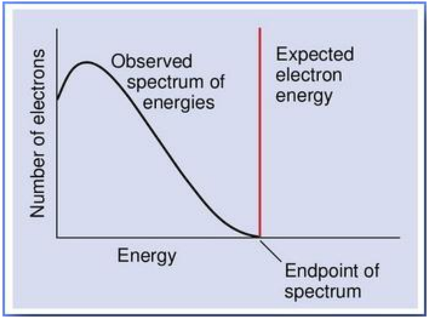
- Measurements of β-rays (aka electrons) showed a continuous energy spectrum (1911).
- Hypothesis:

$$\text{neutral particle} \rightarrow \text{positive particle} + \beta\text{-ray}$$

- Or in modern terms:

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





Kinetic energy of electrons from β-decay

Conservation of energy and momentum

If M decays from rest to $M' + m$, m must always have the same kinetic energy. Where does the energy come from?

Dear Radioactive Ladies and Gentlemen

Dear Radioactive Ladies and Gentlemen,

(. . .) because of the “wrong” statistics of the N and Li6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the “exchange theorem” of statistics and the law of conservation of energy. Namely, the **possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons**, which have spin 1/2 and obey the exclusion principle (. . .). The continuous beta spectrum would then become understandable by the assumption that, **in beta decay, a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant** (. . .)

I agree that my remedy could seem incredible because one should have seen these neutrons much earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honoured predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It’s well better not to think about this at all, like new taxes". (. . .)

Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. (. . .)

W. Pauli

Wolfgang Pauli

Some early dates: from neutrons to neutrinos!

1900 Becquerel measures m/e for β rays and finds the same value as Thomson's "cathode rays" $\rightarrow$ the electron!

1911 Meitner and Hahn see hints that β-decay spectrum is continuous, Chadwick confirmed in 1914.

1930 Pauli proposes an undetectable "neutron" to save conservation of energy:

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

1932 Chadwick discovers the "neutron".

1934 When Fermi is asked whether the neutral particle in the decay is Chadwick's neutron, he says: "no, it's smaller, a little neutron, a *neutrino*!"

$\rightarrow$ Need a strong source of neutrinos to detect them!

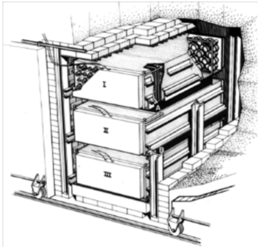
Lise Meitner, first female physics professor in Germany, fled in 1938 to Sweden. Excluded from 1944 Nobel Prize (awarded to Otto Hahn alone for discovery of fission).

First detection of neutrinos (1956)

- Nuclear reactors produce *many* (anti)neutrinos
- Experiment by Reines and Cowan at Savannah nuclear power plant made clever use of "inverse β-decay" reaction to detect neutrino events:

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

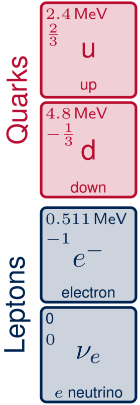
- Since water contains a lot of "free-ish" protons (nuclei of H), it is a good target for the reaction.
- Detection by "triple coincidence":
  - "Prompt" $2\times$ $511\,$keV annihilation γ-rays from positron.
  - "Delayed" (5ms) neutron capture on cadmium (seen as 2-3 gammas summing to $9\,$MeV)



Savannah River Reactor experiment. Two $H_2O + CdCl$ targets between three scintillator detectors.

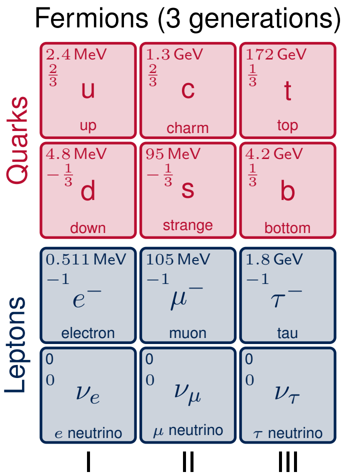
Reines (front) and Cowan (back).

Neutrinos in the Standard Model



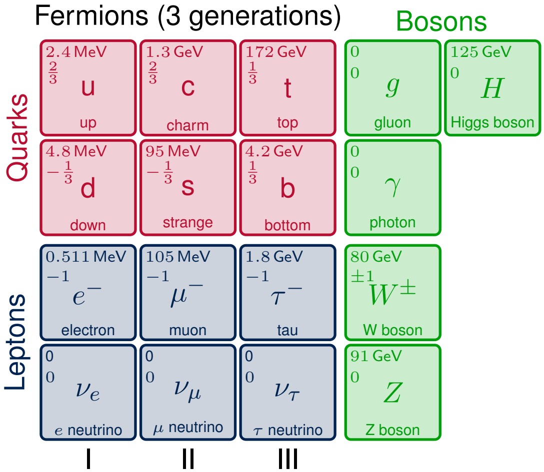
- Regular matter is made of "up" and "down" quarks, electrons, and electron flavour neutrinos.
  - Up and down quarks make up protons and neutrons.
  - Neutrinos are the only neutral particle.
  - Neutrinos are the only mass-less particle.

Neutrinos in the Standard Model



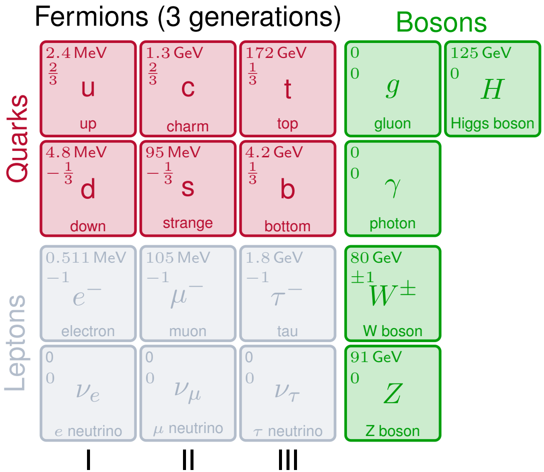
- Regular matter is made of “up” and “down” quarks, electrons, and electron flavour neutrinos.
- There are 3 generations of “fermions”, particle with half-integer spin.
    - The particles in one generation are heavier versions of the ones in previous generations.
    - There is no relation between lepton and quark generations. They don’t have to both have 3 generations.
    - We speak of 3 neutrino “flavours”.

Neutrinos in the Standard Model



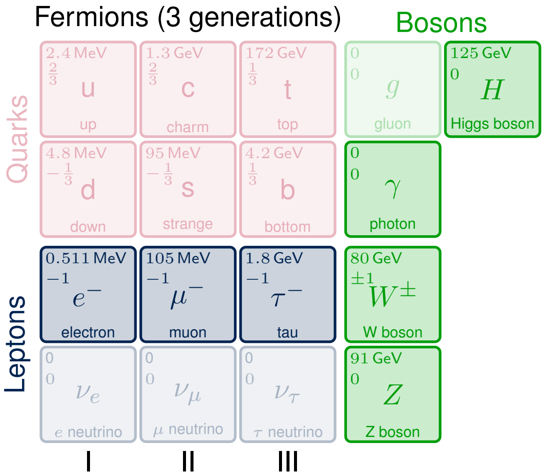
- Regular matter is made of “up” and “down” quarks, electrons, and electron flavour neutrinos.
- There are 3 generations of “fermions”, particle with half-integer spin.
- There are 5 bosons, particles with integer spin.
    - These mediate particle interactions (strong, electromagnetic, weak).
    - Interactions with the Higgs boson give particles their mass.

Neutrinos in the Standard Model



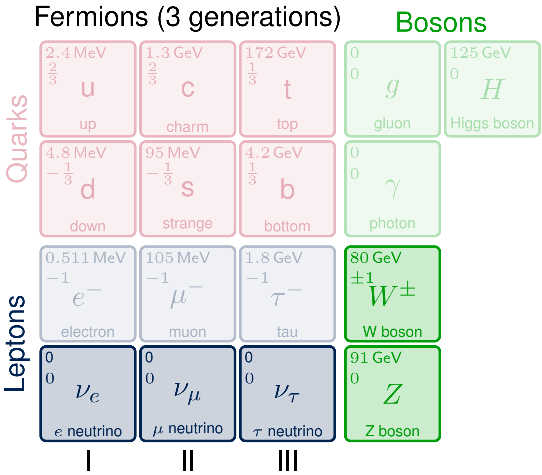
- Regular matter is made of “up” and “down” quarks, electrons, and electron flavour neutrinos.
- There are 3 generations of “fermions”, particle with half-integer spin.
- There are 5 bosons, particles with integer spin.
- Quarks can interact through any of the forces.
  - They mainly interact through the strong interaction.
  - They never exist in unbound states.

Neutrinos in the Standard Model

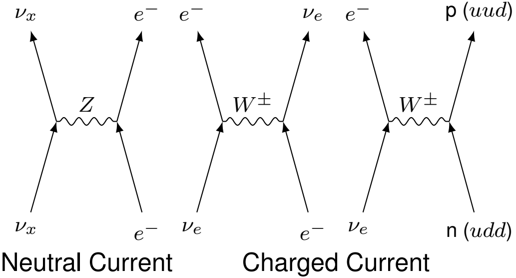


- Regular matter is made of “up” and “down” quarks, electrons, and electron flavour neutrinos.
- There are 3 generations of “fermions”, particle with half-integer spin.
- There are 5 bosons, particles with integer spin.
- Quarks can interact through any of the forces.
- Charged leptons are insentitive to the strong interaction

Neutrinos in the Standard Model



- Neutrinos interact only through the Weak interaction:
  - Interactions with Z or W boson.
  - Only left-handed neutrinos can be created through WI, *this requires neutrinos to be massless!*



The Solar Neutrino Problem

Energy production in the Sun

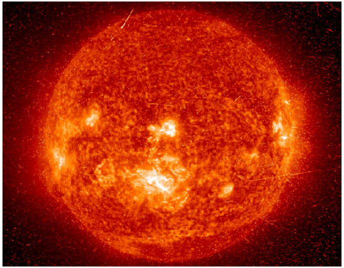
- The Sun works by fusing hydrogen into helium. Something like taking 4 hydrogens to make an alpha-particle [a]:

$$p + p + p + p + 2e^- \rightarrow \alpha + \nu_e + \nu_e + \text{energy}$$

- Stuff on the left is heavier than stuff on the right:

$$\begin{aligned} 4m_p + 2m_e &= 3754.2\,\text{MeV}/\text{c}^2 \\ m_\alpha &= 3725.5\,\text{MeV}/\text{c}^2 \\ \therefore \Delta E &= 26.7\,\text{MeV} \end{aligned}$$

[a] It's more complicated, but this gives the right order of magnitude!



A fiery ball.

Energy production in the Sun

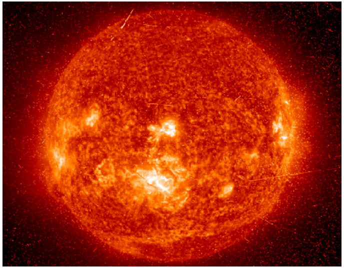
- The Sun works by fusing hydrogen into helium. Something like taking 4 hydrogens to make an alpha-particle [a]:

$$p + p + p + p + 2e^- \rightarrow \alpha + \nu_e + \nu_e + \text{energy}$$

- Stuff on the left is heavier than stuff on the right:

$$\begin{aligned} 4m_p + 2m_e &= 3754.2\,\text{MeV}/\text{c}^2 \\ m_\alpha &= 3725.5\,\text{MeV}/\text{c}^2 \\ \therefore \Delta E &= 26.7\,\text{MeV} \end{aligned}$$

[a] It's more complicated, but this gives the right order of magnitude!



A fiery ball.

- The brightness of the Sun gives its luminosity:

$$\begin{aligned} L_\odot &= 3.29 \times 10^{29}\ \text{J}/\text{s} \\ &= 24.4 \times 10^{39}\ \text{MeV}/\text{s} \end{aligned}$$

Neutrino production in the Sun

- Rate of fusion reactions in the Sun:

$$\Gamma_\odot = \frac{L_\odot}{\Delta E} = 9.1 \times 10^{37}\,\mathsf{s}^{-1}$$

- Rate of neutrinos produced in the Sun:

$$\Gamma_\nu = 2\Gamma_\odot = 18.2 \times 10^{37}\,\mathsf{s}^{-1}$$

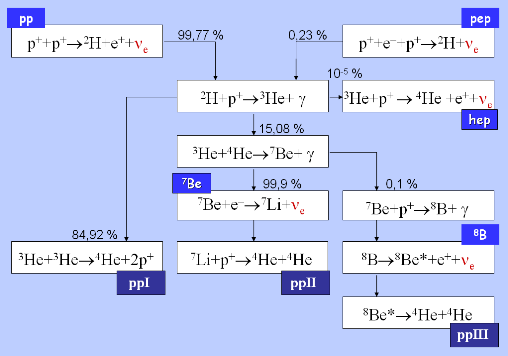
- Rate of neutrinos at the Earth:

$$\Gamma_\nu^\oplus = \frac{\Gamma_\nu}{4\pi D^2} = 6.4 \times 10^{14}\,\mathsf{m}^{-2}\mathsf{s}^{-1}$$
$$= 6.4 \times 10^{10}\,\mathsf{cm}^{-2}\mathsf{s}^{-1}$$

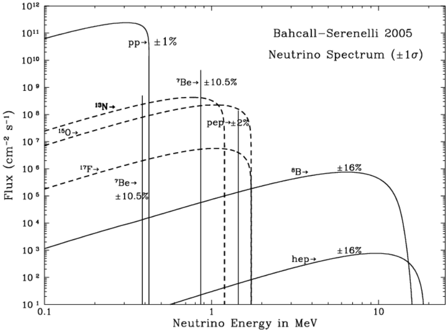
- That's a lot of neutrinos...

John Bahcall developped the solar models that allowed solar neutrino fluxes to be calculated.

Actual neutrino production in the Sun



There are many reactions in the fusion process, some making neutrinos. There is a separate set of reactions (CNO cylce) not shown here that also makes neutrinos.



Solar neutrinos are emitted with a variety of energy spectra, depending on the reaction that produced them (CNO cycle neutrinos in dashed lines).

- Any experiment to detect neutrinos will have an energy threshold below which it cannot detect neutrinos.

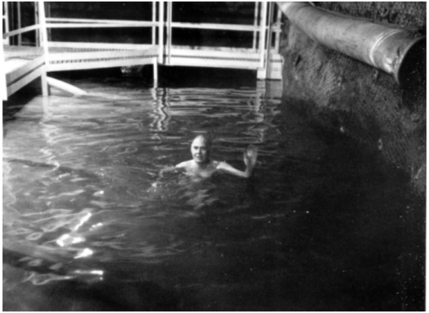
Detecting solar neutrinos

John Bahcall and Ray Davis proposed to detect solar neutrinos through inverse β-decay on $^{37}\mathrm{Cl}$ (1964):

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

- Experiment in Homestake mine, 1.5 km underground in South Dakota.
- In $400\,000$ l of $\mathrm{C_2Cl_4}$, produce about 15 atoms that are extracted every month to be counted (for 10^{30} chlorine atoms).

The idea of counting argon atoms is as crazy as that of precisely predicting the flux of solar neutrinos...



Ray Davis swimming in his experiment.

Results from the Ray Davis experiment

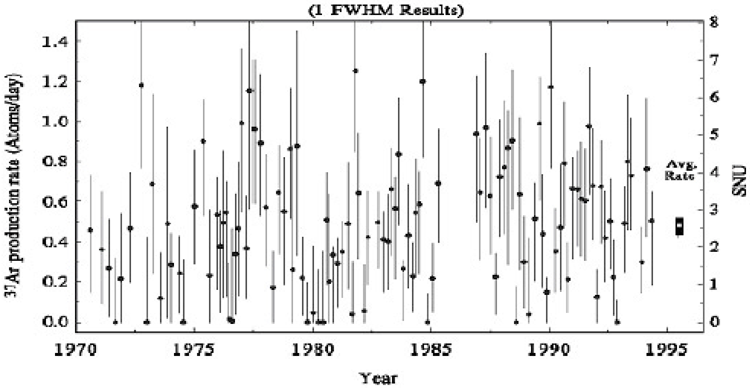
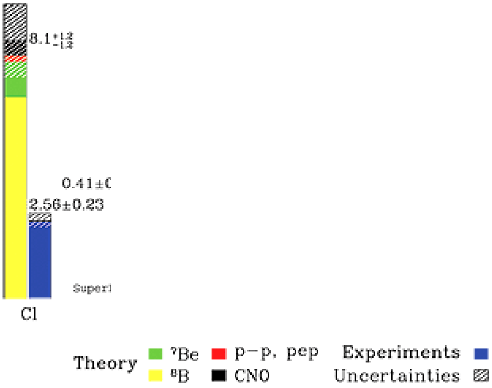


Fig. 2 Final results of Davis experiment (Cleveland et al. 1998). The average rate of about 2.5 SNU is much lower than the calculated rate of about 8.6.

- Note the time scale of the measurements, that's dedication!
- Measure 2.5 SNU instead of 8.6 SNU, what gives?

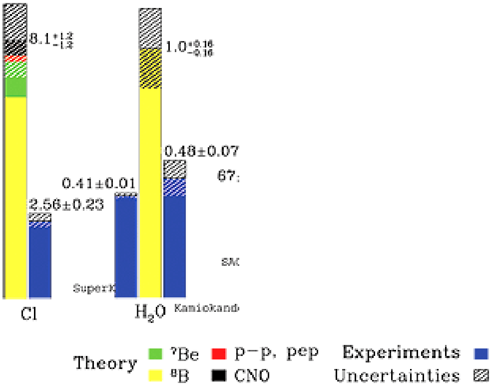
The solar neutrino problems

- Ray Davis experiment saw a deficit in solar neutrinos using chlorine.



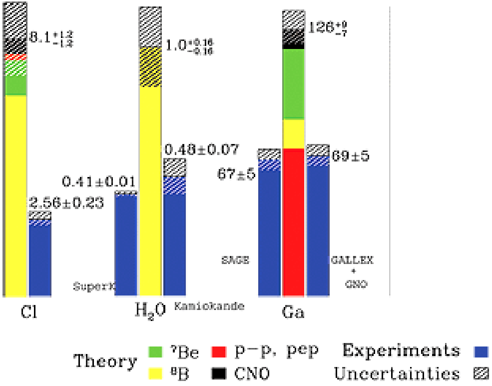
The solar neutrino problems

- Ray Davis experiment saw a deficit in solar neutrinos using chlorine.
- Kamiokande and SuperK experiments saw a deficit using water.



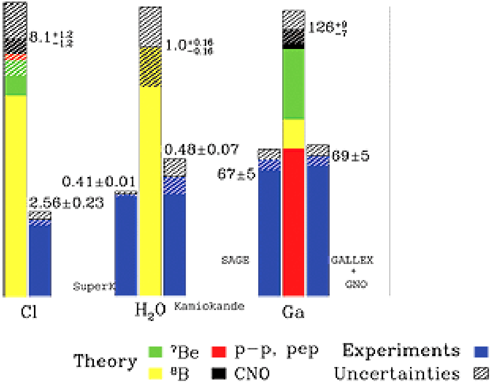
The solar neutrino problems

- Ray Davis experiment saw a deficit in solar neutrinos using chlorine.
- Kamiokande and SuperK experiments saw a deficit using water.
- SAGE and GALLEX/GNO experiments saw a deficit using gallium.



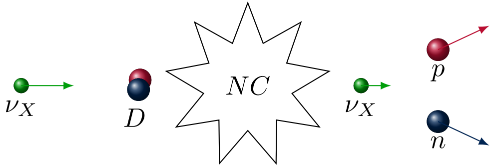
The solar neutrino problems

- Ray Davis experiment saw a deficit in solar neutrinos using chlorine.
- Kamiokande and SuperK experiments saw a deficit using water.
- SAGE and GALLEX/GNO experiments saw a deficit using gallium.
- After 30 years, people were starting to really worry about what is going on
- Herb Chen proposed an experiment using *Heavy Water* to test whether this was a theory or an experiment problem.

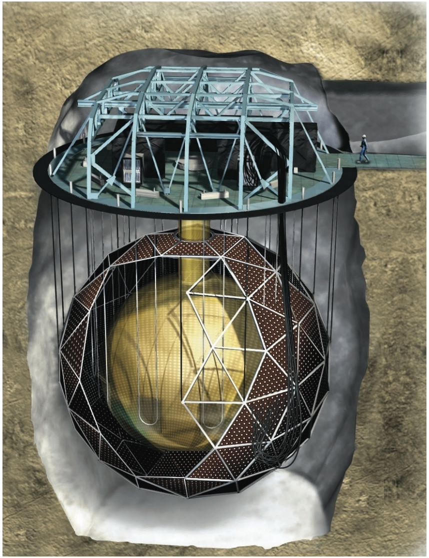


The Sudbury Neutrino Observatory

- 1000 tonnes of Heave Water $(\mathrm{D_2 0})$ in a 12 m diameter acryllic vessel.
- $10\,000$ PMTs supported by 18 m diameter support structure.
- Immersed in 7000 tonnes of ultra pure water, 2 km underground.
- Clever use of Heavy Water:

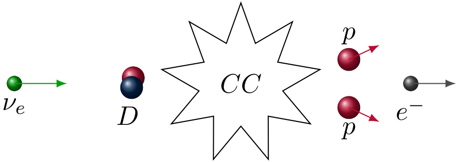


*Any flavour of neutrino can split up a deuterium nucleus through a neutral current reaction. The subsequent **neutron capture** forms the detectable signal.*

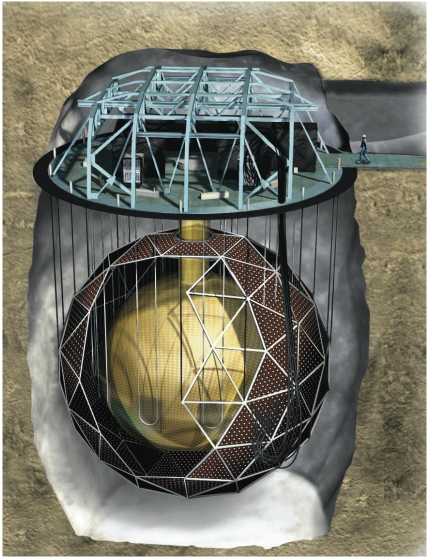


The Sudbury Neutrino Observatory

- 1000 tonnes of Heave Water $(D_2 0)$ in a 12 m diameter acryllic vessel.
- $10\,000$ PMTs supported by 18 m diameter support structure.
- Immersed in 7000 tonnes of ultra pure water, 2 km underground.
- Clever use of Heavy Water:

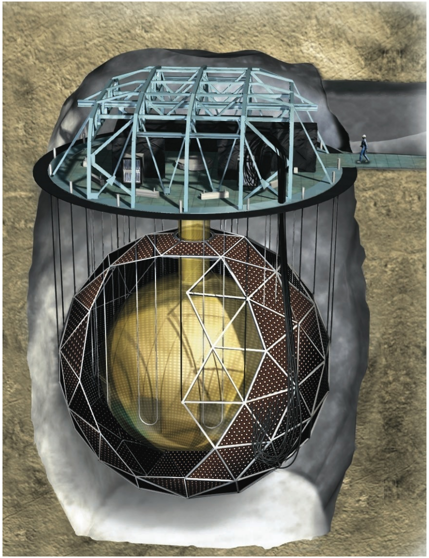


Only electron flavour neutrinos can interact through the charged current, converting the neutron into a proton and ***detectable electron****.*

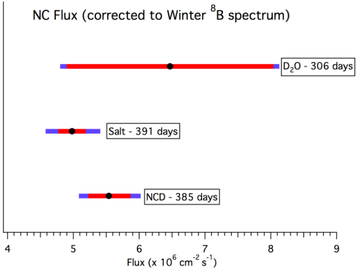


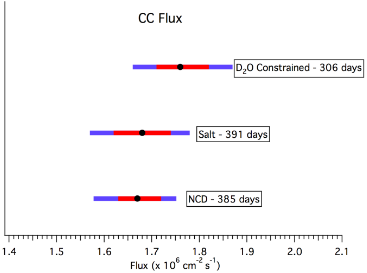
The Sudbury Neutrino Observatory

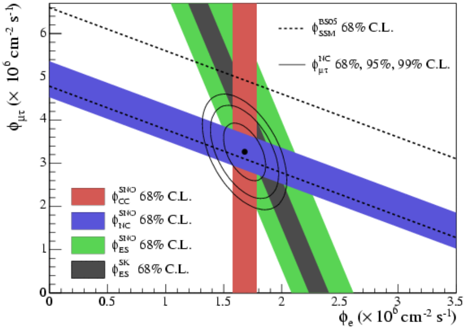
- 1000 tonnes of Heave Water $(D_2 0)$ in a 12 m diameter acryllic vessel.
- $10\,000$ PMTs supported by 18 m diameter support structure.
- Immersed in 7000 tonnes of ultra pure water, 2 km underground.
- Clever use of Heavy Water:
  - $\rightarrow$ The rates of CC (ν_e) and NC (ν_X) events in the detector independently measure the electron and total neutrino fluxes.



Results from SNO





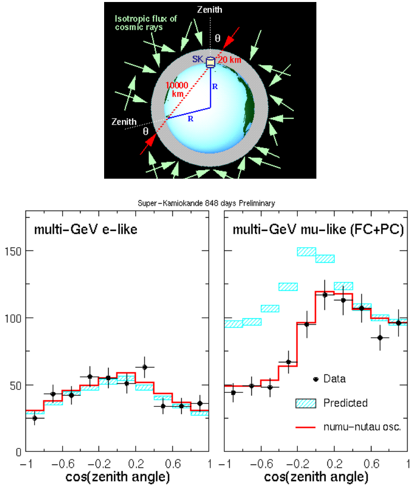


- 3 phases produced consistent results.
- CC measurements consistent with Ray Davis.
- NC measurements consistent with Bahcall prediction.
- They were both right! The issue is the neutrino!

Neutrino oscillations

Neutrinos change flavour

- The results from the SNO experiment show that neutrinos change flavour on their way from the Sun to the Earth.
  - → This solves the solar neutrino problem, since previous experiments were only sensitive to electron flavour neutrinos (through charged-current reactions).
- The SuperK experiment showed that the flavour composition of atmospheric neutrinos is dependent on the zenith angle, namely, the distance that they travelled.



The flavour composition of atmospheric neutrinos in SuperK depends on the zenith angle.

Neutrino oscillations

- Neutrinos exist in a quantum-mechanical superposition of flavour states until they are measured:

$$|\nu\rangle = A_e |\nu_e\rangle + A_\mu |\nu_\mu\rangle + A_\tau |\nu_\tau\rangle$$

- Solar neutrinos are well-modelled in a two-neutrino model (the third neutrino doesn't contribute much at these energies):

$$P_{\nu_e \to \nu_e} = 1 - \frac{1}{2}\sin^2(2\theta_{12})\left[1 - \cos\left(\frac{\Delta m^2_{21} L}{2c\hbar E}\right)\right]$$

- Atmospheric neutrinos are well-modelled by *a different set of two neutrinos*.

Schrödinger's cat is modelled as a superposition of alive and dead.

Neutrino oscillations

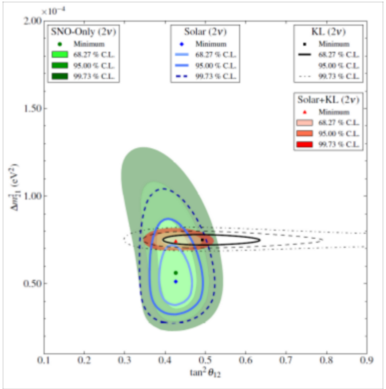
- Neutrinos exist in a quantum-mechanical superposition of flavour states until they are measured:

$$|\nu\rangle = A_e\,|\nu_e\rangle + A_\mu\,|\nu_\mu\rangle + A_\tau\,|\nu_\tau\rangle$$

- Solar neutrinos are well-modelled in a two-neutrino model (the third neutrino doesn't contribute much at these energies):

$$P_{\nu_e\to\nu_e} = 1 - \frac{1}{2}\sin^2(2\theta_{12})\left[1 - \cos\left(\frac{\Delta m^2_{21} L}{2c\hbar E}\right)\right]$$

- Atmospheric neutrinos are well-modelled by *a different set of two neutrinos*.



*SNO and KamLAND are sensitive to different oscillation parameters. PRC **88** 025501 (2011).*

Neutrino oscillations

- Neutrinos exist in a quantum-mechanical superposition of flavour states until they are measured:

$$|\nu\rangle = A_e |\nu_e\rangle + A_\mu |\nu_\mu\rangle + A_\tau |\nu_\tau\rangle$$

- Solar neutrinos are well-modelled in a two-neutrino model (the third neutrino doesn't contribute much at these energies):

$$P_{\nu_e \to \nu_e} = 1 - \frac{1}{2}\sin^2(2\theta_{12})\left[1 - \cos\left(\frac{\Delta m^2_{21} L}{2c\hbar E}\right)\right]$$

- Atmospheric neutrinos are well-modelled by *a different set of two neutrinos*.

Neutrino mixing. Neutrino oscillations arise because the eigenstates ($\nu_{1,2,3}$) of the Hamiltonian are "rotated" with respect to the flavour eigenstates ($\nu_{e,\mu,\tau}$) :

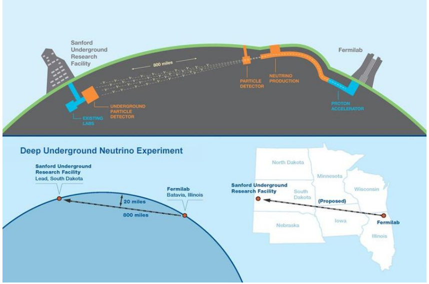
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Open questions and current experiments

Neutrinos - what we still don’t know

Well, neutrinos have mass, so the Standard Model is wrong! This leaves some open questions (aka opportunities to apply for funding):

1. What are the rest of the oscillation parameters?



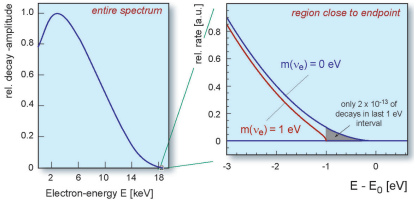
DUNE is a long-baseline precision neutrino oscillation experiment.

Neutrinos - what we still don't know

Well, neutrinos have mass, so the Standard Model is wrong! This leaves some open questions (aka opportunities to apply for funding):

1. What are the rest of the oscillation parameters?
2. What is the neutrino mass?

The spectrometer for the KATRIN experiment



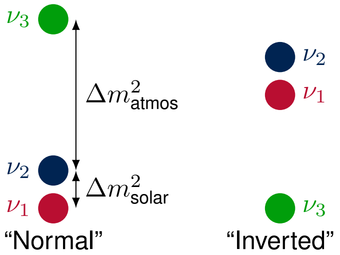
Neutrino mass is inferred from the maximum energy of the betas.

Neutrinos - what we still don't know

Well, neutrinos have mass, so the Standard Model is wrong! This leaves some open questions (aka opportunities to apply for funding):

1. What are the rest of the oscillation parameters?
2. What is the neutrino mass?
3. What is the neutrino mass hierarchy?

We do not know the "hierarchy" because we do not know the sign of the atmospheric neutrino mass difference:



Neutrinos - what we still don’t know

Well, neutrinos have mass, so the Standard Model is wrong! This leaves some open questions (aka opportunities to apply for funding):

1. What are the rest of the oscillation parameters?
2. What is the neutrino mass?
3. What is the neutrino mass hierarchy?
4. How to put neutrino mass into the Standard Model?

Do neutrinos acquire mass like the other particles?

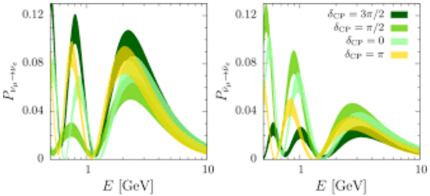
- Are they Dirac particles?
  - Mass through the Higgs?
  - Must exist right and left-handed neutrinos, but for some reason right-handed ones cannot interact???
- Are they Majorana particles?
  - So neutrinos are the same as antineutrinos?
  - Could help explain some things...

Neutrinos - what we still don't know

Well, neutrinos have mass, so the Standard Model is wrong! This leaves some open questions (aka opportunities to apply for funding):

1. What are the rest of the oscillation parameters?
2. What is the neutrino mass?
3. What is the neutrino mass hierarchy?
4. How to put neutrino mass into the Standard Model?
5. Do neutrinos violate CP?

Under CP (charge and parity) transformations, particles go to their antiparticles. Do neutrino oscillations look different from antineutrino oscillations?



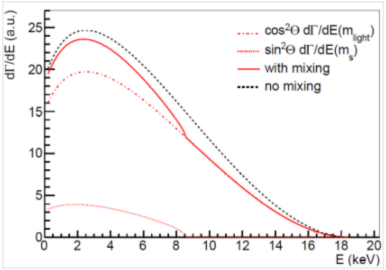
DUNE would see different oscillation between neutrinos (left) and antineutrinos (right).

Neutrinos - what we still don't know

Well, neutrinos have mass, so the Standard Model is wrong! This leaves some open questions (aka opportunities to apply for funding):

1. What are the rest of the oscillation parameters?
2. What is the neutrino mass?
3. What is the neutrino mass hierarchy?
4. How to put neutrino mass into the Standard Model?
5. Do neutrinos violate CP?
6. Are there additional types of neutrinos that don't interact through the Weak Interaction?

Experiments at reactors have suggested a third mass-squared difference, suggesting a fourth "sterile" neutrino. Measurements of the Z decay imply only 3 charged leptons.



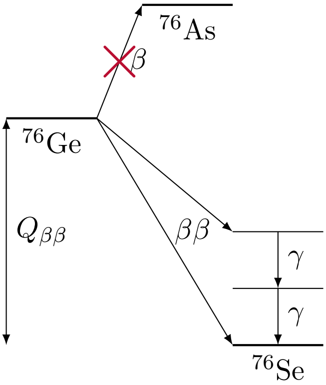
A sterile neutrino could have an impact on the energy spectrum of betas in the KATRIN experiment.

Neutrinoless double-beta decay

One experiment to answer all the questions!
(almost)

Neutrinoless double-beta decay

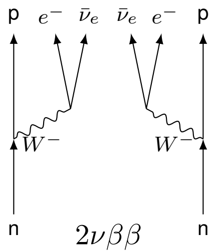
- Beta decay is forbidden in certain isotopes.



^{76}Ge cannot β-decay to ^{76}As because that nucleus has higher energy. Instead, two neutrons can simultaneously decay to two protons (double β-decay) leadinig to ^{76}Se. The difference in energy is $Q_{\beta\beta}$

Neutrinoless double-beta decay

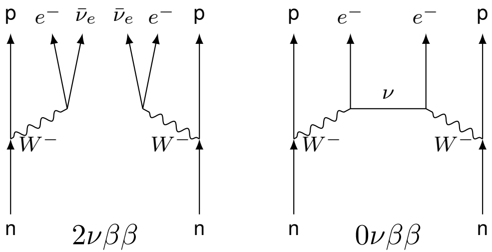
- Beta decay is forbidden in certain isotopes.
- Double beta decay is sometimes allowed and has been observed.



In $2\nu\beta\beta$-decay two neutrinos are emitted after two neutrons simultaneously decay to two protons and two electrons. The electrons share the available energy with the neutrinos.

Neutrinoless double-beta decay

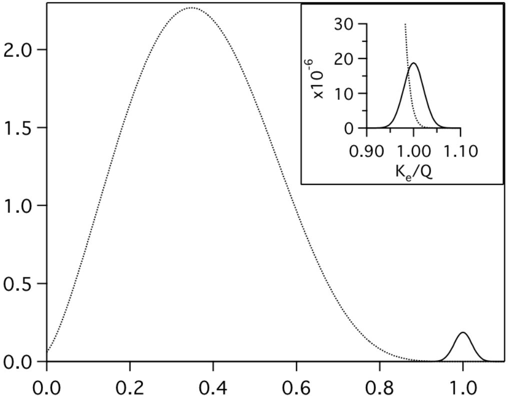
- Beta decay is forbidden in certain isotopes.
- Double beta decay is sometimes allowed and has been observed.
- If neutrinos are Majorana, a fraction of those decays may be "neutrinoless".



In $0\nu\beta\beta$*-decay no neutrinos are emitted and the total kinetic energy of the electrons is* $Q_{\beta\beta}$

Neutrinoless double-beta decay

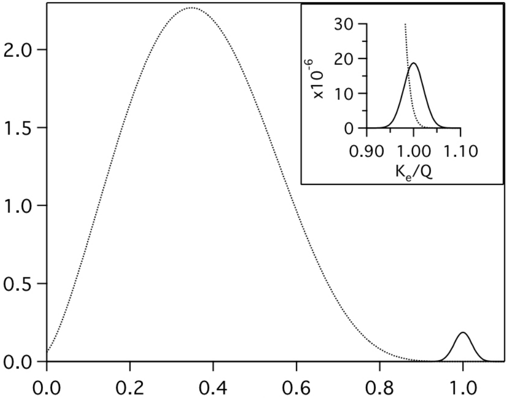
- Beta decay is forbidden in certain isotopes.
- Double beta decay is sometimes allowed and has been observed.
- If neutrinos are Majorana, a fraction of those decays may be “neutrinoless”.
- Experimental signature is a peak at the end of the energy spectrum of the emitted electrons.



Now, we expect a continuum of energies for the electrons emitted in the decay. If neutrinos are Majorana, we expect a peak at the end of the spectrum, at the Q value for the decay.

Neutrinoless double-beta decay

- Beta decay is forbidden in certain isotopes.
- Double beta decay is sometimes allowed and has been observed.
- If neutrinos are Majorana, a fraction of those decays may be "neutrinoless".
- Experimental signature is a peak at the end of the energy spectrum of the emitted electrons.
- This is the only practical way to test whether neutrinos are Majorana particles! It can also reveal their absolute mass!



Now, we expect a continuum of energies for the electrons emitted in the decay. If neutrinos are Majorana, we expect a peak at the end of the spectrum, at the Q value for the decay.

Experimental searches for $0\nu\beta\beta$

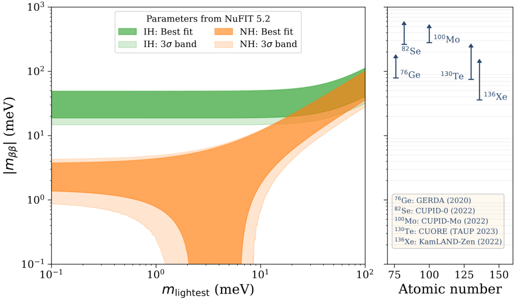
- The half-life for $0\nu\beta\beta$-decay would be:

$$T^{0\nu}_{1/2} = \left(G_{0\nu} |M_{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_\beta} \right)^2 \right)^{-1}$$

$$m_{\beta\beta} = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|$$

- Experimental sensitivity with exposusre Mt, background rate, B, energy resolution σ_E, isotopic abundance, a, and detect. efficiency ϵ:

$$T^{0\nu}_{1/2} \propto a\epsilon \sqrt{\frac{Mt}{\sigma_E B}}$$



Possible phase space for the mass of $0\nu\beta\beta$-decay, depends on the oscillation parameters and the mass hierarchy. *https://github.com/toej93/LobsterPlot*

A few $0\nu\beta\beta$-decay experiments

Name	Type	Location	Description
SNO+	$0\nu\beta\beta$	SNOLAB	$^{130}\mathrm{Te}$ dissolved in liquid scintillator
LEGEND	$0\nu\beta\beta$	LNGS (Italy)	Detectors enriched $^{76}\mathrm{Ge}$ deployed in LAr
nEXO	$0\nu\beta\beta$	SNOLAB (?)	Large TPC with xenon enriched in $^{136}\mathrm{Xe}$
CUPID/CUORE	$0\nu\beta\beta$	LNGS (Italy)	Scintillating bolometers with $^{130}\mathrm{Te}$, $^{82}\mathrm{Se}$

That's all for νow!

Thank you for listening!