Searching for Matter Creation

How the neutrino may help unlock the mystery of our existence

Jason Detwiler, University of Washington
Seattle Art Institute, April 19, 2018
Matter and Antimatter

Early Universe

For every 1,000,000,001 particles, there are 1,000,000,000 anti-particles.
Matter and Antimatter

Current Universe

“The Great Annihilation”
Recreating the Big Bang
Recreating the Big Bang
Recreating the Big Bang
Recreating the Big Bang

The universe
~0.00001 seconds
after the Big Bang

Temperature:
4,000,000,000,000 C
Recreating the Big Bang

The universe
~0.00001 seconds
after the Big Bang

Temperature:
4,000,000,000,000 C

Matter and antimatter are always created in pairs.
The Ubiquitous Neutrino

1 neutrino for every ~3 photons
All known forms of matter:

- Quarks
  - u, c, t, d, s, b
- Forces
  - Z, W, g, H
- Leptons
  - e, μ, τ, ν_e, ν_μ, ν_τ

+ Dark Matter
+ Dark Energy
All known forms of matter:

- Us
- Light
- Dark Matter
- Dark Energy
All known forms of matter:

- Quarks
  - Gives all particles mass
  - "Glues" quarks together

- Leptons

- Forces
  - Light
  - Cosmic Rays
  - + Dark Matter
  - + Dark Energy

- Cosmic Rays + Dark Matter + Dark Energy
All known forms of matter:

- Quarks: Gives all particles mass
- Forces: Light, "Glues" quarks together
- Leptons: Cosmic Rays
- Neutrinos
- Cosmic Rays
- Dark Matter
- Dark Energy
All known forms of matter:

- Us
- Quarks
- Leptons
- Forces
- Cosmic Rays
- Light
- "Glues" quarks together

Gives all particles mass

+ Dark Matter
+ Dark Energy
1 light year
(6 trillion miles)
Beta Decay

Bismuth

Meitner and Hahn, 1911
Beta Decay

Polonium

electron (beta ray)

Meitner and Hahn, 1911
Beta Decay

Polonium

? → electron (beta ray)

Meitner and Hahn, 1911
Beta Decay

Polonium

\( \nu \)

electron (beta ray)

Wolfgang Pauli, 1931
Beta Decay

Polonium → antimatter (electron (beta ray)) → matter

Wolfgang Pauli, 1931
Hydrogen Fusion

H + H → D + e+ + v
Hydrogen Fusion

\[ \text{H} + \text{H} \rightarrow \text{D} + \text{e}^+ \]

antimatter

\[ \nu \rightarrow \text{matter} \]
The Sun in Neutrinos

Actual size of sun:
~one pixel

Credit: Super-Kamiokande Collaboration
Super-Kamiokande

3,300 feet below Kamioka (Hida), Japan
50,000 tons of water, 11,000 light detectors

Credit: Super-Kamiokande Collaboration
The Sudbury Neutrino Observatory (SNO)

6,800 feet below Sudbury, Ontario, Canada
1,000 tons of heavy water, 10,000 light detectors

Credit: SNO Collaboration
KamLAND

Just down the hall from Super-Kamiokande
1,000 tons of mineral oil, 2,000 light detectors
KamLAND

Just down the hall from Super-Kamiokande
1,000 tons of mineral oil, 2,000 light detectors

J. Detwiler

Credit: KamLAND Collaboration
Neutrino Oscillation

$\nu_e$, part $\nu_e$, part $\nu_{\mu/\tau}$

$\nu_e$, part $\nu_{\mu/\tau}$

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Neutrino Oscillation

Requires neutrinos to have mass.
Neutrino Oscillation

Requires neutrinos to have mass.

Kajita (SuperK) 2016

MacDonald (SNO)
Ettore Majorana

There are several categories of scientists in the world; those of second or third rank do their best but never get very far. Then there is the first rank, those who make important discoveries, fundamental to scientific progress. But then there are the geniuses, like Galilei and Newton. Majorana was one of these.

— (Enrico Fermi about Majorana, Rome 1938)
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- “Discovered” the neutron
- Invented “Majorana Particles”
- Mysteriously disappeared in 1938
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Annihilation

positron → electron
Annihilation

positron → Y → electron

don't remember the exact symbol for positron.
Annihilation

\[
\begin{align*}
\text{positron} & \quad \rightarrow \quad \gamma \\
\text{electron} & \quad \rightarrow \quad \text{e}^+ \\
\bar{\nu} & \quad \rightarrow \quad \nu \\
\nu & \quad \rightarrow \quad \text{e}^- \\
\text{“Normal” (Dirac) neutrinos} &
\end{align*}
\]
Annihilation

\[ \gamma + \gamma \rightarrow e^+ + e^- \]

Positron: \( e^- \)\rightarrow \( e^+ \)

Electron: \( e^+ \rightarrow e^- \)

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

“Normal” (Dirac) neutrinos:

\[ \nu = \bar{\nu} \]

Majorana neutrinos:

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

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Direction of motion

neutrinos: left-handed

antineutrinos: right-handed
neutrinos: left-handed

antineutrinos: right-handed

Direction of motion

Direction of spin
Grand Unification

1 proton = 1 GeV
New particles are expected with masses $>10^{16}$ times as heavy as a proton. These particles would have been present in the universe when the temperature was $>10,000,000,000,000$ C.

1 proton = 1 GeV
Leptogenesis

“N”

Super-heavy version of the neutrino
A Majorana particle: $N = \bar{N}$
Leptogenesis

- left- or right-handed neutrinos

Higgs

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Leptogenesis

N decays violate Charge-Parity symmetry: decays to left-handed particles happens more often than decays to right-handed anti-particles
Leptogenesis

- N would have existed in copious amounts in the early universe
- The Higgs field causes the N to mix with neutrinos and confer its properties onto the neutrinos
- Predictions:
  - Neutrino oscillations will differ from antineutrino oscillations (CP violation)
  - Neutrinos would also be Majorana particles
Testing Neutrino CP Violation: DUNE

Beyond the scope of this talk.
Testing the Majorana Nature of the Neutrino

- Cross two beam of neutrinos and see if they annihilate each other
- Move faster than the neutrino to get it to spin the “wrong” way, and see if that particle generates any positrons
- Search for neutrinoless double-beta decay
Testing the Majorana Nature of the Neutrino

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Nuclear Beta Decay

Example: $^{76}\text{As} \rightarrow ^{76}\text{Se}$

Blue: neutrons
Red: protons
Nuclear Beta Decay

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Blue: neutrons
Red: protons
Nuclear Beta Decay

Possible because $^{76}\text{As}$ is 0.004% heavier than $^{76}\text{Se}$: $E = mc^2$

Half life: 1 day

Example: $^{76}\text{As} \rightarrow ^{76}\text{Se}$

Blue: neutrons
Red: protons

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Double Beta Decay

Example: $^{76}\text{Ge} \rightarrow ^{76}\text{Se}$

Blue: neutrons
Red: protons
Double Beta Decay

Example: $^{76}\text{Ge} \rightarrow ^{76}\text{Se}$

Blue: neutrons  
Red: protons
Double Beta Decay

Possible because \(^{76}\text{Ge}\) is 0.003% heavier than \(^{76}\text{Se}\) (but lighter than \(^{76}\text{As}\))

Half life: \(10^{21}\) years!

Example: \(^{76}\text{Ge} \rightarrow ^{76}\text{Se}\)

Blue: neutrons
Red: protons
Neutrinoless Double Beta Decay

Example: $^{76}\text{Ge} \rightarrow ^{76}\text{Se}$

Blue: neutrons
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Neutrinoless Double Beta Decay

Example: $^{76}\text{Ge} \rightarrow ^{76}\text{Se}$
Neutrinoless Double Beta Decay

Example: $^{76}\text{Ge} \rightarrow ^{76}\text{Se}$

Matter Creation!
Half life: $>10^{26}$ years

Blue: neutrons
Red: protons

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Germanium Detectors

- ~1 kg detector: a giant single crystal containing $\sim 10^{25}$ Ge nuclei
- A decay generates an electronic pulse
- The pulse size is proportional to the energies (speeds) of the two electrons
Germanium Detectors

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Germanium Detectors

- "Standard" double beta decay: the neutrinos carry away some of the energy.
- Neutrinoless double beta decay: no "missing" energy.
- Search for pulses with energy equal to \((M_{\text{Ge}} - M_{\text{Se}} - 2m_e)c^2\).
Challenges

• Need to eliminate all other sources of pulses with the same energy
• Need to measure the energy very well
• Need dozens of detectors (complex and pricey)
Hunting for Neutrinoless Double-Beta Decay

The MAJORANA Collaboration at the Homestake Mine

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Getting the Ge Detectors

\[ \text{nat}^\text{Ge} \rightarrow \text{nat}^\text{Ge}_4 \text{ gas} \rightarrow ^{76}\text{Ge}_4 \text{ gas} \rightarrow ^{76}\text{Ge}_2 \text{O}_2 \]

\[ ^{76}\text{Ge}_2 \text{O}_2 \rightarrow ^{76}\text{Ge}_\text{metal} \rightarrow \text{Single crystal } ^{76}\text{Ge} \]

Ultracentrifuge facility in Krasnoyarsk, Russia

Czochralski crystal growth method
Blocking Natural Radiation

Block cosmic rays: go 1 mile underground

Shield gamma radiation and use ultra pure materials

Credit: M. Kapust, SURF
Working 1 Mile Underground
Ultra-Clean Materials

Make the world’s cleanest copper 30x cleaner

Parts stored under nitrogen cover gas

Also: ultra-clean plastics, cables, connectors, electronics boards, vacuum seals, bolt thread coatings…
Building the Detector

PPC HPGe Detector  Low-Mass Mount  String  7-String Array  Cryostat  Shield

Photos by James Leach & Matt Kapust

Micah Buuck  Ian Guinn  Julieta Gruiszko  Clara Cuesta
First Results

Search for Neutrinoless Double-$\beta$ Decay in $^{76}$Ge with the MAJORANA DEMONSTRATOR

C. E. Aalseth et al. (Majorana Collaboration)
Phys. Rev. Lett. 120, 132502 – Published 26 March 2018

See Viewpoint: The Hunt for No Neutrinos
First Results

Counts/(5 keV)/kg/yr

Energy (keV)

NDBD here

Counts/(5 keV kg yr)

All Cuts
90% C.L Limit

MAJORANA-1710.03C

Q_\beta\beta

data cleaning + \mu veto
All cuts
First Results

Counts/(5 keV)/kg/yr

NDBD here

record low BG

record resolution

Energy (keV)

Counts/(3 keV kg yr)

Qββ

All Cuts

90% C.L Limit

- data cleaning + μ veto
- All cuts

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Future Plans

- Join forces with a similar experiment in Europe
- Use hundreds of detectors
- Test ~50-75%* of theoretical predictions

* somewhat subjective
Summary

- Leading theories explaining the matter asymmetry of the universe predict that neutrinos are Majorana particles.

- The only known method of testing the Majorana nature of the neutrino is searches for neutrinoless double-beta decay.

- A massive international campaign is underway to search for this novel process. Discovery could come at any time!