Towards Revealing the Unique Nature of Neutrino Mass Using Precision Detection of Photons

Andrey Elagin
University of Chicago
Purpose of This Talk
Discuss the importance of fast timing and suggest the next steps in the development of affordable Large-Area Picosecond Photodetectors (LAPPD)

Important remarks:
• There are other fast timing technologies
• A lot of what I will be talking about applies there (e.g. SiPMs)

Fast timing is needed at colliders, fixed target, and neutrino experiments

• Assign tracks to vertices
• Separate overlapping tracks
• Particle ID by TOF
• Heavy particles, displaced vertices

• Vertex reconstruction
• 3D tracking
These techniques have been developed at CDF without using fast timing, but Kaon identification by TOF could have further improved energy resolution of hadronic taus.
Neutrino Properties

Stroboscopic approach

PRD 100 (2019) 3, 032008
E. Angelico, J. Eisch, A. Elagin, H. Frisch, S. Nagaitsev, M. Wetstein

- Lower energy neutrinos arrive later
- Time slicing of neutrino events relative to the time of their parent bunch time allows for selecting different neutrino energy spectra and flavor content
- Could be complementary to NuPrism
Outline

• How precision photon measurements can be used to discover neutrino-less double-beta decay

• How LAPPD can become affordable for large-scale experiments

An example of a large-scale experiment
Surface area of the JUNO detector sphere is \( \sim 980 \, m^2 \)

picture credit: the JUNO collaboration
Is the Neutrino Its Own Antiparticle?

• It is possible because the neutrino has no electric charge
• It is intriguing question because no other fermion can be its own antiparticle

It is not only possible, but may be necessary to explain
- the origin of matter-antimatter asymmetry in the universe
- why the neutrino mass is so tiny?

plot credit: Hitoshi Murayama
(taken from Forbes 07/14/2020)

Search for neutrino-less double beta decay ($\nu\beta\beta$-decay) is the most feasible way to answer this question
Double Beta Decay

Total energy of two electrons

Nuclear Process

Nucleus Z | Nucleus Z+2

Rare processes

Maria Goeppert-Mayer

Wendell Furry
Neutrinoless Decay Is Unique

Only possible if neutrino is its own antiparticle

\[ n \rightarrow p + e^-_L + \bar{v}_R \]

\[ \nu_L + n \rightarrow p + e^-_L \]

Need helicity flip!
It may reveal the nature of neutrino mass

If neutrino is Majorana then \( \nu_R \) is just a CP-conjugate of \( \nu_L \), i.e. \( \nu_L^C = \nu_R \)

Therefore \( 0\nu\beta\beta \)-decay requires a mechanism for \( \nu_L^C \leftrightarrow \nu_L \) transition

Need coupling between \( \nu_L \) and \( \nu_L^C \)

Such coupling can be effectively introduced into SM Lagrangian via “See-Saw” mechanism
Electron mass term in the Standard Model Lagrangian

\[ m_e e_L e_R \]
(Example of a Dirac mass term)

**See-Saw Mechanism**

Possible extension of the SM Lagrangian to introduce neutrino mass

\[
\begin{pmatrix}
\bar{\nu}_l, \bar{N}_R^c
\end{pmatrix}
\begin{pmatrix}
0 & m_D \\
\begin{pmatrix} m_D^T & M_{RR}^T \end{pmatrix}
\end{pmatrix}
\begin{pmatrix}
\nu_L^c \\
N_R
\end{pmatrix}
\]

In the limit \( M_{RR} \gg m_D \) the eigenvalues are

\[ m_D^2/M_{RR} \] (light neutrino)
\[ M_{RR} \] (heavy neutrino)

This is not the only option
There are other mechanisms leading to 0\(\nu\beta\beta\)-decay

"Effectively" in the limit \( M_{RR} \gg m_D \)

This is exactly what's needed for 0\(\nu\beta\beta\)-decay
How to Find $0\nu\beta\beta$-decay?

Step 1: Choose an isotope where $0\nu\beta\beta$-decay is allowed

Step 2: Wait for emission of two electrons with the right total energy

**Challenges:**
1. Rare process
2. $2\nu\beta\beta$-background
3. Natural radioactivity

**Solutions:**
1. Very large detector mass
2. Good energy resolution
3. Purification and shielding

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<th>Isotope</th>
<th>Q-Value</th>
<th>Abundance (%)</th>
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<tr>
<td>Ca 48</td>
<td>4.271</td>
<td>0.187</td>
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<tr>
<td>Ge 76</td>
<td>2.039</td>
<td>7.8</td>
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<tr>
<td>Se 82</td>
<td>2.995</td>
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<td>Pd 110</td>
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<td>Cd 116</td>
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<td>Te 130</td>
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<tr>
<td>Xe 136</td>
<td>2.479</td>
<td>8.9</td>
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<tr>
<td>Nd 150</td>
<td>3.367</td>
<td>5.6</td>
</tr>
</tbody>
</table>

$^{130}$Te-loaded multi-kiloton liquid scintillator detector may become the only viable option for discovery

[See S.Biller, PRD87 (2013) 071301]
New Challenge for a Large Detector

Electron scattering of neutrinos coming from $^{8}\text{B}$-decays in the sun

$^{8}\text{B}$ can become dominant “irreducible” background without event topology reconstruction
Example of Background Budget

Is it possible to separate two-track and one-track events?

Q^{(^{130}\text{Te})} = 2.53 \text{ MeV}

The largest background in the ROI is coming from $^8\text{B}$ solar neutrinos.

It has only 1 electron, while $0\nu\beta\beta$-decay has 2 electrons.
Double-Beta Decay Kinematics

Angle ($\cos(\theta)$) between two electrons

- Lots of “back-to-back” (large angle) events
- Most of electrons are above Cherenkov threshold

Event generator based on phase factors from J. Kotila
PRC 85 (2012) 034316

Cherenkov threshold
A detailed Geant4 simulation was built to study how to separate directional Cherenkov light from abundant isotropic scintillation.
Normalized Che/Sci Spectra

An example of a scintillator model similar to KamLAND

Spectral threshold sorting for che/sci separation is also being investigated.
See T. Kaptanoglu et al PRD 101 (2020) 7, 072002

The focus of this talk is on timing

Many groups are exploring various aspects of che/sci separation

E.g. see also
PRC95 (2017) 055801
NIMA 830 (2016) 303

There is more
It's a hot field!

Scintillation emission is slower
Longer (red) wavelengths travel faster

370 nm → 0.191 m/ns
600 nm → 0.203 m/ns
~2 ns difference over 6.5m distance
Cherenkov Light Comes First

Distribution of photon arrival times

(central events, $R_{\text{detector}} = 6.5$ m, TTS($\sigma$) = 100 ps)

Cherenkov light arrives earlier

$\tau_r = 1$ ns
$\tau_{d1} = 6.9$ ns
$\tau_{d2} = 8.8$ ns
Dilute scintillators for large-volume tracking detectors

R.A. Reeder, B.D. Dieterle, C. Gregory, F. Schaefer and K. Schum
University of New Mexico, Albuquerque, NM 87131, USA
W. Strossman
University of California, Riverside, CA 92521, USA
D. Smith
Embry-Riddle Aeronautical University, Prescott, AZ 86301, USA
Los Alamos National Laboratory, Los Alamos, NM 87545, USA
M. Albert and K. Yaman
University of Pennsylvania, Philadelphia, PA 19104, USA
C. Athanassopoulos, L.B. Auerbach, P. Hermida and D. Works
Temple University, Philadelphia, PA 19122, USA

Received 2 April 1993

Dilute scintillation mixtures emit isotropic light for both fast and slow particles, but retain the Cherenkov light cone from fast particles. Large volume detectors using photomultipliers to reconstruct relativistic tracks will also be sensitive to slow particles if they are filled with these mixtures. Our data show that 0.03 g/l of b-PBD in mineral oil has a 2.4:1 ratio (in the first 12 ns) of isotropic light to Cherenkov light for positron tracks. The light attenuation length is greater than 15 m for wavelength above 400 nm, and the scintillation decay time is about 2 ns for the fast component. There is also a slow isotropic light component that is larger (relative to the fast component) for protons than for electrons. This effect allows particle identification by a technique similar to pulse shape discrimination. These features will be utilized in LSND, a neutrino detector at LAMPF.

LSND did separation of Cherenkov and scintillation light in a diluted scintillator

Che:Sci = 2.4:1
Cherenkov/Scintillation Separation

Simulation of a KamLAND-like detector non-diluted high light-yield scintillator

Photon arrival times for events originated at the center of the detector

Cherenkov

Scintillation

2014 JINST 9 P06012
Event Topology

Idealized event displays
• no multiple scattering of electrons
• QE=30%
• no time cut on PE arrival time

Tagging Cherenkov photons would clearly separate signal and background

Potential markers to tag Cherenkov photons
1) Timing
2) Spectral sorting
3) Polarization
Early Light Topology

Realistic event displays
- full Geant4 simulation
- QE: Che~12%, Sci~23% (modeled after KamLAND PMTs)
- early PEs only (first 2.5ns)

Timing alone allows for getting a sample of PEs with high enough fraction of Cherenkov light to apply various pattern recognition algorithms to separate signal from background
Pattern Recognition Problem

Single-track background (one $^8$B event)

Two-track signal (one $0\nu\beta\beta$-decay event)

There are plenty ideas on how to “see” $0\nu\beta\beta$-decay in liquid scintillator via prompt directional Cherenkov light

Efforts by me and my collaborators:
JINST 9 (2014) P06012
NIMA 849 (2017) 102-111
JINST 14 (2019) 02, P02005
NIMA 947 (2019), 162604
arXiv:1902.06912 (submitted to NIMA)

See Eur.Phys.J.C 80 (2020) 5, 416 for a complete overview of all recent efforts
Which Pattern Recognition Works Best?

$0\nu\beta\beta$-decay vs $^8$B classification

When the vertex location is explicitly reconstructed separately, all neural networks (CNNs, PCA, Fully Connected, Locally Connected, and LSTM) have similar performance. Actual AUC depends on photo-coverage, QE, and vertex resolution.

LSTMs work well without vertex reconstruction

Thank you to I. Vukotic and E. Toropov for introducing me to all these ML acronyms.
Don’t Forget Directionality

$^8$B neutrinos are coming from the Sun

Dot product of reconstructed and true direction of an electron

A. Elagin, R. Jiang
arXiv:1902.06912

- Combined signal-background separation based on both topological and directionality reconstruction is subject of ongoing studies
- A lot depends on actual detector parameters (scintillator properties, quantum efficiency, photo-coverage, total fiducial volume, etc)

The goal of suppressing 50% of $^8$B background at 75% signal efficiency is within the reach
How Good the Timing Should Be?

A. Elagin, R. Jiang submitted to NIM

Event topology reconstruction (based on spherical harmonics)

Directionality reconstruction

Classifier output for TTS = 100 ps

Classifier output for TTS = 1.0ns

100 ps is close to optimal for a KamLAND-like detector
Photo-Detector Candidates

1) Regular PMTs
   Large area, but slow...

   [Image of a large area detector with a diameter of 17-20 inches]
   photo credit: http://kamland.stanford.edu

2) MCP-PMTs
   Fast, but small...and not really available in quantities required to cover large areas

   [Image of a small detector with a width of 5 cm]
   photo credit: E.Oberla PhD thesis
Large-Area Picosecond Photo-Detector

Atomic Layer Deposition (ALD)
- J. Elam and A. Mane at Argonne (process is now licensed to Incom Inc.)
- Arradiance Inc. (independently)

LAPPD™

Porous glass
Resistive coating ~100nm (ALD)
Emissive coating ~ 20nm (ALD)
Conductive coating (thermal evaporation)

Material: borofloat glass
Area: 8x8" 
Thickness: 1.2mm
Pore size: 20 μm
Open area: 60-74%

LAPPD™ is being commercialized by Incom Inc.
There are two very distinct scenarios to define Transit Time Spread (TTS):

1) Single Photo-Electron (SPE TTS)
- applications with a low number of photons per surface area (e.g. neutrino experiments)
- 50 ps has been demonstrated
- can be improved with smaller pores size

2) Multi Photo-Electrons (MPE TTS)
- applications with lots of light (e.g. Cherenkov light from charged particle on the front window)
- effort is ongoing to measure MPE TTS

Oshima et al demonstrated ~5 ps MPE TTS for MCP-PMTs

Anatoly Ronzhin and Caltech team got ~7 ps at the Testbeam at Fermilab
Vacuum Transfer

LAPPDs are now routinely produced using this process at Incom Inc

Industry standard vacuum transfer process

- Photocathode is synthesized in a separate volume of the assembly chamber
- The window is transferred in ultra-high vacuum to be hermetically sealed over the pre-assembled MCP-Anode stack-up ("tile")
Can We Make LAPPDs in Batches Like PMTs?

Chicago group has been exploring if a process without vacuum transfer can be inexpensive and easier to scale for a very high volume production.
Air-Transfer

Transfer the window with a pre-deposited Sb precursor in air to synthesize photocathode after hermetic package is formed.
Air-Transfer Processing Chamber

Dual vacuum system
Heaters are around the tile, not around the vacuum vessel
After Bakeout and Hermetic Seal

Ultra-sensitive (~10\(^{-12}\) cc/s of He) check for leaks can be done at this step.

Indium seal line (The most tricky part. A lot of effort has gone into development of a robust hermetic packaging.)

Buttons appear gray/white color (view through a window with a thin Sb layer)
Photocathode Synthesis

In-situ photocathode synthesis with full access to the detector

Note reddish color of the buttons appearance (view through a window with Cs-Sb layer)
Chemistry of photocathode synthesis using Sb in equilibrium with Cs is well known

Making photocathode after Sb exposure to air is a well established industry process
• MELZ-FEU Ltd., Zelenograd, Russia, catalog item FEU-527
• Hamamatsu [NIMA 970 (2020) 163373]
Material Characterization

XPS

Signal of oxidized Sb going down, Sb metal is growing.

SEM and EDS

Sealing surface after 400°C bake.

(X-ray) optical microscope

Turning (very) good recipes into well understood processes.

X-ray showing continuity and quality of indium in capillary seal.

Inside vacuum

Atmosphere
This was not a competition with industry

- The entire time we worked closely with our industry partners from Incom Inc.
- We took a risky R&D path while Incom were focusing on another difficult and very important task - making LAPPDs available by scaling up the vacuum-transfer process to an unprecedented 8x8" format.
Towards Batch Production

Two processing chambers for the air-transfer LAPPD at the UChicago PSEC Lab

• I believe that as a small team at a university settings we have gone as far as we could
• Feasibility of using air-transfer for LAPPD production has been demonstrated
• Optimization is still to be done, but
• There are no showstoppers

UC Team:
Evan Angelico, Henry Frisch, Eric Spieglan, and AE behind the camera
(only 75% of the group can be on the same photo)
Proposal

• I would like to bring the UC processing chamber to Fermilab
• Optimize process for single tile production
• Build an 18-tiles production table
• Transfer the technology to industry so that we can focus on how to use LAPPDs for new discoveries

We have a plan
• A detailed proposal is written
• There are several related patents

It’s not a substitute for industry development, it’s building a bridge
How Large the Effort Would Be?

People

- 1 Engineer (~75% FTE)
- 2 Experienced Techs (full time)
- 1 Postdoc (mostly TestBeam and LAPPD applications)
- 1 Junior Tech (part time, mostly to help with Testbeam)

Equipment

- For a 3-year period, MCPs would be about half of the total price tag for the hardware
- The other half is a typical cost of building a mid-size vacuum system

Important clarifications

- It’s a project with an end day in about 3 years
- That’s the time for the bridge
- The 18-tile production table is just a prototype for industry to pick up and scale-up further
- The goal is to enable an industrial yield of up to 100 LAPPDs/week
- The goal is NOT to turn Fermilab into an LAPPD factory
Why at Fermilab?

MCP electroding at Fermilab - the week of Sep 24 2013

Eileen Hahn, P. Murat

Over 70 large-size 8x8” MCP were electroded by Eileen Hahn, thank you!

Fermilab has already played a major role in LAPPD development

(many thanks to Pasha Murat and Erik Ramberg)
Fermilab has the necessary infrastructure that we are already using
(many thanks to Petra Merkel, Luciano Ristori, Rick Ford)
Why at Fermilab?

**ANNIE**

Currently can use up to 32 LAPPDs, Phase III ANNIE can use up to 200 LAPPDs

Commercial LAPPDs by Incom Inc.

Testbeam

Fermilab already has the largest number of LAPPDs on site

Potential candidate for IOTA run at 150 MeV
Performance summary

- Gain: mid-10⁶ and above
- Dark rate: 10³/cm² (in the mid-10⁶ gain range)
- TTS: ~55 ps or better
- QE: 20-30% @ 365 nm

Availability status

- Established reproducible process
- Present capacity 4 LAPPDs/month
- Plan 6 LAPPDs/month by late 2020
- LAPPDs are available for rent or purchase
- Qualified prospects that don’t presently have a budget or the ability to either rent or purchase an LAPPD may qualify for special negotiated terms.

Particle physics community needs high production yield of LAPPDs (50+/week)

Working closely with Incom on batch production is important
Enable users to:
• Identify particles in the beam
• Measure how their detector respond to different flavors (e.g. calorimeter response to K and pi)
• Reject unwanted particles from their data analysis sample
A commercially available clock synchronization system (White Rabbit) has been identified and is being implemented at FTBF.
TOF Particle ID at FTBF

Particle ID sensitivity between 14-19 ps time-of-flight resolution

- 7.2 GeV
- 5.9 GeV
- 2.4 GeV
- 3.4 GeV
- 8.2 GeV
- 11.6 GeV
- 19.5 GeV
- 20.0 GeV
- 24.5 GeV
- 33.7 GeV
- 41.3 GeV

- Detector separation, examples in red (m)

- Maximum particle momentum for 1σ identification (GeV)

- Pion/Kaon
- Proton/Kaon
- Pion/Electron
# A 3 Year Plan for FTBF

<table>
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<tr>
<th></th>
<th>$\sigma_L / \sqrt{N_{pe}}$</th>
<th>$\sigma_{\text{pulse}}$</th>
<th>$\sigma_{\text{WR}}$</th>
<th>$\sigma_{\text{tof}}$</th>
<th>Maximum $\pi/K$ momentum at 5 m / 45 m</th>
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<tr>
<td>Present installation</td>
<td>55 ps / $\sqrt{30}$</td>
<td>7 ps</td>
<td>5 ps</td>
<td>19 ps</td>
<td>7.0 / 21 GeV/c</td>
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<td>7 ps</td>
<td>5 ps</td>
<td>14 ps</td>
<td>8.2 / 25 GeV/c</td>
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<td>Low-jitter WR-ZEN</td>
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<td>7 ps</td>
<td>&lt; 0.5 ps</td>
<td>13 ps</td>
<td>8.5 / 25 GeV/c</td>
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<td>10 $\mu$m pores and higher cathode voltages</td>
<td>10 ps / $\sqrt{200}$</td>
<td>7 ps</td>
<td>&lt; 0.5 ps</td>
<td>11 ps</td>
<td>9.2 / 28 GeV/c</td>
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<td>PSEC4 chip development</td>
<td>10 ps / $\sqrt{200}$</td>
<td>1 ps</td>
<td>&lt; 0.5 ps</td>
<td>1.7 ps</td>
<td>24 / 70 GeV/c</td>
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ANNIE

Accelerator Neutrino Neutron Interaction Experiment

- Fermilab is already leading the field in the development of the next-generation water-based neutrino detector as the home of the ANNIE experiment
- International collaboration with 12 institutions from 3 countries:
  - 🇺🇸 🇩🇪 🇬🇧
- Fermilab approved and deployed on the Booster Neutrino Beam (former SciBooNE Hall)

New technologies
- First application of LAPPDs in a neutrino detector
- First Gd-loaded water on a neutrino beam and only Gd-loaded near detector.
- Likely first deployment of WbLS

New reconstruction capabilities
- Demonstration of Ch/Sc separation using LAPPDs in a neutrino detector
- Able to efficiently count final-state neutrons
- Able to resolve energy from sub-Cherenkov particles

New physics opportunities
- Ability to measure neutrino-Oxygen cross-sections with unprecedented statistics and detail
- Particular attention to neutron yields of neutrino-Oxygen scatters

The material for this slide is courtesy of Matt Wetstein

Built, commissioned, and ready for beam data in November
Longer Time Scale Plan for the Field

Large Directional Liquid Scintillator

• Large scintillator detectors and large water-Cherenkov detectors have been very effective in measuring neutrino properties.

• Combining the two technologies may allow expanded physics reach of the next generation large neutrino experiments:
  - Cherenkov light provides directionality
  - Scintillation light provides good energy measurements

• Physics Program of THEIA:
  - Neutrinoless double beta decay
  - Solar neutrinos
  - Geo-neutrinos
  - Supernova burst neutrinos & DSNB
  - Nucleon decay
  - Long-baseline physics (mass hierarchy, CP-violation)
  - Unexpected surprises

Currently there are several smaller scale experiments that can develop components and test ideas for such hybrid detector

Besides ANNIE there is CHESS, NuDot, Watchman, and more
0νββ-decay Sensitivity

Assuming 50% rejection of \(^8\)B at 75% signal efficiency.

10 years of running with a 7 m radius fiducial volume loaded with either 5% of natural Te or 3% of enriched Xe.

\[ 3 \sigma \text{ discovery sensitivity on } m_{\beta\beta} \text{ [eV]} \]

Legend:
- CUPID
- SNO+II
- PandaX-III-1000
- KamLAND-2-Zen
- NEXT-HD
- nEXO
- Thelia-Xe
- Thelia-Te
Mid-Term Opportunities at Fermilab

Stroboscopic approach

TOF Particle ID System at FTBF

Single photon detection experiments at IOTA
Take Away Messages

Dirac/Majorana nature of the neutrino is a fundamental question

A very large liquid scintillator surrounded by LAPPDs has a good chance of answering that question

High volume production of LAPPDs requires a bridge between industry’s yield at the present and the future demand of particle physics

There are many other opportunities for fast timing at Fermilab

These opportunities are not limited to LAPPDs
Acknowledgments

- We are thankful for the support from the DOE Office of Science (Helmut Marsiske, Michelle Shinn)
- We also acknowledge support from the Physical Sciences Division at the University of Chicago
- We are grateful for the help from our staff at UC
- Many thanks to the team at Incom Inc
- We value crucial contributions from SSL Berkeley, Argonne, and Fermilab

A very large number of people contributed to the work presented today. I thank them all.
Thank You
Back-ups
Experimental Status of $0\nu\beta\beta$-decay

- EXO ($\sim$200 kg $^{136}$Xe)
- KamLAND-Zen ($\sim$300 kg $^{136}$Xe, before Summer 2016)
- GERDA ($\sim$20 kg $^{76}$Ge)

Projections by
- CUORE ($\sim$200 kg $^{130}$Te)
- SNO+ (0.8 ton $^{130}$Te)
- SNO+ (8 ton $^{130}$Te)

Current best limit is set by KamLAND-Zen:
$T_{1/2} > 1.07 \times 10^{26}$ years
$m_{\beta\beta} < 61$-$165$ meV

$|m_{\beta\beta}| = |\cos^2 \theta_{12} \cos^2 \theta_{13} m_1 + e^{2i\alpha_{12}} \sin^2 \theta_{12} \cos^2 \theta_{13} m_2 + e^{2i\alpha_{12}} \sin^2 \theta_{13} m_3|$

$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i}$
Double-Beta Disintegration

Maria Goeppert-Mayer

\[(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\nu_e\]

SEPTEMBER 15, 1935

PHYSICAL REVIEW

VOLUME

Double Beta-Disintegration

M. Goeppert-Mayer, The Johns Hopkins University

(Received May 20, 1935)

From the Fermi theory of \(\beta\)-disintegration the probability of simultaneous emission of two electrons (and two neutrinos) has been calculated. The result is that this process occurs sufficiently rarely to allow a half-life of over \(10^{17}\) years for a nucleus, even if its isobar of atomic number different by 2 were more stable by 20 times the electron mass.

The author wishes to express her gratitude to Professor E. Wigner for suggesting this problem, and for the interest taken in it.
On Transition Probabilities in Double Beta-Disintegration

W. H. Furry

Physics Research Laboratory, Harvard University, Cambridge, Massachusetts

(Received October 16, 1939)

The phenomenon of double $\beta$-disintegration is one for which there is a marked difference between the results of Majorana's symmetrical theory of the neutrino and those of the original Dirac-Fermi theory. In the older theory double $\beta$-disintegration involves the emission of four particles, two electrons (or positrons) and two antineutrinos (or neutrinos), and the probability of disintegration is extremely small. In the Majorana theory only two particles—the electrons or positrons—have to be emitted, and the transition probability is much larger. Approximate values of this probability are calculated on the Majorana theory for the various Fermi and Konopinski-Uhlenbeck expressions for the interaction energy. The selection rules are derived, and are found in all cases to allow transitions with $\Delta i = \pm 1,0$. The results obtained with the Majorana theory indicate that it is not at all certain that double $\beta$-disintegration can never be observed. Indeed, if in this theory the interaction expression were of Konopinski-Uhlenbeck type this process would be quite likely to have a bearing on the abundances of isotopes and on the occurrence of observed long-lived radioactivities. If it is of Fermi type this could be so only if the mass difference were fairly large ($\epsilon \gtrsim 20, \Delta M \gtrsim 0.01$ unit).

Proposed $(A,Z) \rightarrow (A,Z+2) + 2e^-$ via virtual neutrino exchange

Quite optimistic experimentally:

- $0\nu\beta\beta$-decay is a factor of $10^6$ more favorable than $2\nu\beta\beta$-decay due to the phase factor advantage
- $V-A$ structure of weak interactions is not known yet
Neutrinoless double-$\beta$ decay in SU(2)×U(1) theories

J. Schechter and J. W. F. Valle

Department of Physics, Syracuse University, Syracuse, New York 13210
(Received 14 December 1981)

It is shown that gauge theories give contributions to neutrinoless double-$\beta$ decay $\langle (\beta\beta)_{0w} \rangle$ which are not covered by the standard parametrizations. While probably small, their existence raises the question of whether the observation of $\langle (\beta\beta)_{0w} \rangle$ implies the existence of a Majorana mass term for the neutrino. For a "natural" gauge theory we argue that this is indeed the case.

FIG. 2. Diagram showing how any neutrinoless double-$\beta$ decay process induces a $\nu_e$-to-$\nu_e$ transition, that is, an effective Majorana mass term.
Light yield: Cherenkov vs scintillation

\[ \frac{1}{2} Q (^{116}\text{Cd}) = 1.4 \text{ MeV} \]

\[ \frac{1}{2} Q (^{48}\text{Ca}) = 2.1 \text{ MeV} \]
Backgrounds in Liquid Scintillators

Q-value of most interesting $0\nu\beta\beta$-decay isotopes is 2-3 MeV
A lot is going on in the MeV range. Let’s consider two (major) backgrounds.

1) Electron scattering of neutrinos coming from $^8\text{B}$-decays in the sun

Key background for the SNO+ experiment

$\nu \rightarrow e^- + e^- + \text{one-track event}$

2) $^{10}\text{C}$ decays produced by cosmic muon spallation

Key background for the KamLAND-Zen experiment

$^{10}\text{B}^* \rightarrow ^{10}\text{B} + \gamma(\gamma)$

multi-track multi-vertex event
Early Light Topology

Realistic event displays: early PEs only, KamLAND PMTs QE: Che~12%, Sci~23%

Spherical harmonics analysis

\[ f(\theta, \varphi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} f_{\ell m} Y_{\ell m}(\theta, \varphi). \]

Rotation invariant power spectrum

\[ S_{ff}(\ell) = \sum_{m=-\ell}^{\ell} |f_{\ell m}|^2. \]

Runyu Jiang and AE have updated this technique

See arXiv:1902.06912
Timing of $0\nu\beta\beta$-decay vs $^{10}\text{C}$

$^{10}\text{C} \xrightarrow{\text{Multi-track-vertex topology}}$ leads to different timing distribution

$^{10}\text{B}^* \rightarrow ^{10}\text{B} + \gamma(\gamma)$

$e^{+}$ (via annihilation) $\gamma \gamma$

~3ns delay from ortho-positronium is not included (~50% of $^{10}\text{C}$ have even longer delay)

arXiv:1812.02906
A.Li, A.Elgin, S.Fraker, C.Grant, L.Winslow
PE Spatial Distribution: $^{10}\text{C}$ vs $0\nu\beta\beta$

CNN input: theta x phi x time = 25 x 50 x 34

arXiv:1812.02906
A.Li, A.Elagin, S.Fraker, C.Grant, L.Winslow
CNN for $^{10}$C Suppression at KamLAND-Zen

Bkg rejection is 0.55 if only timing is used

arXiv:1812.02906
A.Li, A.Elagin, S.Fraker, C.Grant, L.Winslow
Table 1  THEIA physics reach. Exposure is listed in terms of the fiducial volume assumed for each analysis. For NLDBD the target mass assumed is the mass of the candidate isotope within the fiducial volume.

<table>
<thead>
<tr>
<th>Primary physics goal</th>
<th>Reach</th>
<th>Exposure/assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long-baseline oscillations</td>
<td>$&gt;5\sigma$ for 30% of $\delta_{CP}$ values</td>
<td>524 kt-MW-year</td>
</tr>
<tr>
<td>Supernova burst</td>
<td>$&lt;1(2)^{\circ}$ pointing accuracy</td>
<td>100(25)-kt detector, 10 kpc</td>
</tr>
<tr>
<td></td>
<td>20,000 (5000) events</td>
<td></td>
</tr>
<tr>
<td>DSNB</td>
<td>$5\sigma$ discovery</td>
<td>125 kton-year</td>
</tr>
<tr>
<td>CNO neutrino flux</td>
<td>$&lt;5$ (10)%</td>
<td>300 (62.5) kton-year</td>
</tr>
<tr>
<td>Reactor neutrino detection</td>
<td>2000 events</td>
<td>100 kton-year</td>
</tr>
<tr>
<td>Geo neutrino detection</td>
<td>2650 events</td>
<td>100 kton-year</td>
</tr>
<tr>
<td>NLDBD</td>
<td>$T_{1/2} &gt; 1.1 \times 10^{28}$ year</td>
<td>211 ton-year $^{130}$Te</td>
</tr>
<tr>
<td>Nucleon decay $p \rightarrow \bar{\nu}K^+$</td>
<td>$T &gt; 3.80 \times 10^{34}$ year (90% CL)</td>
<td>800 kton-year</td>
</tr>
</tbody>
</table>
Gen-II LAPPD: "inside-out" anode

- Custom anode is outside
- Capacitively coupled
- Compatible with high rate applications

Chose your own readout pattern

For details see NIMA 846 (2016) 75