Revealing the Unique Nature of Neutrino Mass Using Fast Timing

Andrey Elagin
University of Chicago
Outline

• What can we learn about neutrinos by looking for neutrinoless double beta decay (0νββ-decay)?
• What instrumentation and experimental techniques are needed to find 0νββ-decay?
  - Cherenkov/scintillation light separation
  - development of the Large-Area Picosecond Photo-Detectors (LAPPD™)
Periodic Table of Elements

For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.
Helium Atom

Not to scale!
As a graduate student I was searching for the Higgs

I now turned my attention to neutrinos

I'd like to build new kind of “microscopes” to study neutrinos
Discoveries and Instrumentation

Nobel Prize 2013: the Higgs boson is found
P. Higgs and F. Englert

Nobel Prize 2015: neutrinos change while travel long distances
A. McDonald and T. Kojita

State of the art instrumentation made these discoveries possible
Future discoveries are waiting for new instrumentation
This Is What We Know
We Don't Know 95% of the Story

We have to build more instruments. More telescopes and “microscopes” are needed to find out what are those 95%

Also we are not done with the ordinary matter yet!
Is the neutrino its own antiparticle?

It is possible because the neutrino has no electric charge.

No other fermion can be its own antiparticle.

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

Search for neutrino-less double beta decay ($0
\nu\beta\beta$-decay) is the most feasible way to answer this question.
Meet the Neutrino

Crisis in 1930
(known particles: $\gamma$, p, $e^-$)

beta decay: $(A,Z) \rightarrow (A,Z+1) + e^- + \nu_e$
Lieber Radioaktive Damen und Herren!

Wie der Überbringer dieser Zeilen, den ich huldvollst anzu hören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6-Kerne, sowie des kontinuierlichen β-Spektrums auf einen zweifelten Ausweg verfallen, um den "Wechselsatz" der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin \( \frac{1}{2} \) haben und das Ausschließungsprinzip befolgen und sich von Lichtquanten außerdem noch dadurch unterscheiden, daß sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müßte von derselben Größenordnung wie die Elektronenmasse sein und jedenfalls nicht größer als 0,01 Protonenmasse. – Das kontinuierliche β-Spektrum wäre dann verständlich unter der Annahme, daß beim β-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, daß die Summe der Energien von Neutron und Elektron konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiß der Überbringer dieser Zeilen) dieses zu sein, daß das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment \( \mu \) ist. Die Experimente verlangen, daß die ionisierende Wirkung eines solchen Neutrons nicht größer sein kann, als die eines γ-Strahls und dann darf \( \mu \) wohl nicht größer sein als \( e \times (10^{-13} \text{ cm}) \). Ich trau mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10 mal größeres Durchdringungsvermögen besitzen würde, wie ein γ-Strahl.

Ich gebe zu, daß mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen mag, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt, und der Ernst der Situation beim kontinuierlichen β-Spektrum wird durch einen Ausspruch eines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: „O, daran soll man am besten gar nicht denken, so wie an die neuen Steuern.“ – Darum soll man jeden Weg zur Rettung ernstlich diskutieren.

Also liebe Radioaktive, prüft, und richtet. – Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7. Dezember in Zürich stattfindenden Balles hier unabhängig bin. – Mit vielen Grüßen an Euch, sowie auch an Herrn Back, Euer untertänigster Diener

W. Pauli
"β-Strahlen"

\[(A,Z) \rightarrow (A,Z+1) + e^- + \nu_e\]

4 particle interaction theory predicted the electron energy spectrum remarkably well.
Double Beta Decay

A, Z

A, Z

A, Z+1

A, Z+2

Nuclear Energy Level

e−
e−
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.

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

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

Only possible if neutrino is its own antiparticle
Noticed that symmetry of Dirac's theory allows to avoid solutions with negative energies (antiparticles) for neutral spin $\frac{1}{2}$ particles.

Fermi's theory of beta decay is unchanged if $\bar{\nu} = \nu$. 
Proposed a “chain” reaction

\[(A, Z) \rightarrow (A, Z+1) + e^- + \bar{\nu} \]

\[\bar{\nu} + (A', Z') \rightarrow (A', Z' + 1) + e^-\]

to distinguish between Dirac and Majorana neutrinos
Note on the Theory of the Neutral Particle

W. H. Furry

Physics Research Laboratory, Harvard University, Cambridge, Massachusetts
(Received March 28, 1938)

Majorana has recently shown by using a special set of Dirac matrices that the symmetry properties of the Dirac equations make possible the elimination of the negative energy states in the case of a free particle. We present here a further investigation of this possibility, in a treatment based on an arbitrary Hermitian representation of the Dirac matrices instead of Majorana’s special representation. The new procedure is compared with Schroedinger’s early attempt to eliminate the negative energy states. The question of Lorentz invariance is discussed, and also the possibility of subjecting the particle to forces; it is found that the only sort of force having a classical analogue which is consistent with Majorana’s way of eliminating the negative energy states is the nonelectric force of a scalar potential. The theory is worked through for this case, and it is pointed out that, in spite of the fact that the exclusion of negative energy states is accomplished without the introduction of antiparticles, the formalism still shows the stigmata associated with subtraction theories of the positron; the presence of otiose infinite terms which should be removed by subtraction, and the creation and destruction of pairs of particles. The application of Majorana’s formalism to the theory of β-radioactivity is discussed at the end of the paper. Here the physical interpretation is quite different from that of the ordinary theory, since only neutrinos appear instead of the neutrinos and antineutrinos of the usual picture. The results predicted for all observed processes are nevertheless identical with those of the ordinary theory. An experimental decision between the formulation using neutrinos and antineutrinos and that using only neutrinos will apparently be even more difficult than the direct demonstration of the existence of the neutrino.

Pessimistic conclusion about experimental prospects to observe Racah’s “chain” reaction:
- cross section is \( \sim 10^{-40} \)
- no intense source for neutrinos (no reactors yet)
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 Decay Is Unique

It may reveal the nature of neutrino mass

\[ n \rightarrow p + e_{L}^- + \bar{\nu}_{R} \]

But \( \nu_{R} \neq \nu_{L} \)

Need helicity flip!

\[ \nu_{L} + n \rightarrow p + e_{L}^- \]

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
See-Saw Mechanism

Possible extension of the SM Lagrangian to introduce neutrino mass

$\left( \bar{\nu}_l, \bar{N}_R \right) \left( \begin{array}{cc} 0 & m_D \\ m_D^T & M_{RR} \end{array} \right) \left( \begin{array}{c} \nu_L^c \\ N_R \end{array} \right)$

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

This is exactly what's needed for $0\nu\beta\beta$-decay
Search for $0\nu\beta\beta$-decay is an Active Field

Oscillation experiments established that neutrino is massive which is a pre-requisite for the helicity flip required for $0\nu\beta\beta$ decay.

Today we have many ongoing or planned experiments:
- Majorana
- EXO
- Super-NEMO
- SNO+
- GERDA
- CUORE
- KamLAND

In 2015 NSAC report $0\nu\beta\beta$-decay was ranked as a high priority for US nuclear physics.
EXO (~200 kg $^{136}$Xe)  
KamLAND-Zen (~300 kg $^{136}$Xe, before Summer 2016)  
GERDA (~20 kg $^{76}$Ge)  

Projections by  
CUORE (~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

Experimental Status of $0\nu\beta\beta$-decay

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

$$m_{\beta} = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$
Experimental Status of $0\nu\beta\beta$-decay

None of currently running or planned experiments is sensitive to $m_{\beta\beta} \sim 1$ meV

It’s not too early to think how to get there

Current best limit is set by KamLAND-Zen:

$T_{1/2} > 1.07 \times 10^{26}$ years

$m_{\beta\beta} < 61-165$ meV

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)
How to Find $0\nu\beta\beta$-decay?

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

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

<table>
<thead>
<tr>
<th>Isotopes</th>
<th>Q-value (Total energy of 2 electrons), MeV</th>
<th>Natural abundance, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca 48</td>
<td>4.271</td>
<td>0.187</td>
</tr>
<tr>
<td>Ge 76</td>
<td>2.039</td>
<td>7.8</td>
</tr>
<tr>
<td>Se 82</td>
<td>2.995</td>
<td>9.2</td>
</tr>
<tr>
<td>Zr 96</td>
<td>3.350</td>
<td>2.8</td>
</tr>
<tr>
<td>Mo 100</td>
<td>3.034</td>
<td>9.6</td>
</tr>
<tr>
<td>Pd 110</td>
<td>2.013</td>
<td>11.8</td>
</tr>
<tr>
<td>Cd 116</td>
<td>2.802</td>
<td>7.5</td>
</tr>
<tr>
<td>Sn 124</td>
<td>2.288</td>
<td>5.64</td>
</tr>
<tr>
<td>Te 130</td>
<td>2.529</td>
<td>34.5</td>
</tr>
<tr>
<td>Xe 136</td>
<td>2.479</td>
<td>8.9</td>
</tr>
<tr>
<td>Nd 150</td>
<td>3.367</td>
<td>5.6</td>
</tr>
</tbody>
</table>
Challenge #1

Very Small Decay Probability

Life-time for $0\nu\beta\beta$-decay is more than $> 10^{26}$ years

This is much longer than the age of the universe

Solution: look at many atoms at the same time
- Avogadro number is large $N_A = 6 \times 10^{23}$
- one ton of material can have $>10^{27}$ atoms
- even with one ton we are talking about ~10 events per year
Challenge #2

Background from $2\nu\beta\beta$–decay

Solution: good energy resolution
Challenge #3

Natural Radioactivity
There are 3g U-238 and 9g of Th-232 per ton of rock

These decays are a factor of \( \sim 10^{16} \) more likely than 0\( \nu \beta \beta \)-decay

Solution: purification and shielding
Ideal $0\nu\beta\beta$-decay Experiment

1) Large mass (more nuclei at the same time)

2) Good energy resolution (discriminate from $2\nu\beta\beta$-decay)

3) Purification and shielding (natural radioactivity)

$$T_{1/2} \sim \sqrt{\frac{M \cdot t_{meas}}{bkg \cdot \Delta E}}$$
New Challenge for a Large Detector

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

$^8\text{B}$ solar neutrino interactions can become dominant background

This is 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

• Lots of “back-to-back” (large angle) events
• Most of electrons are above Cherenkov threshold
Can We See This?

Simulation of a back-to-back $0\nu\beta\beta$ event

R=6.5m

2014 JINST 9 P06012

Lots of activity to answer this question:
055801; arXiv:1610.02011  
[NOTE: this list is very likely incomplete]

Preliminary answer is yes, but need fast photo-detectors and slow scintillators
Can We Detect Cherenkov Light?

Scintillation light is more intense and Cherenkov light is usually lost in liquid scintillator detectors.

Scintillation model based on KamLAND-Zen simulation.

- Scintillation emission is slower
- Longer wavelengths travel faster
- Cherenkov light arrives earlier

370 nm $\rightarrow$ 0.191 m/ns
600 nm $\rightarrow$ 0.203 m/ns

$\sim$2 ns difference over 6.5m distance
Cherenkov Light Comes First

Need good timing to see the effect
Using Directionality of Early Light

Directionality

Simulation:
- single electrons along X-axis at the center of 6.5m sphere
- KamLAND scintillator

Reconstruction:
WCSim adapted for low energy

Directionality “survives” some detector effects
Vertex resolution is promising

Directionality is already a handle on $^8$B events
Solar neutrinos come from the sun and outgoing electrons “remember” that
Directionality or Topology?

Idealized event displays: no multiple scattering of electrons, all PEs, QE=30%

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

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

Realistic event displays: early PEs only, KamLAND PMTs QE: \textcolor{red}{Che\sim12\%, Sci\sim23\%}

Early PE: $\text{0}\nu\beta$-decay

Cherenkov PEs

Early PE: \text{$^8$B event}

Scintillation PEs

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

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

$S_0$, $S_1$, $S_2$, $S_3$
$0\nu\beta\beta$ vs $^8B$

**Simulation details:**
- 6.5m radius detector, scintillator model from KamLAND simulation
- TTS=100 ps, 100% area coverage, QE(che) $\sim$12, QE(sci) $\sim$23%
**0νββ vs 8B**

Ideal vertex, **central events only**
Scintillation rise time 1 ns

Key parameters determining separation of $0νββ$-decay from $^8B$
- Scintillator properties (narrow spectrum, slow rise time)
- Photo-detector properties (fast, large-area, high QE, red-sensitive)
0νββ vs 8B

For details see NIM A849 (2017) 102

Vertex res 5cm, events within R<3m
Scintillation rise time 1 ns

Vertex res 5cm, events within R<3m
Scintillation rise time 5 ns

Background rejection factor = 2
@ 70% signal efficiency

Background rejection factor = 3
@ 70% signal efficiency

Other backgrounds (gammas, alphas, 10C, etc) also have distinct topologies
Event reconstruction in liquid scintillator would enable new opportunities
What about Machine Learning?

ROC curve for central events

- $0\nu\beta\beta$-decay event labeled as such
- $^{8}\text{B}$ event mislabeled as $0\nu\beta\beta$-decay

While ML techniques currently provide small improvements, they do not use any information about vertex -> important simplification in dealing with off-center events as well as with gammas, positrons, and $^{10}\text{C}$ backgrounds.

Ongoing work with E. Toropov (Carnegie Mellon) and I. Vukotic (Chicago)
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 lots of smaller scale experiments that can develop components and/or test ideas for a Large Directional Liquid Scintillator Detector e.g., ANNIE, CHESS, NuDot, Watchman
Photo-Detector Options

MCP-PMT by Photonis:
Fast, but small...

PMT by Hamamatsu
Large area, but slow...

photo credit: E.Oberla PhD thesis

photo credit: http://kamland.stanford.edu
Photo-Detectors

Photo-Multiplier Tube (PMT) is a classical example of a photo-detector
- use photo-electric effect to convert a photon to an electron
- use secondary electron emission (SEE) to amplify the signal

Uncertainty on the electron path causes uncertainty on the signal timing
The shorter the electron path the better the time resolution
No existing fast photo-detectors can cover large area at a reasonable cost
Atomic Layer Deposition (ALD)
- J. Elam and A. Mane at Argonne
  (process is now licensed to Incom Inc.)
- Arradiance Inc. (independently)

Material: borofloat glass
Area: 8×8"
Thickness: 1.2mm
Pore size: 20 μm
Open area: 60-80%
LAPPD Prototype Testing Results

Single PE resolution

Demonstrated characteristics:
- single PE timing ~50 ps
- multi PE timing ~35 ps
- differential timing ~5 ps
- position resolution < 1 mm
- gain > $10^7$

RSI 84, 061301 (2013),
NIMA 732, (2013) 392
NIMA 795, (2015) 1

See arXiv:1603.01843
for a complete LAPPD bibliography
A. DOE Funding to establish and demonstrate pilot production (4/2014)

B. Facility operational, Commissioning trials initiated (12/2015)

C. LAPPD Early Adopter Deliveries (2/2018)
   o #22 - Erik Brubaker, Sandia National Labs,
   o #25 - Matt Wetstein, Iowa State University, ANNIE Program

D. Exploitation (2018)
   o Operate Pilot Production on a routine basis
   o Produce prototypes for early adopters
Affordable large-area many-pixel photo-detector systems with picosecond time resolution

Example of a Super Module

LAPPD module 20x20 cm²

We are exploring if an air-transfer process (without vacuum transfer) can be inexpensive and easier to scale for a very high volume production.

Production rate of 50 LAPPDs/week would cover 100m² in one year

UChicago goal is to develop alternative high volume, scalable, low cost processing options (in close collaboration with Incom Inc.)
Can We Make LAPPDs in Batches Like PMTs?
Air-Transfer Assembly Steps

Transfer the window in air and make photo-cathode after the top seal

**Step 1:** pre-deposit Sb on the top window prior to assembly

**Step 2:** pre-assemble MCP stack in the tile-base

**Step 3:** do top seal and bake in the same heat cycle using dual vacuum system

*can vent the outer vacuum and access the detector prior to PC synthesis*

**Step 4:** bring alkali vapors inside the tile to make photo-cathode

**Step 5:** flame seal the glass tube or pinch the copper tube
LAPPD Air-Transfer Processing

Old UChicago PSEC Lab

Heat only the tile not the vacuum vessel

Intended for parallelization
Glass LAPPD

August 18, 2016

(Cs-Sb photo-cathode)

Flame seal by J. Gregar, Argonne
LAPPD Air-Transfer Facility

The idea is to achieve volume production by operating many small-size vacuum processing chambers at the same time or/and make several tiles in bigger chambers.

New UChicago PSEC Lab
Ceramic Tile Assembly Process
Before Introducing Cs

Indium seal line

Buttons appear gray/white color (view through a window with a thin Sb layer)
After Introducing Cs

Note reddish color of the buttons appearance (view through a window with Cs-Sb layer)

Laser induced pulses

10 ns/div
10 mV/div
“Squinshing”
“Squinshing”
After “Squinshing”

This tile had no getter inside and therefore had a limited lifetime. Next tiles will have getter inside.
Take Away Messages

Dirac/Majorana nature of the neutrino is a fundamental question

Search for $0
\nu\beta\beta$-decay is the most feasible approach to answer this question

Very large detector mass (kilo-ton) is required to probe small $m_{\beta\beta}$

$^8$B solar neutrinos become dominant background - traditionally viewed as irreducible

Directionality and event topology provide handles on $^8$B background

Fast timing is critical and there has been lots of progress in the development of LAPPD™
Thank You
Gen-II LAPPD

- Robust ceramic body
- Anode is not a part of the sealed detector package
- Enables fabrication of a generic tile for different applications
- Compatible with air-transfer and vacuum transfer assembly processes

Joint effort with Incom Inc. via DOE SBIR
Gen-II LAPPD: “inside-out” anode

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

For details see NIMA 846 (2016) 75
Optical Time Projection Chamber

- Like a TPC but drifts photons instead of electrons
- Exploits precise location and time for each detected photon
- Would allow track / vertex reconstruction in large liquid counters

Need < 100 ps

Suggestion to use LAPPD’s for DUSEL and the name (OTPC) due to Howard Nicholson

- It doesn’t have to be water (use prompt Cherenkov light that arrives early)
- In fact, for long tracks optical tracking should also work using just scintillation
Eric Oberla’s Optical TPC

Water

H₂O

Direct Cherenkov light (yellow)

Flat mirrors

Photonis MCPs and Chicago striplines/PSEC4

1 foot/1000 psec muon

Reflected Cherenkov light (green)

780 psec later
OTPC at Fermilab Test Beam

Eric Oberla’s Ph.D thesis

Five Photonis Planacons
Progress on Experimental Side

1950 - Experimental limits on $0\nu\beta\beta$ exceeded predictions (a hint that neutrino is a Dirac particle???)

1955 - R. Davis sets strong limits on $\bar{\nu} + ^{37}\text{Cl} \rightarrow ^{37}\text{Ar} + e^-$ (interpreted as a proof that neutrino is a Dirac particle)

1957 - V-A nature of weak interactions $\rightarrow$ dramatic decrease in probability of $0\nu\beta\beta$-decay rate, also R.Davis' experiment doesn't solve Dirac/Majorana questions for neutrinos

From reactor: $n \rightarrow p + e^- + \bar{\nu}_R$

At the target: $\nu_L + n \rightarrow p + e^-$ is allowed

$\bar{\nu}_R + n \rightarrow p + e^-$ is forbidden by V-A couplings

helicity flip is required $\rightarrow 0\nu\beta\beta$ can't happen even for Majorana neutrino if it has no mass

The fact that $0\nu\beta\beta$-decay requires massive neutrino and lepton number violation discouraged experimental searches
Only Three Flavors*

\[ N_\nu = 2.9840 \pm 0.0082 \]
Neutrino Mixing

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= 
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

Flavor eigen states (interaction)  
Mass eigen states (propagation)
Neutrino Mass Hierarchy
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 \[(\beta\beta)_{0v}\] which are not covered by the standard parametrizations. While probably small, their existence raises the question of whether the observation of \[(\beta\beta)_{0v}\] implies the existence of a Majorana mass term for the neutrino. For a “natural” gauge theory we argue that this is indeed th

![Diagram](image)

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.
Neutrinoless Decay Is Unique

It may reveal the nature of neutrino mass

\[ n \rightarrow p + e_{L}^{-} + \bar{\nu}_{R} \]

\[ \bar{\nu}_{i} \rightarrow \nu_{i} \]

\[ \nu_{L} + n \rightarrow p + e_{L}^{-} \]

Even if neutrino is its own antiparticle \( \nu_{R} \neq \nu_{L} \)

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

Such transition is connected to a mass term in the Lagrangian

Example of a Majorana mass term: \( M_{N}N^{C}N \)
See-Saw Mechanism

Electron mass term in the Standard Model Lagrangian

\[ m_e e_L e_R \]

(Example of a Dirac mass term)

Possible extension of the SM Lagrangian to introduce neutrino mass

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

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

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

\( 0\nu\beta\beta \)-decay provides access to the neutrino mass mechanism

This is exactly what's needed for \( 0\nu\beta\beta \)-decay

Electron mass term in the Standard Model Lagrangian

\[ m_e e_L e_R \]

(Example of a Dirac mass term)
My e-mail exchange with Jenni Kotila:

"...The angular correlation is basically the $a^{(1)}/a^{(0)}$, where $a^{(i)}$ are defined in Eq. (24) for 2nbb and in Eq. (51) for 0nbb. In case of 0nbb only thing that matters are the electron wavefunctions but in case of 2nbb there are these additional factors that are a combination of $<K_N>$ and $<L_N>$, that are defined in Eq. (23) and include the electron energies, the neutrino energies and the closure energy. So even with small neutrino energies, for example $e_1=0.749Q$, $e_2=0.249Q$, $w_1=0.002Q$, $w_2=0$ a factor of 0.4329 is obtained. Regarding the question about the situation for different isotopes, the closure energy entering the equations is different for each isotope and can be approximated by $1.12A^{(1/2)}$ MeV..."
Directionality of Early Photons

C. Aberle, A. Elagin, H. Frisch, M. Wetstein, L. Winslow
2014 JINST 9 P06012

Cherenkov photons from center of 6.5m-radius sphere: TTS=100 psec

Cosine of angle between the photoelectron hit and the original electron direction after the 34 ns cut. Both Cherenkov and scintillation light are included. Note the peak at the Cherenkov angle.
Light yield: Cherenkov vs scintillation

E [MeV] vs PEs per event

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

$\frac{1}{2} Q (^{48}\text{Ca}) = 2.1 \text{ MeV}$

What About Lower Energies?
$0\nu\beta\beta$ vs $^8B$

Vertex res 5cm, events within R<3m
Sci rise time 1 ns

$I_{\text{overlap}} = 0.79$
$0\nu\beta\beta$ vs $^8B$

Vertex res 5cm, events within $R<3m$
Sci rise time 5 ns

$I_{\text{overlap}} = 0.64$
Off-Center Events

\begin{align*}
\vec{z}'_{\text{hit}} &= \frac{\vec{a}}{|\vec{a}|} \cdot R \\
\vec{a} &= \vec{z}_{\text{hit}} - \vec{z}_{vtx} \\
\vec{z}'_{\text{hit}} &= \frac{\vec{z}_{\text{hit}} - \vec{z}_{vtx} \cdot R}{|\vec{z}_{\text{hit}} - \vec{z}_{vtx}|} \\
x' &= \frac{a_x}{\sqrt{a_x^2 + a_y^2 + a_z^2}} \cdot R \\
y' &= \frac{a_y}{\sqrt{a_x^2 + a_y^2 + a_z^2}} \cdot R \\
z' &= \frac{a_z}{\sqrt{a_x^2 + a_y^2 + a_z^2}} \cdot R \\
a_x &= x_{\text{hit}} - x_{vtx}, \quad a_y = y_{\text{hit}} - y_{vtx}, \quad a_z = z_{\text{hit}} - z_{vtx}
\end{align*}
$^{10}$C decay chain:

- $^{10}$C final state consist of a positron and gamma (e+ also gives 2x0.511MeV gammas after losing energy to scintillation)
- Positron has lower kinetic energy than $\nu\beta\beta$ electrons
- Positron scintillates over shorter distance from primary vertex
- Gammas can travel far from the primary vertex
- $^{10}$C background can be large at a shallow detector depth
**0νββ-decay vs 10C**

Time profile for events uniformly distributed within the fiducial volume, R<3m. Vertex resolution of 3cm is assumed.

- [Graph of 130Te 0νββ-decay and 10C events with TTS=100 ps]

Photons count in early light sample

- [Graph comparing 130Te 0νββ-decay and 10C events]

Spherical harmonics help here too

- [Graph showing normalized distribution of S0 and S1 for 130Te 0νββ-decay and 10C events]

**Disclaimer:** there are other handles on 10C that are already in use (e.g., muon tag, secondary vertices). Actual improvement in separation power may vary.
**NuDot - Directional Liquid Scintillator**

**R&D Towards Large Scale Detector**

- 140 2” fast PMTs for timing
- 72 10” regular PMTs for energy resolution

**Goals**

- Demonstrate directionality and event topology reconstruction using che/sci separation by fast timing
  - ideally by measuring $2\nu\beta\beta$-decay
- Study scintillators, including quantum dots

- Nanocrystals of CdS, CdSe, CdTe
- Interesting optical properties
- $\nu\beta\beta$-decay candidates
- Q-dots can be suspended in organic solvents and water
- In-depth R&D is needed to evaluate Q-dots potential

*Under construction at MIT, led by L. Winslow*
Water

Flat mirrors

Reflected Cherenkov light arrives 780 psec later depending on position and angle

Beam’s Eye View of the OTPC

Eric Oberla’s Ph.D thesis

Photonis MCPs and Chicago striplines/PSEC4

Beam-tagging MCP-PMT

Stereo view mirror mount

Normal view mirror mount

Normal view

Stereo view
- 60 mrad angular resolution over a lever arm of 40cm
- 1.5 cm spatial resolution (radiation length of H2O is 40cm)
- See 780 psec separation of direct and mirror-reflected light
Optical Tracking Demonstration

180-channel PSEC4 system

Example event

Typical event (thru-going μ)

0 ns

20 ns

PSEC4 timestep, 97 ps

-570 mm

-160 mm

OTPC installed at MCenter, FNAL

Eric Oberla PhD thesis

NIM A814 (2016) 19

Optical Tracking Demonstration

OTPC installed at MCenter, FNAL

180-channel PSEC4 system

Example event

Typical event (thru-going μ)

0 ns

20 ns

PSEC4 timestep, 97 ps

-570 mm

-160 mm

OTPC z-position [mm]
The ANNI E Experiment

- Measure neutron multiplicity in neutrino-nucleus interactions
- R&D towards water-based neutrino detection technology
- Explore optical tracking using novel photo-detectors
The time projection of the direct Cherenkov photons on the OTPC z-axis is a measure of the Cherenkov angle ($\beta$) and the particle angle with respect to the OTPC longitudinal axis:

$$\Delta t_{\gamma_2} = t_0 \left(1 - \frac{\beta c}{<v_{\text{group}}>} \tan \theta_i\right)$$

$$\Delta z_{\gamma_2} = \beta c t_0 \cos \theta_i$$

$$\frac{dt}{dz} \approx \frac{1}{\beta c} - \frac{\tan \theta_i}{<v_{\text{group}}>}$$
OTPC Optics – direct + reflected light

Time-resolving the direct and reflected photons provides the lateral particle displacement from the OTPC center-line as a function of z- and φ-position.

\[ r = (\Delta t < v_{group} > - D / 2) \left( \frac{1}{\sin \theta_c} - \frac{< v_{group} >}{\beta c \tan(\theta_c)} \right)^{-1} \]
OTPC Photodetector Module (PM)

- 1024 anode pad mapped to thirty-two 50Ω micro-strips with custom anode card
- MCP-PMT mounted to anode card with low-temperature Ag epoxy
- Terminate one end of micro-strip, other end open (high-impedance):

Expressions for the position and time-of-arrival of the detected photon:

\[
x = v_{\text{prop}} \frac{t_2 - t_1}{2} - \frac{D + 2C_1}{2}
\]

\[
t_0 = \frac{t_2 + t_1}{2} - \frac{1}{v_{\text{prop}}} (D + C_2 + C_1)
\]
OTPC spatial reconstruction (3)

Example event

Typical event (thru-going μ)

Projecting the direct photons onto the reconstructed r-coordinate at each PM

track x vs. z coordinates

track y vs. z coordinates
Production rate of 50 LAPPDs/week would substitute all PMTs at SNO+ in 3-4 years
Early Adopters of LAPPD

Putting first LAPPD tiles into real experimental settings for testing is the highest priority

Some examples of early adopters:

• ANNIE – Accelerator Neutrino Neutron Interactions Experiment
• Cherenkov/Scintillation light separation for particle ID
• Optical Time Projection Chamber
• TOF measurements at Fermilab Test Beam
• There are many more (lots of interest shown at the “Early Adopters Meeting” hosted by Incom Inc. in 2013)
FlatDot Demonstration

- Intermediate step towards 1m$^3$ spherical NuDot
  - e.g. detection of Cherenkov “rings” from low energy electrons using a tagged Compton source
- Testing different scintillator cocktails
- Readout testing

2” PMTs with TTS=300ps

Note: there is an independent effort on Che/Sci light separation - the CHESS experiment at Berkeley by G. Orebi Gann et al., arXiv:1610.02011 and 1610.02029
First Signals from an In-Situ LAPPD
(Sb cathode)

Near side: reflection from unterminated far end

Far side: reflection is superimposed on prompt source

Readout (50-Ohm transmission line)

The tile is accessible for QC before photo-cathode shot
This is helpful for the production yield

April, 2016
First in-situ commissioning run (Summer 2016)
- saw the first photo-current response from in-situ photo-cathode
- measured relative QE (absolute QE is tricky due to DC current through the whole stack)
- demonstrated a sealed tile configuration
  - no QE drop for 2 weeks after the valve to the pump was closed
  - no QE drop for 3 weeks after flame seal

Note on this commissioning run:
PC is very thick for transmission mode operation (initial 20nm of Sb translates into ~80nm of Cs-Sb)
Gen-II LAPPD: “inside-out” anode

Custom anode is outside

Compatible with high rate applications

Choose your own readout pattern

For details see arXiv:1610.01434 (submitted to NIM)
Inside-out Anode Testing

Evan Angelico and Todd Seiss

arXiv:1610.01434
LAPPD Electronics @ UChicago

Delay-line anode
- 1.6 GHz bandwidth
- number of channels scales linearly with area

PSEC-4 ASIC chip
- 6-channel, 1.5 GHz, 10-15 GS/s

NIM 711 (2013) 124

NIM 735 (2014) 452

30-Channel ACDC Card (5 PSEC-4)

Central Card (4-ACDC;120ch)
Can you make PC after Sb was exposed to air?

Luca Cultrera at Cornell
What about noise in the MCPs after Cs-ation?

Matt Wetstein
Indium seal recipes exist for a long time

We adapted NiCr-Cu scheme from O. Siegmund at SSL UC Berkeley

PLANACON™
(MCP-PMT by Photonis)

Why do we need another indium seal recipe?

Make larger photo-detectors
Our recipe scales well to large perimeter

Simplify the assembly process
Our recipe is compatible with PMT-like batch production
In-Situ Process Pre-requisite

Reliable hermetic seal over a 90-cm long perimeter

Indium Solder Flat Seal Recipe

Input:
- Two glass parts with flat contact surfaces

Process:
- Coat 200 nm of NiCr and 200 nm of Cu on each contact surface (adapted from seals by O. Siegmund at SSL UC Berkeley)
- Make a sandwich with indium wire
- Bake in vacuum at 250-300°C for 24hrs

Key features:
- A good compression over the entire perimeter is needed to compensate for non-flatness and to ensure a good contact
- In good seals indium penetrates through entire NiCr layer (Cu always "dissolves")

This recipe is now understood
It works well over large perimeters

Metallization and compression are critical
Metallurgy of the Seal

Moderate temperatures and short exposure time:

- A thin layer of copper quickly dissolves in molten indium
- Indium diffuses into the NiCr layer

Depth profile XPS

Low melting InBi alloy allows to explore temperatures below melting of pure In (157°C)

Glass with NiCr-Cu metallization exposed to InBi at ~100°C for <1hrs (it seals at these conditions)

InBi was scraped when still above melting (72°C)

The ion etch number is a measure for the depth of each XPS run

XPS access courtesy of J. Kurley and A. Filatov at UChicago
Metallurgy of the Seal

High temperatures and long exposure time

• Indium penetrates through entire NiCr layer

SEM and EDAX of the metal surface scraped at the interface

Glass with NiCr-Cu metallization bonded by pure In at ~250°C for 2hrs (it seals at these conditions)

Cut and scrape at the metal-glass interface

SEM/EDAX data courtesy of J. Elam at Argonne
Metallurgy of a Good Seal

Higher temperatures and longer exposure time

- Indium penetrates through entire NiCr layer

XPS of the glass side of the interface

Glass with NiCr-Cu metallization bonded by pure In at ~350°C for 24 hrs (it seals at these conditions)

Cut and scrape at the metal-glass interface

We now reliably seal at 250-300°C for 12-24 hrs

XPS data courtesy of A. Filatov at UChicago
The 2013 Transition from LAPPD to Production: The 4 Parallel Paths

Dec 12, 2012 Presentation to DOE

LAPPD Pre-production Project

SSL (Ossy)

Incom

ANL/HEPD

BNL,RMD, InnoSys, ESD, UC,....

LAPPD R&D

Frisch, Wagner, Byrum

SSL ceramic tube production

SSL ceramic tube production

SSL ceramic tube production

Frisch, Wagner, Byrum

Technology transfer

Pre-Production Line

Design, Ordering

Commissioning

Frisch, Demarteau

Frisch (ANL, BNL, UC, UCB, UIUC, WashU)

Industrialization

Ceramic tube

Glass tube

First Pre-production

First Production

Tile Facility

Photocathode

High-QE, in-situ deposition, nano-materials, recipe to physics

Frisch (ANL, BNL, UC, UCB, UIUC, WashU)

Presentation to DOE

DOE Argonne Review May 2014

Sept 2012

Sept 2013

Sept 2014

Sept 2015

Slide credit: Henry Frisch
Argonne 6x6 cm² Photo-Detectors

- Argonne routinely producing 6X6 cm² functional detectors with K$_2$CsSb photocathode
- New IBD-1 design allows HV optimization, as biasing individual components possible
- In addition to assembly of photo-detectors, laser testing facility available and photocathode research ongoing.
- Performance:
  - Gain $> 10^7$
  - Quantum efficiency $\sim 15\%$
  - Time resolution including the laser jitter: $\sigma \sim 35$ ps
  - Position resolution along anode strip: $< 1$ mm
  - Rate capability $> 1$ MHz/cm² for single photoelectrons

Slide courtesy of R. Darmapalan and R. Wagner
SSL Ceramic LAPPD Tile Results

Measurements after full processing cycle inside the vacuum chamber.
Gain map image for a pair of 20 μm pore, 60:1 L/D, ALD borosilicate MCPs, 950 V per MCP, 184 nm UV

Gain is uniform within ~15% across full 20 x 20 cm² area

Noise <0.1 counts cm⁻² s⁻¹