Reducing Irreducible Background
and
Revealing the Unique Nature
of Neutrino Mass Using Fast Timing

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Outline

• What can we learn about neutrinos by looking for neutrinoless double beta decay ($0\nu\beta\beta$-decay)?
• What instrumentation and experimental techniques are needed to find $0\nu\beta\beta$-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.

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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

Evolution of the Universe

Big Bang → Unified Forces → Inflationary Expansion → Forces Separate → Nucleons Form → Atoms Form → Stars Are Born → Today

Time: $10^{-43}$ s, $10^{-35}$ s, $10^{-10}$ s, $10^{-5}$ s, 300 000 Years, $10^9$ Years, $15 \times 10^9$ Years

Energy: $10^{17}$ TeV, $10^{13}$ TeV, 1 TeV, 150 MeV, 1 eV, 4 meV, 0.7 meV

- electroweak phase transition
- QCD phase transition
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!
A Question That Interests Me

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: $(A,Z) \rightarrow (A,Z+1) + e^- + \nu_e$

Electron energy spectrum

- $e^-$
- $p$
- $n$
- $\nu_e$

Kineti Energy (MeV)

Probability
Letter by W. Pauli

Zürich, 4. Dezember 1930
[Maschinenschriftliche Abschrift]

Offener Brief an die Gruppe der Radioaktiven bei der Gauweneins-Tagung zu Tübingen

Lieber Radioaktiver 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 $\beta$-Spektrums auf einen zweifelten Ausweg verfallen, um den „Wechselsatz“ der Statistik und den Energie zu räten. 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 $\beta$-Spektrum wäre dann verständlich unter der Annahme, daß beim $\beta$-Zerfall fest der Elektron jeweils noch ein Neutron emittiert wird, d. h. 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 $\gamma$-Strahls und dann darf $\mu$ wohl nicht größer sein als $e \times (10^{-13})$. Ich traue mich vorläufig aber nicht, über diese Idee zu publizieren und wende mich erst vertrauensvoll zu Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensoles oder etwa 10mal größeres Durchdringungsvermögen besitzen würde, wie ein $\gamma$-Strahl.

Ich gebe zu, daß mein Ausweg vielleicht 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 $\beta$-Spektrum wird durch einen Ausspruch meines 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 ungebührlich bin. – Mit vielen Grüßen an Euch, sowie auch an Herrn Back, Euer untätigster Diener

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

\[ A, Z \xrightarrow[\text{X}]{} A, Z+1 \]

\[ A, Z+1 \xrightarrow{} A, Z+2 \]

Nuclear Energy Level
Double-Beta Disintegration

Maria Goeppert-Mayer

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.

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

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

Nucleus $\rightarrow$ Nucleus $Z+2$

Nuclear Process

Total energy of two electrons

$dN/d(E/Q_{\text{vis}})$
Neutrinoless Decay

It is only possible if the neutrino is its own antiparticle.

How can a particle be its own antiparticle?
Ettore Majorana

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 $\bar{\nu} = \nu$
Giulio Racah

SULLA SIMMETRIA TRA PARTICELLE E ANTIPARTICELLE

Nota di Giulio Racah

_Sunto._ - Si mostra che la simmetria tra particelle e antiparticelle porta alcune modificazioni formali nella teoria di Fermi sulla radioattività β, e che l'identità fisica tra neutrini ed antineutrini porta direttamente alla teoria di E. Majorana.

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
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 those 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)
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 (\( \epsilon \gg 20, \Delta M \gg 0.01 \) 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
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 → 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 → $0\nu\beta\beta$ 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
Current Status

Oscillation experiments established that neutrino is massive and increased interest to $0\nu\beta\beta$ decay searches

Today we have many experiments

MAJORANA
GERDA
CUORE

EXO

SNO+

Super-NEMO

KamLAND

In 2015 NSAC report $0\nu\beta\beta$-decay was ranked as a high priority for US nuclear physics

Why it has high priority?
Neutrinoless Decay Is Unique

It may reveal the nature of neutrino mass

\[ n \rightarrow p + e_L^- + \bar{\nu}_R \]

\[ \nu_L + n \rightarrow p + e_L^- \]

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: \( M_{N^C N} \)
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
\[
\begin{pmatrix}
\nu_l, N_R^c
\end{pmatrix}
\begin{pmatrix}
0 & m_D \\
m_D^T & M_{RR}
\end{pmatrix}
\begin{pmatrix}
\nu_L^c \\
N_R
\end{pmatrix}
\]

In the limit \( M_{RR} \gg m_D \) the eigenvalues are
- \( m_D^2/M_{RR} \) (light neutrino)
- \( M_{RR} \) (heavy neutrino)

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

This is exactly what's needed for \( 0\nu\beta\beta \)-decay
Current best limit is set by KamLAND-Zen: $T_{1/2} > 1.07 \times 10^{26}$ years

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

$T_{1/2}^{-1} = G^{0\nu} \times |M^{0\nu}|^2 \times m_{\beta\beta}^2$

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

$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$
EXO (~200 kg $^{136}$Xe)
KamLAND-Zen (~300 kg $^{136}$Xe, before this Summer)
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

$T_{1/2}^{-1} = G^{0\nu} \times |M^{0\nu}|^2 \times m_{\beta\beta}^2$

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

Isotopes | Q-value (Total energy of 2 electrons), MeV | Natural abundance, %
--- | --- | ---
Ca 48 | 4.271 | 0.187
Ge 76 | 2.039 | 7.1
Se 82 | 2.995 | 9.2
Zr 96 | 3.350 | 2.8
Mo 100 | 3.034 | 9.6
Pd 110 | 2.013 | 11.8
Cd 116 | 2.802 | 7.5
Sn 124 | 2.288 | 5.64
Te 130 | 2.529 | 34.5
Xe 136 | 2.479 | 8.9
Nd 150 | 3.367 | 5.6
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 $\sim 10$ 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 $^{8}$B-decays in the sun

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

This is irreducible background without event topology reconstruction
The largest background is coming from $^8$B solar neutrinos. It has only 1 electron, while $\nu\beta\beta$-decay has 2 electrons.

Is it possible to separate two-track and one-track events using Cherenkov light in a liquid scintillator detector?
Can We See This?

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

Run 1 (1 event)  Thu Mar 28 09:56:40 2013
R=6.5m

2014 JINST 9 P06012
Double-Beta Decay Kinematics

- Distinct two-track topology with preference to be “back-to-back”
- Electrons are above Cherenkov threshold

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

Kinetic energy of each electron

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

Cherenkov threshold
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

\[ 370 \text{ nm} \rightarrow 0.191 \text{ m/ns} \]
\[ 600 \text{ nm} \rightarrow 0.203 \text{ m/ns} \]

~2 ns difference over 6.5m distance
Can We Detect Cherenkov Light?

- Cherenkov light arrives earlier
- Need good timing to see the effect
Directionality and Vertex Reconstruction

Directionality

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

Reconstruction:
WCSim adapted for low energy

2014 JINST 9 P06012

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\%

**Why spherical harmonics?**

- Spherical harmonics analysis is a natural and "easy" choice for a spherical detector
- Advanced machine learning techniques will do even better
- Understanding of requirements on hardware components is now a much higher priority - those are hard to change once the detector is built
Simulation details:

- 6.5m radius detector, scintillator model from KamLAND simulation
- TTS=100 ps, 100% area coverage, QE(che) ~12, QE(sci) ~23%
Ideal vertex, central events only
Scintillation rise time 1 ns

Key parameters determining separation of $0\nu\beta\beta$-decay from $^{8}\text{B}$
- Scintillator properties (narrow spectrum, slow rise time)
- Photo-detector properties (fast, large-area, high QE, red-sensitive)
$0\nu\beta\beta$ 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, $^{10}C$, etc) also have distinct topologies
Event reconstruction in liquid scintillator would enable new opportunities
Potential for $0v\beta\beta$-decay search

- 50kt detector
- 50% reduction of $^8\text{B}$
- 0.5% nat Te loading
- 50t $^{130}\text{Te}$ after fiducial cuts
- 15 meV after 10 years

Broad detector R&D program to realize THEIA

Concept paper - arXiv:1409.5864

Illustration from a presentation by Gabriel Orebi Gann
NuDot - Directional Liquid Scintillator

R&D Towards Large Scale Detector

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

Under construction at MIT, led by L. Winslow

Goals

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

Q-dots

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

Eric Oberla PhD thesis
NIM A814 (2016) 19

OTPC installed at MCenter, FNAL

180-channel PSEC4 system

Example event

Typical event (thru-going μ)

-570 mm 0 ns 20 ns 97 ps

-160 mm
The ANNIE Experiment

- Measure neutron multiplicity in neutrino-nucleus interactions
- R&D towards water-based neutrino detection technology
- Explore optical tracking using novel photo-detectors

ANNIE installation at Fermilab

Data taking is ongoing
Photo-Detector Options

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

photo credit: E.Oberla PhD thesis

PMT by Hamamatsu
Large area, but slow...

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
**LAPPD™**

**Large-Area Picosecond Photo-Detector**

- **Material:** borofloat glass
- **Area:** 8x8"
- **Thickness:** 1.2mm
- **Pore size:** 20 μm
- **Open area:** 60-80%

**Single PE time resolution <50ps**

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

**Micro-Capillary Arrays by Incom Inc.**
- **Material:** borofloat glass
- **Area:** 8x8"
- **Thickness:** 1.2mm
- **Pore size:** 20 μm
- **Open area:** 60-80%
LAPPD Prototype Testing Results

Single PE resolution

Demonstrated characteristics:
- single PE timing \(\sim 50\) ps
- multi PE timing \(\sim 35\) ps
- differential timing \(\sim 5\) 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
LAPPD™ Commercialization

Incom V2.0 LAPPD Integration & Sealing
Process & Hardware

**Process:**
- UHV - with Conflat seals, scroll, turbo and ion pump.
- Tile kit components pre-assembled & locked in place.
- Baked to low $10^{-10}$ torr range
- In-tank operation of tile/scrubbing
- Window Transfer Process
- Multi-alkali Photocathode deposited on underside of window.
- Hot Indium Seal - with grooved sidewalls

**Hardware:**
- Single “Fully Bakeable” Chamber: 30“L X 16”W X 8”H
- Simple window transfer between photocathode deposition & sealing.
- Electrical interconnects for in-process monitoring
- Readily expandable for volume production

Slide courtesy of Incom Inc.
Goal of the R&D Effort at UChicago

Affordable large-area many-pixel photo-detector systems with picosecond time resolution

LAPPD module 20x20 cm²

Example of a Super Module

- High volume production can be challenging for vacuum transfer process
- We are exploring if a non-vacuum transfer process can be inexpensive and easier to scale for a very high volume production

UChicago goal is to enable high volume production at Incom so that LAPPD™ become available for HEP community

Production rate of 50 LAPPDs/week would cover 100 m² in one year
Simplify the assembly process by avoiding vacuum transfer: make photo-cathode after the top seal (PMT-like batch production)

Heat only the tile not the vacuum vessel

Intended for parallelization
In-Situ Assembly Facility UChicago

The idea is to achieve volume production by operating many small-size vacuum processing chambers at the same time.

Looking forward towards transferring the in-situ process to industry.
First Signals from an In-Situ LAPPD

(Sb cathode)

Near side: reflection from unterminated far end

Far side: reflection is superimposed on prompt

The tile is accessible for QC before photo-cathode shot

This is helpful for the production yield
First Sealed In-Situ LAPPD

August 18, 2016

(Cs$_3$Sb photo-cathode)

Flame seal by J. Gregar, Argonne
- Robust ceramic body
- Anode is not a part of the vacuum package
- Enables fabrication of a generic tile for different applications
- Compatible with in-situ and vacuum transfer assembly processes

January, 2017
Lots of Hands On Experience

We need lots of stuff and we often build what we need.

This is fun!
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

Detector R&D is ongoing to demonstrate event topology reconstruction using Cherenkov/scintillation light separation

Fast timing is critical and there has been lots of progress in the development of LAPPD$^{\text{TM}}$
Thank You
Only Three Flavors

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

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

Flavor eigen states (interaction)

Mass eigen states (propagation)
Neutrino Mass Hierarchy

Normal vs. Inverted Mass Hierarchy:

- **Normal**
  - $m_3^2$ (green) is above $m_2^2$ (red)
  - Atmospheric $\sim 2 \times 10^{-3} \text{eV}^2$
  - Solar $\sim 7 \times 10^{-5} \text{eV}^2$

- **Inverted**
  - $m_3^2$ (blue) is below $m_1^2$ (red)
  - Atmospheric $\sim 2 \times 10^{-3} \text{eV}^2$
  - Solar $\sim 7 \times 10^{-5} \text{eV}^2$
Neutrinoless double-\(\beta\) decay in SU(2) \(\times\) 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 \([\langle \beta \beta \rangle_{0\nu}]\) which are not covered by the standard parametrizations. While probably small, their existence raises the question of whether the observation of \([\beta \beta]_{0\nu}\) implies the existence of a Majorana mass term for the neutrino. For a "natural" gauge theory we argue that this is indeed th

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**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.
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 $\langle K_N \rangle$ and $\langle L_N \rangle$, 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

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.

Cherenkov photons from center of 6.5m-radius sphere: TTS=100 psec
What About Lower Energies?

Light yield: Cherenkov vs scintillation

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

$\frac{1}{2} Q \left(^{48}\text{Ca}\right) = 2.1 \text{ MeV}$
$0\nu\beta\beta$ vs $^8B$

Vertex res 5cm, events within $R<3m$

Sci rise time 1 ns

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

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

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

\[ \vec{z}'_{\text{hit}} = \frac{\vec{a}}{\|\vec{a}\|} \cdot R \]

\[ \vec{a} = \vec{z}_{\text{hit}} - \vec{z}_{v+\vec{x}} \]

\[ \vec{z}'_{\text{hit}} = \frac{\vec{z}_{\text{hit}} - \vec{z}_{v+\vec{x}}}{{\|\vec{z}_{\text{hit}} - \vec{z}_{v+\vec{x}}\|}} \cdot R \]

\[ x' = \frac{a_x}{\sqrt{1 + \frac{a_y^2}{a_x^2} + \frac{a_z^2}{a_x^2}}} \cdot R \]

\[ y' = \frac{a_y}{\sqrt{1}} \cdot R \]

\[ z' = \frac{a_z}{\sqrt{1}} \cdot R \]

\[ a_x = x_{\text{hit}} - x_{v+\vec{x}}, \ a_y = y_{\text{hit}} - y_{v+\vec{x}}, \ a_z = z_{\text{hit}} - z_{v+\vec{x}} \]
$^{10}\text{C}$ decay chain:

- $^{10}\text{C}$ 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 $\text{0}\nu\beta\beta$ electrons
- Positron scintillates over shorter distance from primary vertex
- Gammas can travel far from the primary vertex
- $^{10}\text{C}$ background can be large at a shallow detector depth

Diagram by Jon Ouellet
**0νββ-decay vs $^{10}\text{C}$**

Time profile for events uniformly distributed within the fiducial volume, $R<3\text{m}$

Vertex resolution of $3\text{cm}$ is assumed

Displacement of light photons in early light sample

**Photons count in early light sample**

- $^{130}\text{Te }0\nu\beta\beta$-decay
- $^{10}\text{C}$ events

Spherical harmonics help here too

**Disclaimer:** there are other handles on $^{10}\text{C}$ that are already in use (e.g., muon tag, secondary vertices). Actual improvement in separation power may vary.
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:

$$\Delta t_{\gamma 21} = t_o \left( 1 - \frac{\beta c}{<v_{group}>} \tan \theta_i \right)$$

$$\Delta z_{\gamma 21} = \beta c t_o \cos \theta_i$$

$$\frac{dt}{dz} \approx \frac{1}{\beta c} - \frac{\tan \theta_i}{<v_{group}>}$$
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 \( \phi \)-position

\[
\frac{\vec{p}}{|\vec{p}|} = \hat{z}
\]

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

28-7-2015  thesis defense
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):

\[
\begin{align*}
    x &= v_{prop} \frac{t_2 - t_1}{2} - \frac{D + 2C_1}{2} \\
    t_0 &= \frac{t_2 + t_1}{2} - \frac{1}{v_{prop}} \left( D + C_2 + C_1 \right)
\end{align*}
\]

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

PHOTONIS XP85022 (commercial) MCP-PMT

5.1 cm
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
Need for High Volume Production

Key applications

- Cherenkov/scintillation light separation to reconstruct $0\nu\beta\beta$-decay event topology
- Optical tracking
- Particle identification by time-of-flight (colliders and fixed-target experiments)
- Medical imaging, proton therapy, nonproliferation, quantum imaging

How many LAPPDs are needed?

- NuDot needs up to 72 LAPPDs (small-scale prototype with a path to a very large directional liquid scintillator detector for $0\nu\beta\beta$-decay)
- ANNIE needs 20-100 LAPPDs (water Cherenkov detector at Fermilab)
- KamLAND-Zen and SNO+ may benefit from LAPPDs but would need thousands of LAPPDs
- THEIA would need over 20,000 LAPPDs for just a 10% photo-coverage

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

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
In-Situ Assembly Strategy

Simplify the assembly process by avoiding vacuum transfer:
make photo-cathode after the top seal
(PMT-like batch production)

Heat only the tile
not the vacuum vessel

Intended for parallelization

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
Step 4: bring alkali vapors inside the tile to make photo-cathode
Step 5: flame seal the glass tube or crimp the copper tube
**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
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

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

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

Layer depth (uncalibrated)

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 24hrs (it seals at these conditions)

Cut and scrape at the metal-glass interface

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

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

(a UC view)

R&D

Presentation to DOE

LAPPD Pre-production Project

SSL ceramic tube production

SSL ceramic tube production

SSL ceramic tube production

Frisch, Wagner, Byrum

Frisch, Wagner, Byrum

Frisch, Wagner, Demarteau

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

SSL (Ossy)

Incom

ANL/HEPD

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

Industrialization

Tech transfer

Pre-Production Line

Glass tube

Design, Ordering

Commissioning

First Production

Tile Facility

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

Photocathode

Slide credit: Henry Frisch

Dec 12, 2012 Presentation to DOE

Sept 2012

DOE Argonne Review May 2014

Sept 2013

Sept 2014

Sept 2015
Argonne 6x6 cm² Photo-Detectors

- Argonne routinely producing 6X6 cm² functional detectors with K₂CsSb 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 ~ 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

**QE**

- Graph showing Quantum Efficiency vs. Wavelength (nm)
  - Data for different time intervals: 10 days, 9 days, 3 days, Initial QE

**Timing**

- Graph showing FWHM vs. PC Gap Volts
- Graph showing Counts vs. Time (ns)
- Chart showing FWHM and Counts for different voltage gaps (30V, 85V, 145V, 257V, High B/N Laser)
Gain Uniformity

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