Research in Maruyama Group

Research

- Physics Beyond the Standard Model of Particle Physics
- Neutrinos and Dark Matter

- direct detection dark matter experiment at Yale, South Pole and South Korea.
- Is DAMA really seeing dark matter?

- Neutrinoless double beta decay
- Are neutrinos their own anti-particles? Are they Majorana particles?
The Standard Model of Elementary Particles

- Gravity?
- Dark Matter? Dark Energy?
- Neutrino Masses?
- Matter-antimatter asymmetry?

discovery in 2012

http://particleadventure.org/
History of Neutrinos

1930 Pauli postulates neutrinos

1933 Fermi names neutrinos, formulates weak interactions theory

1938 Ray Davis detects solar neutrinos.

1956 Reines & Cowan report the first evidence of neutrinos

1957 Pontecorvo: Neutrinos may oscillate

1958 Goldhaber, Grodzins, & Sunyar at BNL demonstrate left-handed helicity

1962 Steinberger, Lederman, Schwartz, et al demonstrate $\nu_e$ & $\nu_\mu$

1987 SN 1987A

1987 SN 1987A

1998 SuperK reports evidence for oscillation of atmospheric neutrinos.

2001/2002 SNO finds evidence for solar $\nu_e$ flavor change.

2003 KamLAND discovers disappearance of reactor $\nu_e$

2007 Borexino detection of $^7$Be solar neutrinos

2012 Daya Bay, RENO, Double Chooz measure $\theta_{13}$

today
The Nobel Prize in Physics 2015
“for the discovery of neutrino oscillation, which shows that neutrinos have mass”

Takaaki Kajita
Super-K Collaboration
University of Tokyo, Japan

Arthur B. McDonald
SNO Collaboration
Queen’s University, Canada
Open Questions in 2019

What is the nature of neutrinos?

What are the values of the masses?
- absolute scale
- mass ordering

Is there CP-violation?

What are the precise values of mixing angles?

Is the standard picture correct?
- non-standard interactions
- Sterile neutrinos?
- other effects

\[ \nu = \bar{\nu} \]
Absolute Neutrino Mass Scale

\[ \begin{array}{c}
\text{From tritium endpoint (Mainz and Troitsk)}
\end{array} \]

\[ \approx 2 \text{ eV} \]

\[ \text{From tritium endpoint (Mainz and Troitsk)} \]

\[ \approx 0.1 \text{ eV} \]

\[ \text{From } 0\nu\beta\beta \text{ if } \nu \text{ is Majorana} \]

\[ \sum \approx 0.25 \text{ eV} \]

\[ \text{From Cosmology} \]

\[ \approx 20 \text{ eV} \]

\[ \text{Time of flight from SN1987A (PDG 2002)} \]

\[ \approx 2 \text{ eV} \]

\[ \text{From } 0\nu\beta\beta \text{ if } \nu \text{ is Majorana} \]

\[ \approx 2 \text{ eV} \]

\[ \text{From tritium endpoint (Mainz and Troitsk)} \]

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\[ \text{From tritium endpoint (Mainz and Troitsk)} \]

\[ \approx 2 \text{ eV} \]
Two-neutrino double beta decay (2νββ)

for example...

\[ ^{130}\text{Te} \xrightarrow{\beta_X} (A,Z) \xrightarrow{\beta\beta} (A,Z+1) \xrightarrow{\beta\beta} (A,Z+2) \xrightarrow{\text{130I}} \]

Even-even nucleus

\[ (A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{v}_e \]

Proposed in 1935 by Maria Goeppert Mayer

First direct observation by Moe, Elliott, and Hahn in \(^{100}\text{Mo}\) (1988)

- Completely allowed process
- Observed
- No new physics beyond the Standard Model of Particle Physics

\[(2\nu\beta\beta) ~ T_{1/2} \sim 10^{19} - 10^{21} \text{ yrs} \]
Maria Goeppert Mayer (1906 - 1972)
Parity violation in Weak Interaction
• Proposed by Lee & Yang in 1956
• Experimentally demonstrated by Wu, 1957
Parity Violation in Weak Interactions

Experimental Test of Parity Conservation in Beta Decay*

C. S. Wu, Columbia University, New York, New York
AND
E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson,
National Bureau of Standards, Washington, D. C.
(Received January 15, 1957)

In a recent paper on the question of parity in weak interactions, Lee and Yang critically surveyed the experimental information concerning this question and reached the conclusion that there is no existing evidence either to support or to refute parity conservation in weak interactions. They proposed a number of experiments on beta decays and hyperon and meson decays which would


https://physics.aps.org/story/v22/st19

Reina Maruyama
Zero-Neutrino Double Beta Decay ($0\nu\beta\beta$)

- Why is it interesting? Observation of $0\nu\beta\beta$ would mean…
  - Neutrinos must be Majorana particles (not Dirac)
  - New mass scale in nature
  - Potential for absolute neutrino mass scale & hierarchy
  - Explicitly violate lepton number
  - Key ingredient for standard baryogenesis via leptogenesis

Proposed in 1937 by Ettore Majorana

$0\nu\beta\beta$ $T_{1/2} \geq 10^{26}$ y
Double Beta Decay Spectrum

2νββ:
Sum of 2-β energies =>
spectrum similar to single beta decay

0νββ:
Sum of 2 β, full energy =>
sharp peak at end point

We measure half-lives
How Rare?

- Most measured half-lives for $2\nu\beta\beta$ are $O(10^{21})$ years
  
  (The longest directly observed process)

- Compare to lifetime of the universe: $10^{10}$ years

- Compare to Avogadro’s number: $6 \times 10^{23}$

- A mole of the isotope will produce $\sim 1$ decay/day

- If it exists, the half-lives of $0\nu\beta\beta$ would be much longer

  - $^{130}\text{Te}$ $0\nu\beta\beta$ limit is $> 10^{24}$ years*

  - A mole of $^{130}\text{Te}$ produces $< 1$ neutrinoless decay/year

  - A half-life of $10^{26}$ years requires 32 kg of $^{130}\text{Te}$ to see 1 decay/year


Slide from J. Cushman
$0\nu\beta\beta$ Decay rate

\[
( T^{0\nu}_{1/2} )^{-1} = G^{0\nu}(Q,Z) | M^{0\nu} |^2 \frac{ | \langle m_{\beta\beta} \rangle |^2 }{ m_e^2 }
\]

- Transition probability
- Phase space factor
- Nuclear matrix element
- Particle physics

\[
\alpha \frac{m}{Q^2} (Q \sim m_e)
\]

\[
G \sim G_F^4 g_A^4 m_e^5
\]

- E.g., virtual exchange of light Majorana neutrinos
- Coherent superposition

\[
\langle m_{\beta\beta} \rangle = \sum_j | U_{ej} |^2 e^{i\alpha_j} m_j
\]

PMNS matrix
Majorana phases
0νββ Decay rate

\[
(T_{1/2}^{0ν})^{-1} = G^{0ν}(Q, Z) |M^{0ν}|^2 \left( \frac{\langle m_{ββ} \rangle}{m_e^2} \right)^2
\]

\[T_{1/2}^{0ν} = 0νββ \text{ half-life}\]

\[G^{0ν}(Q, Z) = \text{phase space factor } (α Q^5)\]

\[M^{0ν} = \text{nuclear matrix element}\]

\[\langle m_{ββ} \rangle = \text{effective } ββ \text{ neutrino mass}\]

\[m_e = \text{electron mass}\]

**For light neutrino exchange**

All 3 neutrinos will contribute: \[η \sim m \rightarrow \langle m_{ββ} \rangle = \sum_i U_{ie}^2 m_i\]

\[m_{ββ} \sim 1 \text{ eV} \implies T_{1/2} \sim 10^{24} \text{ years}\]

\[m_{ββ} \sim 0.1 \text{ eV} \implies T_{1/2} \sim 10^{26} \text{ years}\]

\[m_{ββ} \sim 0.01 \text{ eV} \implies T_{1/2} \sim 10^{28} \text{ years}\]
Neutrinoless Double Beta Decay Experiments
Double Beta Decay Spectrum

Reina Maruyama


2νββ: Sum of 2-β energies => spectrum similar to single beta decay

0νββ: Sum of 2 β, full energy => sharp peak at end point

We measure half-lives

compare to single beta decay

Fig. 5. Energy distribution curve of the beta-rays.
Choose a Signal:

A diagram that the direct dark matter experiments like to make.

CUORE

Phonon

Light

Ionization

Bolometer + Cherenkov or Scintillating Bolometer: CUORE-Next Family [LUCIFER, LUMINEAU] AmoRE

TPC: nEXO and NEXT

Liquid Scintillator: KamLAND-Zen, SNO+ Scintillating Crystal: CANDLES

Semiconductor: GERDA/Majorana Tracking: SuperNEMO, DCBA

L. Winslow
CUORE Bolometer

TeO₂ Bolometer: Source = Detector

Heat sink:
Cu structure (10 mK)

Thermal coupling:
Teflon (G = 4 pW/mK)

Thermometer:
NTD Ge-thermistor (100 kΩ/μK)

Absorber:
TeO₂ crystal
(C ≅ 2 nJ/K ≅ 1 MeV / 0.1 mK)

For E = 1 MeV: ΔT = E/C ≅ 0.1 mK

Signal size: 1 mV

Time constant: τ = C/G = 0.5 s

Energy resolution: ~ 5-10 keV at 2.5 MeV

main candidate isotope: $^{130}\text{Te}$
Q-value: $2526.515 ± 0.013$ keV
Isotopic abundance: 34%

27.01.2017
First pulse

27 Jan 2017
CUORE

Cryogenic Underground Observatory for Rare Events

- 988 TeO$_2$ crystals run as a bolometer array
  - 5x5x5 cm$^3$ crystal, 750 g each
  - 19 Towers; 13 floors; 4 modules per floor
  - 742 kg total; 206 kg $^{130}$Te
  - $10^{27}$ $^{130}$Te nuclei

- New pulse tube dilution refrigerator and cryostat
- Radio-pure material and clean assembly to achieve low background in region of interest (ROI)
Gran Sasso National Lab, Italy

1.4-km avg. rock overburden
= 3100 m.w.e. flat overburden

factor $10^6$ reduction in muon flux to $\sim 3\times10^{-8} \, \mu/(s \, cm^2)$
Low Background Experiment

- Y-beam
- Vibration isolation
- Cryostat
- \( H_3BO_3 \) panels
- Lead
- Polyethylene
- Borated polyethylene

Main support plate
- Concrete beams
- Sand-filled columns
- Concrete walls
- Screw jacks
- Movable platform

Seismic isolation

Roman lead ingots

- Natural shielding from rock
- Passive lead, polyethylene, and \( H_3BO_3 \) shielding
- 70 tonne of lead, 7 tonne of cold lead
- Material selection: Ancient Lead and low radioactive copper
- Active background veto
CUORE fabrication & cryostat commissioning
CUORE Results

• No evidence of $0\nu\beta\beta$

• Best fit rate: $(0.9 \pm 1.4) \times 10^{-26} \text{ yr}^{-1}$

• Background index = $1.49(4) \times 10^{-2}$ cts/keV/kg/yr

• $T_{1/2}^{0\nu} > 2.2 \times 10^{25} \text{ yr at 90\% C.I}$
What’s Next? CUPID

Measure heat and light from energy deposition
Heat is particle independent, but light yield depends on particle type
Actively discriminate $\alpha$ using measured light yield
CUPID Detector

Single module: Li$_2^{\text{100}}$MoO$_4$, 45x45x45 mm, 280 g
Detector: 57 towers of 14 floors with 2 crystals each, 1596 crystals
~240 kg of $^{\text{100}}$Mo with >95% enrichment
~1.6.10$^{27}$ $^{\text{100}}$Mo atoms
Ge light detector as in CUPID-Mo, CUPID-0

Gravity stacked structure
Crystals thermally interconnected
CUPID Collaboration

International collaboration builds on Italian-US partnership

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https://cupid.lngs.infn.it/