Neutrinoless Double Beta Decay

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The neutrinoless double beta decay ($\nu\beta\beta$) is currently the most feasible physical process to determine whether massive neutinos are Majorana particles. Though theorized over 70 years ago, this process still eludes us. Only relatively recently has this process once again gained interest with the discovery of non-zero neutrino mass through neutrino oscillations. With this interest has come a new generation of experiments searching for this decay. This paper seeks to give a historical context to the neutrinoless double beta decay as well as its importance to nuclear and particle physics. Furthermore, we will outline some of the physical mechanisms behind this process and into the experiments searching for it.

I. INTRODUCTION

A. Early Historical Context

Beta decay is a type of radioactive decay in which an energetic electron or positron and a neutrino are emitted from an atomic nucleus due to the transition from a neutron to a proton or vice versa. Specifically, in beta minus (β^-) a neutron is converted to a proton, emitting an electron and an electron antineutrino.

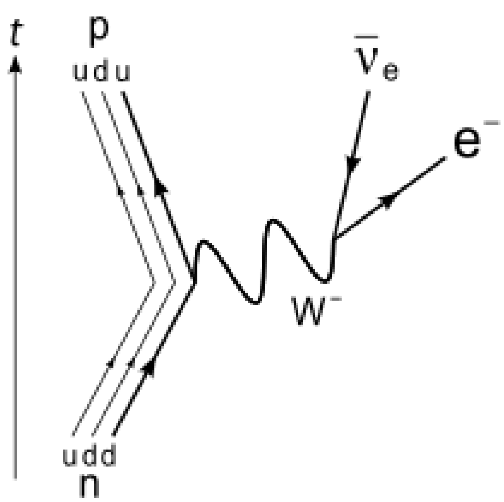

FIG. 1. β^- Feynmann Diagram

This process was originally theorized to occur with only an electron and proton as the decay product. As this process has only two products, with the mass of the proton and electron already known, the expected kinetic energy of the beta ray should be constant. In 1914, however, Chadwick demonstrated that, in fact, the electron kinetic energy was a continuous spectrum for beta decays (figure 2).

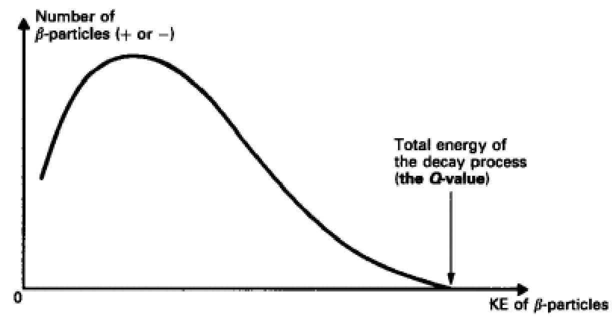

FIG. 2. Spectrum of beta emission energy. If the decay was purely a proton and electron pair the beta kintetic energy would always be at the O-value.

This discovery, in part, lead to Pauli hypothesizing, in 1930, the existence of a neutral particle, the neutrino (ν) – observed shortly after, in 1956, by Reines and Coward–, that is emitted along with the electron which carries away a portion of the final momentum, leading to the spectrum observed. This then lead to the now accepted beta decay shown in figure 1.

Double beta decay, namely two neutrino double beta decay ($2\nu\beta\beta$) was first considered by Goeppert-Mayer in 1935. Additionally, it was later shown by Majorana that if the neutrino was its own antiparticle that the theory of beta decay was unchanged. Ultimately, these theories led to the that of neutrinoless double beta decay by Furry in 1939. In this theorized event, two beta emissions occur simultaneously in which a Majorana neutrino is shared between the electrons as a virtual particle, resulting only in electron emission (figure 3).

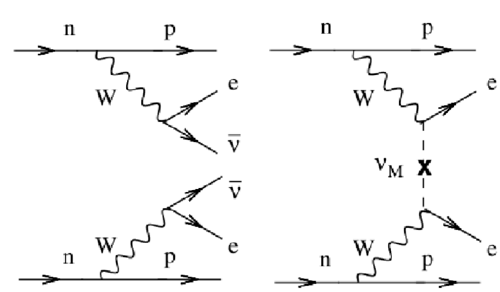

FIG. 3. $2\nu\beta\beta$ (left) and $0\nu\beta\beta$ (right)

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B. Neutrino Mass

In 1955 the Raymond Davis experiment searched for antineutrinos from a reactor via the reaction $\bar{\nu}+^{37}Cl \rightarrow^{37} Ar + e^-$ yielded no result. This was interpreted as proof that the neutrino was not a Majorana particle and instead a Dirac particle with an associated lepton number distinguishing it from its antiparticle. This assumption of lepton number conservation allows for the $2\nu\beta\beta$ node and forbids the $0\nu\beta\beta$ decay.

Within the Standard Model, the assumption of lepton number conservation requires the neutrino to be strictly massless. With the development of Grand Unified Theories (GUT) of the electroweak and the strong interaction, it was realized, however, that lepton number conservation is a result of a global symmetry and had to be broken at some level. The lepton number may only appear to be conserved at low energies because of the large grand unified mass scale, Λ_{GUT}, governing its breaking. Within this paradigm the neutrino has an expected small Majorana mass $m_\nu \sim (light\ mass)^2/\Lambda_{GUT}$.

In recent years, neutrino oscillations have been observed for which neutrinos oscillate from one flavor (electron, muon, or tau) to another. This is expected as a consequence of a non-zero neutrino mass. Measurements of neutrino oscillations from sources such as the sun, the atmosphere, and accelerators have provided convincing evidence of the existence of neutrino masses due to experiments such as SuperKamiokande, SNO, KamLAND and many others. These oscillation experiments, however, cannot determine whether neutrinos are Majorana or Dirac particles nor can they determine the absolute scale of the neutrino mass – only the squared difference between the flavors. This problems can be solved, however, if $0\nu\beta\beta$ decay is observed.

C. Importance

As discussed above, there are significant implications if the neutrinosless double beta decay is observed. One of the most notable, as we have mentioned, is the violation of lepton number conservation. This discovery would show the breakdown of the SM at low energies and give greater insights into GUT parameters. This is obviously a significant contribution to new physics and will give a greater insight into the regime between high and low energy physics.

Furthermore, the observation of $0\nu\beta\beta$ would provide an absolute Majorana neutrino mass as well as provide insight into the dominating process of double beta decay along with neutrino mixing coefficients thus giving us a greater understanding of neutrino behavior.

II. BASIC PHYSICAL MECHANISMS

The effective Hamiltonian for the $0\nu\beta\beta$ decay is given by

$$H(x) = \frac{G_F}{\sqrt{2}} 2 \sum_i \bar{e_L}(x)\gamma_a U_{li}\nu_{iL} j^\alpha(x)$$

for which G_F is the Fermi constant, j^α is the hadronic charged current, and the field ν_i satisfies the condition of neutrinos such that

$$\nu_i^c(x) = C\nu_i^T(x) = \nu_i(x)$$

This assumes the Hamiltonian of weak ineractions given by the Standard Model, that neutrino mixing takes place, and that massive neutrinos are Majorana particles.

Because the neutrinoless double beta decay is a second order process, it is an exceptionally rare event. Following the standard, albeit complex in this case, method of determining the decay rate using this second order matrix elements, the decay rate is found to be

$$\Gamma^{0\nu} = \frac{1}{T_{1/2}^{0\nu}} = |m_{\beta\beta}|^2 |M^{0\nu}|^2 G^{0\nu}(Q,Z)$$

Where $G^{0\nu}$ is the kinematic phase space factor which depends on the source nuclei.

Nucleus	$G^{0\nu}(Q,Z)$ $(10^{-25}y^{-1}eV^{-2})$
^{76}Ge	0.30
^{100}Mo	2.19
^{130}Te	2.12
^{136}Xe	2.26

TABLE I. The value of $G^{0\nu}$ for some known $0\nu\beta\beta$ decay nuclei.

And where

$$m_{\beta\beta} = \sum_i U_{ei}^2 m_i$$

is the effective Majorana mass and

$$M^{0\nu} = M_{GT}^{0\nu} - \frac{1}{g_A^2} M_F^{0\nu}$$

is the nuclear matrix element with $M_F^{0\nu}$ being the Fermi matrix element and $M_{GT}^{0\nu}$ being the Gamov-Teller matrix element.

III. DETECTION METHODS

A. Mass Hierarchy and Sensitivity

One of the largest driving parameters for the sensitivity of $0\nu\beta\beta$ decay detectors is the scale of the neutrino mass. The neutrino mass is scale is dependent on the mass hierarchy that is a result of flavor oscillations.

In the mass basis the three flavor oscillations are given by

$$|\nu_i\rangle = \sum_{l=e,\mu,\tau} U_{li}\,|\nu_l\rangle \tag{1}$$

with U as the neutrino mass matrix. This leads to the probability of finding the component ν_l of each mass eigenstate ν_i as depicted in figure 4

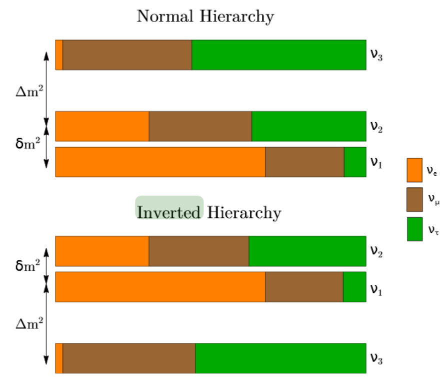

FIG. 4. Probability of finding one flavor eigenstate if the neutrino is in a given mass eigenstate.

Limits on the neutrino mass can be placed depending on the hierarchy of the neutrino mass:

1.) Normal Hierarchy: $m_1 \ll m_2 \ll m_3$ For the masses we have:

$$m_1 \ll \sqrt{\delta m^2}, \quad m_2 \simeq \sqrt{\delta m^2}, \quad m_3 \simeq \sqrt{\Delta m^2}$$

If we ignore the small contribution from m_1 we have

$$|s_{12}^2 c_{13}^2 \sqrt{\delta m^2} - s_{13}^2 \sqrt{\Delta m^2}| \leq m_{\beta\beta} \leq s_{12}^2 c_{13}^2 \sqrt{\delta m^2} + s_{13}^2 \sqrt{\Delta m^2}$$

Using the measured values for the mixing angles an mass squared differences, we have

$$1.4\ meV \leq m_{\beta\beta} \leq 3.6\ meV$$

1.) Inverted Hierarchy $m_3 \ll m_1 < m_2$ Using a similar method as above:

$$m_3 \ll \sqrt{\Delta m^2}, \quad m1 \simeq m_2 \simeq \sqrt{\Delta m^2}$$

$$|1 - 2s_{12}^2| c_{13}^2 \sqrt{\Delta m^2} \leq m_{\beta\beta} \leq c_{13}^2 \sqrt{\Delta m^2}$$

$$20\ meV \leq m_{\beta\beta} \leq 49\ meV$$

This, along with cosmological observations of possible neutrino masses, gives the distribution seen in figure 5.

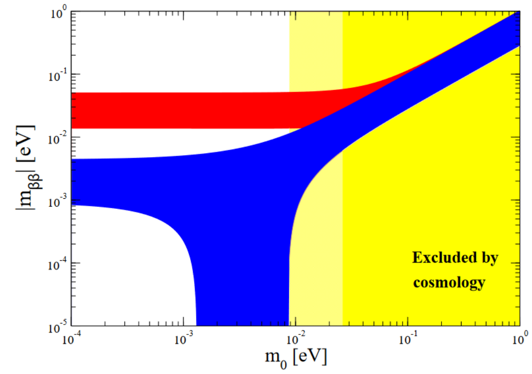

FIG. 5. Predictions of $m_{\beta\beta}$ from neutrino oscillations versus the lightest neutrino mass.

Due to these two possible cases, when designing a detector one must choose the source nuclei to focus on which region they anticipate to see the neutrino mass.

B. Sources

So far $2\nu\beta\beta$ decay has been recorded in eleven nuclei (^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{150}Nd, ^{136}Xe, ^{238}U). As stated above, the choice of source plays a major role in the experiment's energy range and sensitivity. The experiemental sensity of the half life $0\nu\beta\beta$ decay is given by

$$T_{\frac{1}{2}} > ln(2)\frac{\epsilon \cdot N_{source} \cdot T}{UL(B(T) \cdot \Delta E}$$

where ϵ is the detector efficiency, N_{source} is the number of isotopes, T is the observation time, and $UL(B(T)\Delta E$ is the upper limit for expected background events in the region of interest as a function of energy width of the ROI.

C. Experiments

Experiment	Isotope	Techinique	Total mass [kg]	Exposure [kg yr]	FWHM @ $Q_{\beta\beta}$ [keV]	Background [counts/keV/kg/yr]	$S^{0\nu}$ (90% C. L.) [10^{25} yr]
Past							
Cuoricino, [179]	^{130}Te	bolometers	40.7 (TeO_2)	19.75	5.8 ± 2.1	0.153 ± 0.006	0.24
CUORE-0, [180]	^{130}Te	bolometers	39 (TeO_2)	9.8	5.1 ± 0.3	0.058 ± 0.006	0.29
Heidelberg-Moscow, [181]	^{76}Ge	Ge diodes	11 (^{enr}Ge)	35.5	4.23 ± 0.14	0.06 ± 0.01	1.9
IGEX, [182, 183]	^{76}Ge	Ge diodes	8.1 (^{enr}Ge)	8.9	~ 4	$\lesssim 0.06$	1.57
GERDA-I, [167, 184]	^{76}Ge	Ge diodes	17.7 (^{enr}Ge)	21.64	3.2 ± 0.2	~ 0.01	2.1
NEMO-3, [185]	^{100}Mo	tracker + calorimeter	6.9 (^{100}Mo)	34.7	350	0.013	0.11
Present							
EXO-200, [186]	^{136}Xe	LXe TPC	175 (^{enr}Xe)	100	89 ± 3	$(1.7 \pm 0.2) \cdot 10^{-3}$	1.1
KamLAND-Zen, [187, 188]	^{136}Xe	loaded liquid scintillator	348 (^{enr}Xe)	89.5	244 ± 11	~ 0.01	1.9
Future							
CUORE, [189]	^{130}Te	bolometers	741 (TeO_2)	1030	5	0.01	9.5
GERDA-II, [174]	^{76}Ge	Ge diodes	37.8 (^{enr}Ge)	100	3	0.001	15
LUCIFER, [190]	^{82}Se	bolometers	17 (Zn^{82}Se)	18	10	0.001	1.8
MAJORANA D., [191]	^{76}Ge	Ge diodes	44.8 ($^{enr/nat}$Ge)	100 [a]	4	0.003	12
NEXT, [192, 193]	^{136}Xe	Xe TPC	100 (^{enr}Xe)	300	$12.3 - 17.2$	$5 \cdot 10^{-4}$	5
AMoRE, [194]	^{100}Mo	bolometers	200 (Ca^{enr}MoO$_4$)	295	9	$1 \cdot 10^{-4}$	5
nEXO, [195]	^{136}Xe	LXe TPC	4780 (^{enr}Xe)	12150 [b]	58	$1.7 \cdot 10^{-5}$ [b]	66
PandaX-III, [196]	^{136}Xe	Xe TPC	1000 (^{enr}Xe)	3000 [c]	$12 - 76$	0.001	11 [c]
SNO+, [197]	^{130}Te	loaded liquid scintillator	2340 (^{nat}Te)	3980	270	$2 \cdot 10^{-4}$	9
SuperNEMO, [198, 199]	^{82}Se	tracker + calorimeter	100 (^{82}Se)	500	120	0.01	10

FIG. 6. Parameters and performance of $0\nu\beta\beta$ experiements

Detection methods early on where primarily Germanium diodes in which a ^{76}Ge emmiter is embedded in a solid state detector using a calorimetric approach. Germanium, however, has a low natural abundance meaning that, for these detectors, isotopically enriched material needs to be produced.

^{130}Te is another common emitter for $\beta\beta$ decay and has a high natural abundance. This source is used in the form TeO_2 to build bolometric detectors. Bolometric detectors are operated at milli-kelvin temperatures so that the energy released into the crystal due to decays can be measured by the rise in temperature of the crystal. Other sources, such as ^{100}Mo can be used in bolometers with the same process as described above.

Other detector types include pressurized gas vessels, in which the gas is its own emitter, as well as scintillators and tracker detectors enclosing the source.

Most of the present day detectors still in their early phases, including construction and determining background counts, and will likely take quite some time two observe these events, due to their theorized rarity, even if the event does exist. At present, however, most detectors, while extremely sensitive, can only provide insight into the inverted hierarchy regime shown in figure 5. As such, further refinements and phases are being made to these experiments even now to be able to probe these lower energy events.

IV. SUMMARY

Neutrinoless double beta decay is an exiting physical topic that has gained traction in recent years. This even would play a unique role into neutrino physics, such as the neutrino mass and Majorana nature, as well as would provide evidence for lepton number violation. Many large mass, high sensitivity, experiments are running or are soon to be running which will provide important results on this process.

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