A Review of Double Beta Decay

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Abstract

Double beta decay is a rare transition between two nuclei with the same mass number but nuclear charge changes by two units. Double beta decay is presently very important topic in nuclear and particle physics, in this review paper we have discussed all historical and recent development in this field and latest compilation of data in this field is presented.

Keywords: Double Beta Decay, neutrino, oscillations etc.

Introduction:

In radioactivity phenomenon when neutrons becomes excessive in comparison of proton then ratio of n/p becomes greater than one then this phenomenon predominantly occurs. Basically there are three type of beta decay which naturally occurs. In this type of decay neutron transforms into the proton and at the same time electron and antineutrino are also formed. These two particles eject out from the nucleus consequently in the nucleus value of neutron decreases and value of proton increases and daughter nucleus approach towards the maximum stability lines. This process is known as negative beta emission.

$$^{14}{}_{6}C \rightarrow {}^{14}{}_{7}N + \beta^{-} + \bar{\nu} \quad \text{(negative beta decay)}$$

In radioactivity phenomenon when protons becomes excessive in comparison of neutron then ratio of p/n becomes greater than one then this phenomenon predominantly occurs. In this type of decay proton transforms into the neutron and at the same time positron and neutrino are also formed. These two particles eject out from the nucleus consequently in the nucleus value of proton decreases and value of neutron increases and daughter nucleus approach towards the maximum stability lines. This process is known as positive beta emission.

$$^{22}{}_{11}Na \rightarrow {}^{22}{}_{10}Ne + \beta^{+} + \nu \quad \text{(positive beta decay)}$$

In third mechanism of the beta decay nucleus captures one of its orbital electron and then proton of the orbital electron is converted into a neutron and a neutrino is emitted.

$$^{54}{}_{25}Mn + \beta^{-} \rightarrow {}^{54}{}_{24}Cr + \nu \quad \text{(orbital electron capture)}$$

This orbital electron is usually captured from the K-shell but some times capturing of electron from the L-level are also known. If capturing electron comes from the K- shell then the process is said to be K -capture if from the L- shell then the process is said to be L- capture and so on. Electron captures occurs more frequently then positron emission in heavy nucleus because in such nuclei electron orbits are much nearer to the nucleus and so electrostatic attractive force between the protons of the nucleus and electrons of the orbits becomes enormously large and capturing of orbital electron by the proton of the nucleus take place.

When electron from the K-shell is captured by the proton then orbital electron from the L- shell jumps into K – shell to fill the vacancy created due to K- capturing and so a X-ray photon is emit out which have the energy between the difference of K- shell energy and L -shell energy if this X -ray photon have the energy greater than the binding energy of L- shell electron and it falls upon the L-shell electron then this electron also eject out from the atom and this electron is said to be Auger electron and phenomenon is said to be Auger effect.

Double beta decay is a rare transition between two nuclei with the same mass number (A) that change the nuclear charge (Z) by two unit. This type of decay can proceed on the if the initial nucleus is the less bound than the final one, and both must be more bounded then the intermediate nucleus. In 1935 Goepper, Mayer introduce the possibility of two neutrino double beta decay and this process can be described as

$${}^{A}{}_{Z}X \to {}_{Z+}{}^{A}{}_{2}Y + 2\beta^{-} + 2\bar{\nu}$$

Wigner was the first physicist who consider such possibility and Majorona in 1937 shows that theory of beta decay remains unchanged if neutrino and antineutrino have same properties.

Decay	Transformation	Reason for instability
Beta decay	${}_{A}X \to {}_{Z+A1}Y + e_{-} + \bar{\nu}$ $_{Z}$	Nucleus has too many neutrons relative to protons
Positron emission	${}_{A}X \to {}_{Z-A1}Y + e_{+} + \nu$ $_{Z}$	Nucleus has too many protons relative to neutrons
Orbital electron capture	${}_{A}X + e_{-} \to {}_{Z-A1}Y + \nu$ $_{Z}$	Nucleus has too many protons relative to neutrons
Auger Effect	Orbital e^{-} capture + Auger e^{-}	Nucleus has too many protons relative to neutrons
Double beta decay	${}^{A}X \to {}_{Z+}{}^{A}{}_{2}Y + 2\beta^{-} + 2\bar{\nu}$ $_{Z}$	To move closer to the optimal ratio of protons and neutrons

Double Beta Decay:

In the double beta decay process

$${}^{A}{}_{Z}X \to {}_{Z+}{}^{A}{}_{2}Y + 2\beta^{-} + 2\bar{\nu}$$

This is the second order process of weak interaction and this process occurs because of pairing force renders the even- even nuclei with even number of protons and neutrons more stable than the odd – odd nuclei with broken pairs.

Massive neutrino: all the basic properties of neutrino is not known . Majorona predicted that it is its own antiparticle, the number of massive neutrino depends on mixing of neutrino and various others (3 -6 together) and finite mass of neutrino is directly linked to problem of flavor violation, the standard model strictly conserve lepton flavor but GUT extensions of standard model violet it.

Neutrino Oscillation and challenges:

By the time the neutrino gets to the earth through the cosmic radiation and there are three type of neutrino which exist in nature

ν_e e- neutrino

ν_μ µ- neutrino

ν_τ τ- neutrino

Neutrino are very difficult to detect. Still there are many properties which are still unresolved for the scientist

1. What is the exactly antiparticle of neutrino ?
2. Still mass of three neutrino is unknown.
3. Form of neutrino and its all properties is still unknown.
4. Why and how neutrino change its shape and property.

Double Beta Decay Historical Development

Date/Period	Discovery	Names
1935	2νββ decay	M.G Mayer
1939	First consideration of 0νββ decay	W.H Furry
Around 1950	First experiment to detect ββ decay	E.L Firemann, M.G Inghram and others
1956	Discovery of parity violation in weak interaction	T.D Lee, C.N Yang and S.Wu
Around late 60's	Verification of existence of 2νββ decay	T.Kirsten, O.K Manuel and others
Later 1970	Grand unification theory which predict finite mass of neutrino	H.Georgi and P Minkowski
1979-80	See Saw mechanism	M Gell Mann and others
Early 1980	Finite mass of neutrino	J.W.F Valli, W.Haxton and others
1987	First discovery of 2νββ decay with experiment	M.Moe
1997	Extension of theory for finite mass of neutrino	H.V Klapdon, M Hirsch and others
1986-2000	Lapto Quarks	J.D Vargadas and others
2015	Discovery of neutrino oscillations	Takaaki Kijita and A.M Mcdonald (Nobel prize)

Neutrino Mass Theoretical Aspects:

Majorana and Dirac Neutrinos: neutrino masses are much smaller than the masses of the charged leptons with which they form the weak iso doublets and interact with weak interaction basically neutrino are massive Majorana fermions and Majorana particles are identical with there own antiparticle where as Dirac particles can be distinguish from there anti particles and Majorana fermions have two component objects and Dirac fermions have four component objects. Therefore Majorana and Dirac neutrino properties and their distinguishability is really challengeble to physics community.

Fury introduced the two way process of two beta decay

1. Initially parents nucleus emits one electron and transits to a virtual intermediate nucleus and virtual antineutrino.

2. The virtual antineutrino is the same as neutrino is absorbed by the intermediate nucleus and it induced to decay with the emission of second electron and this process can be described as

   $_{AZ}X \rightarrow {}_{Z+A2}Y + 2\beta-$

   During the era of 1940-50 experiments search for Dirac Majorana neutrino was done and Ingharm and Reyholds detected the two beta decay of Te^{130} and they obtained half life of the order of 1.4×10^{21} years. In 1975 Manuel and team observed first time the 2 β decay of Te^{128} through the experiment. In the era of 1980-90 Lubimov observed the detection of neutrino mass in the measurement of of β spectrum of tritium.

   Model independent evidence of neutrino oscillations done in 1998 by super kamiokandle. In 2002 neutrino was detected by the help of solar neutrino experiment.

Characteristics of Commonly used ββ Decay Isotopes

Isotope	**Natural Abundance**	**$Q_{\beta\beta}$(MeV)**
Ca_{48}	0.187	4.263
Ge_{76}	7.8	2.039
Se_{82}	8.7	2.998
Zr_{96}	2.8	3.348
Mo_{100}	9.8	3.035
Cd_{116}	7.5	2.813
Te_{130}	34.08	2.527
Xe_{136}	8.9	2.459
Nd_{150}	5.6	3.371

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Energies and Ranges of Beta Particle

Nuclide	**Endpoint energy (MeV)**	**Range mg/cm^2**
Ra_{228}	0.053	6
Rb_{87}	0.13	20
Nb_{95}	0.146	30
Lu_{176}	0.22	48
Co_{60}	0.31	81
Zr_{95}	0.400	122
Be_{10}	0.555	181
I_{131}	0.600	213
Sb_{124}	0.65	254
Mn_{56}	0.73	277
Au_{198}	0.97	399
C_{11}	0.98	447
Ba_{140}	1.022	426
Mn_{56}	1.05	462

Cd_{115}	1.13	527
Bi_{210}	1.17	508
N_{13}	1.24	557
Na_{24}	1.39	601
Sr_{89}	1.50	741
P_{32}	1.71	810
Te_{129}	1.80	812
Mg_{27}	1.80	821
Homogeneous rays	2.00	965
Y_{90}	2.18	1065
Bi_{212}	2.25	1023
Rh_{106}	2.30	1080
Pa_{234}	2.32	1105
Sb_{124}	2.37	1220
As_{76}	2.56	1384
Rh_{104}	2.6	1198
Mn_{56}	2.86	1440
Cu_{62}	2.92	1440
Homogeneous rays	3.00	1540
Pr_{144}	3.07	1575
As_{76}	3.12	1454
Rh_{106}	3.55	1770

Katz and Penfold: Revs. Modern Phys. 24, 28 (1952) **Development in ββ Decay:**

1. The discovery of neutrino oscillation in last two decades shows that all neutrino mass are different and at least two of them being non zero and lepton mixing occurs at large scale.
2. Standard model forbidden the neutrino less double beta decay process. This process cofirms the lepton number violation and Majorana nature of neutrino.
3. Range of neutrino in 0γββ model lies from few electron volt in lighter neutrino and upto TeV in heavy size neutrino.
4. Energy released in the double β decay process can be evaluated from the process $_{A}X \rightarrow$ $_{Z+A2}Y + 2\beta_{-} + 2\bar{\nu} +$ $Q_{\beta\beta}$
   Z
   This process is second order weak decay and having life time of the order of 10^{19} years.
5. Standard model forbidden ββ decay mode can be expressed as
   $_{AZ}X \rightarrow {}_{Z+A2}Y + 2\beta_{-} +$ $Q_{\beta\beta}$
   Here in this process no neutrino are emitted and lepton number is violated by two unit ($\Delta L = 2$) but experimental verification of this process is still challengable to the scientist community.
6. In recently 0γ ββ decay was experimentally confirmed and it is providing half life time in the range of 10^{25} to 10^{26} years.
7. In the standard model lepton number represents an accidental global symmetry therefore GUT needs new type of neutral fermions. Observation shows that matter exist in the universe and to explain the beyond standard model we needed matter and anti matter creation theory and its existance.

8. In the standard light neutrino mechanism (SLNM) for 0γ ββ decay half life time is directly proportional to λ^2 where λ is said to be scale of neutrino mass generation.
9. According to standard model neutrino are massless and total lepton number and individual flavor lepton number are conserved. But observation of neutrino mass and oscillation providing departure from the standard model.
10. Half life time of the process is inversely proportional to phase space factor and it also depends upon axial vector and NME.
11. For measuring the half life of the decay large detector masses, high isotopic abundance good energy resolution and ultra low background noise is needed. 12. For 0γ ββ decay half life time can be given as

$$T_{1/2} \quad 10^{27} - 10^{28} \left(\frac{0.01eV}{<m_{\beta\beta}>} \right)^2 \cong \text{years}$$

Here $< m_{\beta\beta} > \cong 0.2$ eV and this expression shows that half life time is inversely proportional to square of $m_{\beta\beta}$.

13. For 0γ ββ decay half life in terms of measuring time (T) and detection efficiency (ε) can be described as

$T_{1}{}^{0}/{}^{\nu}{}_{2} = log2^{T\varepsilon}{}_{N}\underline{\quad\quad}{}^{N_{peak}\beta\beta}$ here $N_{\beta\beta}$ = no. of ββ decay nuclei under observation, N_{peak}

= number of counts at peak.

LEGEND and other Experiments

Experiment	Iso	$T_{0\nu 1/2}$ Years	$< m_{\beta\beta} >$ (meV)
LEGEND-200	Ge_{76}	10_{27}	34-74
LEGEND-1000	Ge_{76}	6×10^{27}	14-30
Super NEMO	Se_{82}	10_{26}	58-144
CUPID	Se_{82}	2.1×10^{27}	13-31
AMoRE-I	Mo_{100}	2.8×10^{25}	74-126
AMoRE-II	Mo_{100}	10_{27}	12-21
CUPID	Te_{130}	2.6×10^{27}	8-38
SNO+Phase I	Te_{130}	1.9×10^{26}	31-139
SNO+Phase II	Te_{130}	7.4×10^{26}	16-71
KamLAND-Zen800	Xe_{136}	4.6×10^{26}	24-77
KamLAND2-Zen	Xe_{136}	1.4×10^{27}	14-44
nEXO	Xe_{136}	6×10^{27}	7-21
NEXT-100	Xe_{136}	8.5×10^{27}	56-180
PandaX-III 200	Xe_{136}	1.3×10^{26}	45-145
PandaX-III 1000	Xe_{136}	1.3×10^{27}	14-46

LEGEND- Large enriched Germanium Experiment for Neutrinoless ββ Decay

14. First observation of double beta decay was made by S.R Elliott, A.A Hahn and M.K Moe at University of California in 1987. They measured double beta decay in a sample of Se^{82}.
15. Now a days European researchers in the Germanium detector as a collaboration (GERDA) based at Gran Sasso laboratory in Italy have achieved the best sensitivity in the search for

double beta decay. They are using high purity germanium as the detector medium and radioactive Ge^{76} which has an unstable nucleus that decay through double beta decay.

16. GERDA saw no neutrinoless double beta decay even with the highest yet sensitivity so hunt for double beta decay continue by the scientific community.
17. Various organization like as GERDA is using Ge^{76} as a radio isotope and HPGe as a detector. Organization like as EXO is using Xe^{136} as a radio isotope and TPC +Ba^{+} as a detector. Organization like as KamLAND-Xe is using Xe^{136} as a radio isotope and liquid scintillator as a detector. Organization like as CUORE is using Te^{130} as a radio isotope and cryogenic as a thermal detector.

18. The nobel prize in physics in 2015 was awarded to Takaaki Kajita and Arthur B Mcdonald for the discovery of neutrino oscillations which provided that neutrino have finite mass.
19. For the detection and measurement of neutrinoless double beta cecay following crystal scintillation detector are using.
    a) Cd^{106} and Cd^{116} with $CdWO_4$ crystal scintillator.
    b) Ca^{48} with CaF_2 and $CaWO_4$ crystal scintillator
    c) Zn^{64}, W^{180} and W^{186} with $ZnWO_4$ crystal scintillator.
    d) Mo^{100} with $CaMoO_4$ crystal scintillator.
    e) Gd^{160} withGd_2SiO_5: Ce scintillator crystal.

20. The name neutrino (little neutral 1) was proposed by Pauli in 1930 and he proposed that it carries the momentum and energy and responsible for continuous spectrum of beta rays.

21. Reines and Cowan detected the neutrino in 1953 at Hanford. For this detection Reines won the nobel prize in 1995 but unfortunately Cowan had died and nobel was not awarded to him.
22. In 1988 Nobel prize in physics was awarded to Lederman, Schwartz and Steinberger for the neutrino beam method and showing that there are two different neutrinos exist in the nature.
23. Koshiba and Davis got the nobel prize in physics for the detection of cosmic neutrinos in 2002.
24. When neutrino oscillation takes place and neutrino reaches on the surface of the earth then we have the same number of neutrinos but many of neutrinos have change the type. After the 8 min. which is the time taken to reach the neutrino from the sun on the earth they all are mixed up.
25. Wolfenstein, Mikheyev and Smirnov proposed that neutrino should have finite mass if it makes the oscillations.
26. Ca^{40},Zr^{96} and Nd^{150} are best suited for ββ decay because they have high Q value in the range of 3MeV but they have low natural isotopic abundance.
27. Se^{82}, Mo^{100} and Cd^{116} Q value between 2.8 to 3 MeV so they are not affected by β/γ natural radioactivity but in these cases isotopic abundance is very low and enrichment is very costly.
28. Te^{130} and Xe^{136} have smaller Q value but they have high natural abundance and can be easily enriched at lower cost.
29. Detector sensitivity for 0γββ decay depends upon isotopic abundance of the source, detection efficiency etc and mathematically we have

$$T_{\frac{1}{2}}(0\gamma\beta\beta) = a\varepsilon\frac{\sqrt{M.T}}{B.dE}$$

Where a = isotopic abundance of a source
ε = detection efficiency M = total mass
T = exposure time
B = back ground in 0γββ ROI dE
= energy resolution **References:**

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