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Double beta decay: experiments

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Abstract. The results obtained so far and those of the running experiments on neutrinoless double beta decay are reviewed. The plans for second generation experiments, the techniques to be adopted and the expected sensitivities are compared and discussed.

1. Introduction

As it is well known double beta decay (DBD) is a rare process where, in the two negatron case, a nucleus (A,Z) directly transforms itself in its isobar (A,Z+2). This transition can be detected when the single beta decay of (A,Z) to (A,Z+1) is either energetically forbidden or at least strongly hindered by a large change in the spin-parity state. Two neutrino DBD, where two neutrinos are emitted with the two electrons is allowed by the standard model and has been observed in ten nuclei [1, 2]. Lepton number is on the contrary violated when the two electrons are emitted alone or with one or more massless Goldstone bosons named *majoron.* In the former of these channels, normally named *neutrinoless DBD*, the two electron share the total transition energy. A peak would appear in this case at the energy corresponding to the transition one. While generally regarded at the beginning as a very powerful tool to test the lepton number, neutrinoless DBD is presently considered an essential method to determine the absolute value [3] of the $|m_{0\nu}|$, for a Majorana neutrino. A model independent way to determine the neutrino mass has been provided by the single beta decays of ^{3}H and of ^{187}Re [2], but the present sensitivity on the bounds on $|m_{0\nu}|$ is of 2.2 eV only, even if a constraint of 0.2 eV is expected from the KATRIN experiment [5]. A model dependent upper limit from .7 to 1.7 eV on the sum of the masses of the neutrinos of the three different flavors can be obtained from the results of the full sky microwave maps of WMAP together with 2dF Galaxy Redshift Survey [4]. A claim for a finite mass of 0.56 eV has also been presented [6].

2. Present results on neutrinoless DBD

DBD can be searched for with *indirect* (geochemical or radiochemical) experiments [1, 2] based on the detection of the isobar (A,Z+2) in rocks of geological age or in stored materials containing the nucleus(A,Z) These experiment have proven the existence of DBD in ^{82}Se, ^{128}Te, ^{130}Te and, with a lower statistical significance, in ^{96}Zr. They cannot however discriminate among the different DBD channels, including those of DBD to excited nuclear levels of the daughter nucleus.

The *direct* experiments are based on two different experimental approaches. In the *source=detector* or *calorimetric* ones the detector itself is made by a compound which contains

Table 1. Results on two neutrino DBD

Nucleus	%	$Q_{\beta\beta}$(keV)	$T^{2\nu}_{1/2}(measured)(y)$	$T^{2\nu}_{1/2}(calculated)(y)$
^{48}Ca	0.19	4271	$4.2^{+2.1}_{-1.0} \times 10^{19}$	$6 \times 10^{18} - 5 \times 10^{20}$
^{76}Ge	7.8	2039	$1.42^{+.09}_{-.07} \times 10^{21}$	$7 \times 10^{19} - 6 \times 10^{22}$
^{82}Se	9.2	2995	$(.9 \pm .1 \times 10^{23}$	$3 \times 10^{18} - 6 \times 10^{21}$
^{96}Zr	2.8	3350	$4.2^{+2.1}_{-1.0} \times 10^{19}$	$3 \times 10^{17} - 6 \times 10^{20}$
^{100}Mo	9.6	2995	$(8 \pm .7 \times 10^{18}$	$1 \times 10^{17} - 2 \times 10^{22}$
^{100}Mo(0^{+*})	9.6	2995	$(6.8 \pm 1.2 \times 10^{20}$	$5 \times 10^{19} - 2 \times 10^{21}$
^{116}Cd	7.5	3034	$3.3^{+.4}_{-.3} \times 10^{19}$	$3 \times 10^{18} - 2 \times 10^{21}$
^{128}Te	34	867	$(2.5 \pm .4 \times 10^{24}$	$9 \times 10^{22} - 3 \times 10^{25}$
^{130}Te	33.8	2530	$(.9 \pm .15 \times 10^{21}$	$.2 \times 10^{19} - 7 \times 10^{20}$
^{150}Nd	5.6	3367	$(7 \pm 1.7 \times 10^{18}$	$6 \times 10^{16} - 4 \times 10^{20}$
^{238}U	99.3	1145	$(2.0 \pm .6 \times 10^{21}$	1.2×10^{19}

the candidate nucleus for DBD. In the *source≠detector* ones on the contrary the DBD source, normally in the form of thin sheets to reduce the energy dispersion, is interleaved with the detector. The positive results obtained so far on two neutrino DBD are reported in Table 1 together with theoretical predictions. The agreement looks good (sometimes even too good!). The great quality of these experiments is indicated by the fact that, especially for some nuclei, the measured lifetimes are very large. This indicates strenuous experimental efforts to reduce the background. The results are often among the best ever obtained in low radioactivity physics. One could also note that in some experiments on neutrinoless DBD, where an extraordinary reduction of the background is required and where the detector resolution is not sufficiently good, the unavoidable *background* from two neutrino DBD in the neutrinoless region could represent an insurmountable limit..

Searches on neutrinoless DBD are at present considered as a powerful way to determine the absolute neutrino mass $|m_{0\nu}|$ and to test if neutrino is a Majorana or a Dirac particle. The rate of this process is proportional to a phase term, which can be rather easily calculated, to the square of $|m_{0\nu}|$ and to the square of the nuclear matrix element. Calculation of this last term is quite difficult and has led so far to different results from different authors. As a consequence it is mandatory to search for neutrinoless DBD in two or more nuclei. From the experimental point of view there is another reason to do this. The presence of neutrinoless DBD is revealed in the background spectrum of the sum of the two electron energies by a peak in correspondence to the transition energy. Natural and androgenic radioactivity produces however many peaks in the spectrum in all experiments. As a consequence, if a peak appear indicating neutrinoless DBD appears, one should ensure that it has not been mimicked by some unforeseen radioactivity peak. It is therefore mandatory for a undisputable evidence of this very important phenomenon to search for neutrinolss DBD in two or more different nuclei. The appearance of peaks at the different positions expected for the corresponding values of the transition energy, would definitely prove the existence of neutrinoless DBD.

The results obtained so far on neutrinoless DBD and the techniques adopted for these searches are shown in Table 2.

As it can be seen in Table 2 no evidence has been reported so far for neutrinoless DBD with the exception of that claimed by a subset of the Heidelberd-Moscow collaboration [7]

Table 2. Results on neutrinoless DBD

Nucleus	Experiment	%	$Q_{\beta\beta}$(keV)	Technique	$T_{0\nu}$ (y)	$\|m_{0\nu}\|$(eV)
^{48}Ca	Elegant IV	0.19	4271	Scintillator	$> 1.4 \times 10^{22}$	7-45
^{76}Ge	Heidelberg-Moscow	7.8	2039	Ionization	$> 1.9 \times 10^{25}$	.12-1
^{76}Ge	IGEX	"	"	"	$> 1.6 \times 10^{25}$	.14-1.2
^{76}Ge	Klapdor et al	"	"	"	1.2×10^{25}	.44
^{82}Se	NEMO 3	9.2	2995	Tracking	$> 1 \times 10^{23}$	1.8-4.9
^{100}Mo	NEMO 3	"	"	"	$> 4.6 \times 10^{23}$	.7-2.8
^{116}Cd	Solotvina	7.5	3034	Scintillator	$> 1.7 \times 10^{23}$	1.7-?
^{128}Te	Bernatovitz	34	867	Geochemical	$> 7.7 \times 10^{24}$	.1-4
^{130}Te	CUORICINO	33.8	2530	Bolometric	$> 2 \times 10^{24}$	.2-1.0
^{136}Xe	DAMA	8.9	2476	Scintillator	$> 1.2 \times 10^{24}$	1.1-2.9
^{150}Nd	Irvine	5.6	3367	Tracking	$> 1.2 \times 10^{21}$	3-?

which has been however widely disputed [8, 9, 10], also by other members of the Heidelberg-Moscow collaboration [11]. Replies to these contestations and a more detailed analysis have been published more recently [12, 13]. I consider the question still quite open. As mentioned before, I believe that this result, even if proven to be true for ^{76}Ge, should be confirmed by detection of the peak indicating neutrinoless DBD in one or more different nuclei.

Two running experiments are presently challenging the Klapdor-Kleingrothaus results : NEMO 3 and CUORICINO,

NEMO 3 [14] is a source≠detector experiment carried out in the Frejus tunnel between France and Italy. The detector is made by thin layers of ^{116}Cd, ^{96}Zr, ^{150}Nd, ^{48}Ca, ^{130}Te and natural Te interleaved with drift wire chambers, operated in the Geiger mode, and with plastic scintillators. Since the tracks of the two electrons are curved in a weak magnetic field, this experiment has an extraordinary power for the suppression of the background. It has produced very good results in searching and measuring two neutrino DBD in various nuclei. The very valuable results on neutrinoless DBD are somewhat limited , as in all source≠detector experiments, by the energy spread inside the source.

CUORICINO is the only running experiment based on the new technique of thermal detection of particles, presently amply used in searches for interactions of WIMPS. This approach, suggested since more than 20 years for experiments on DBD [15] is based on the fact that the heat capacity of a suitable crystal (possibly a diamagnetic and dielectric one) decreases with the third power of the operating temperature. As a consequence, when the detector is sufficiently cold, even the tiny energy released in it by a particle, can produce a sizable increase of temperature which can be revealed and measured by means of a suitable thermal sensor [16]. A series of experiments have been carried out in the Gran Sasso laboratory at a depth of 3500 m.w.e. on neutrinoless DBD of ^{130}Te. The DBD transition energy for this nucleus is 2530 keV, and its isotopic abundance is of 33.8 %, thus not requiring isotopic enrichment. The last of these experiments, presently running, is CUORICINO, an array of large crystals of TeO_2 where the temperature pulses are measured by means of Neutron Transmutation Doped (NTD) thermistors. The total mass of the array is 40.7 kg, making it by far the most massive running cryogenic detector. The present results of CUORICINO, reported to this conference [17] exclude at 90 % C.L. a half lifetime lower than 2×10^{24} years and constrain the average neutrino mass in the range 0.2-1.0 eV. As shown in Table 2 it almost entirely covers the span 0.1-.9 eV presented as evidence for neutrinoless DBD by Klapdor Kleingrothaus et al.

3. Future experiments on neutrinoless DBD

The present results proving the existence of neutrino oscillations have stimulated great interest in searches for neutrinoless DBD and various second generation experiments have been proposed with different techniques. They are listed in Table 3

Table 3. Second generation experiments on neutrinoless DBD

Experiment	Nucleu	%	$Q_{\beta\beta}$	$T_{0\nu}$ (y)	Technique	$\lvert m_{0\nu}\rvert$(meV)
CUORE	^{130}Te	34	2533	1.8x10^{27}	Bolometric	9-57
GERDA	^{76}Ge	7.8	2039	2x10^{27}	Ionization	29-94
Majorana	^{76}Ge	7.8	2039	4x10^{27}	Ionization	21-67
GENIUS	^{76}Ge	7.8	2039	1x10^{28}	Ionization	13-42
SuperNEMO	^{82}Se	8.7	2995	2x10^{26}	Tracking	54-167
EXO	^{136}Xe	8.9	2476	1.3x10^{28}	Tracking	12-31
MOON-3	^{100}Mo	9.6	3034	1.7x10^{27}	Tracking	13-48
DCBA	^{150}Nd	5.6	3367	1x10^{26}	Tracking	16-22
Candles	^{48}Ca	.19	4271	3x10^{27}	Scintillation	29-54
CARVEL	”	”	”	3x10^{27}	Scintillation	29-54
GSO	^{160}Gd	22	1750	1x10^{26}	Scintillation	
COBRA	^{116}Cd	7.5	2805		Scintillation	
SNOLAB+	^{150}Nd	5.6	3367		Scintillation	

Some of these experiments are presented at this Conference [17, 18, 19, 14, 20, 21, 22] and others at the recent Workshop at SNOLAB [23, 24]. I will shortly describe here a few experiments with definite proposals, already partially funded or being officially considered.

3.1. GERDA

After the end of Heidelberg-Moscow experiment, GERDA [18] has been presented and approved in its first stage by the Scientific Committee of the Laboratori Nazionali del Gran Sasso, where it will be installed. It will consist in an array of Ge solid state detectors immersed in liquid Nitrogen or Argon. This first stage, approved also by the Italian Institute for Nuclear Physics (INFN), will consist in an array of massive Ge diodes enriched in ^{76}Ge coming from the Heidelberg-Moscow and IGEX experiments. It is intended to check at the 5 σ level the already mentioned evidence by Klapdor-Kleingrothaus et al. In the following Phase II the authors plan to add new enriched segmented detectors with special care to reduce the background coming from neutron activation. A further phase III with a ton of enriched germanium diodes is considered only in the frame of an international collaboration.

3.2. Majorana

This experiment [19] also plans to search for neutrinoless DBD of ^{76}Ge and will likely be installed in the SNOLAB Laboratory. The phase I of this experiment should be performed with three modules of 57 crystals of enriched Germanium each, with a total mass of 180 kg. Various actions are considered to reduce the background like those based on granularity, pulse shape discrimination, detector segmentation etc. A further collaboration with GERDA for an enlarged experiment is considered. It is in my opinion quite advisable, since both experiments are searching for neutrinoless DBD on the same nucleus. Majorana has been recommended, even if at a reduced size, by the Neutrino Scientific Assessment Group (SuSAG) established jointly in USA by DOE and NSF.

3.3. EXO

The ambitious aim of this experiment is the suppression of the background in the search for the neutrinoless DBD ^{136}Xe - ^{136}Ba with 63% enriched Xenon by detecting with LASER optical spectroscopy single Ba^{+} ions. The final experiment is being proposed for operation in SNOLAB [23]. Two options are being considered: an high pressure Xenon TPC and a liquid Xenon TPC plus scintillation. At present a prototype with 200 kg enriched Xenon without tagging is being constructed It has also been approved by NuSAG and is practically totally funded. An additional important aim of this first stage experiment is the search for two neutrino DBD, a process that has not yet been found for this nucleus.

3.4. MOON

This *source≠detector* experiment [20] plans to search for neutrinoless DBD of ^{100}Mo. The detector is an array made by thin sheets of Molybdenum enriched to 85% in ^{100}Mo, interleaved with fiber scintillators. A very interesting feature of this experiment is that ^{100}Mo is also an excellent target to investigate in real time solar neutrino interactions leading to ^{100}Tc, with a threshold of 168 keV only. A pilot experiment (Moon 1) is in operation since April 2005 in the Oto Laboratory in Japan.

3.5. SuperNEMO

Supernemo [14] is a tracking calorimeter whose design is based on a *source≠detector* approach already amply tested in the series of previous and running NEMO experiments, even if with a somewhat different geometry. Like in MOON this tracking technique allows to detect the two electron tracks generated by DBD with a consequent strong suppression of the background. Like NEMO 3 it could investigate two neutrino and neutrinoless DBD in various nuclei, but the present interest is based on neutrinoless DBD of ^{82}Se. The final goal of the experiment is to use 100 kg of enriched Se, but funds for 5 kg of enriched material are already secured.

3.6. CUORE

This experiment [17] is the logical consequence of the already running CUORICINO. It will in fact consist in an array made by 19 columns, substantially identical and containing the same TeO_2 crystal as CUORICINO. The total mass of Tellurium will be 750 kg. An intense R&D activity is going on in the Gran Sasso Undergound Laboratory using a second dilution refrigerator operating in Hall C. The main aim is to reduce the background that in these types of detectors comes mainly from the surface of the crystals and of the Copper frames. CUORE has been approved by the Scientific Committee of the Gran Sasso Laboratory and its location there is being implemented. It has also been approved and partially funded by INFN . It has been recommended by NuSAG as a "timely experiment with potential for good energy resolution and low background".

3.7. Other thermal detectors as candidates for searches on neutrinoless DBD

As pointed out since 1984 [15], thermal detectors offer a wide possibility of compounds containing a candidate nucleus for DBD. A first indicative list of possible absorbers is shown in Table 4.

All these compounds have been tested by the Milano group as thermal detectors successfully, with the exception of natural NdF_3 and $NdGaO_3$ which could not be cooled down to a sufficiently low temperature. This could be due to the paramagnetic nature of some isotopes of Neodimium (fortunately not ^{150}Nd !). As a consequence the possibility of detectors made with crystals

Table 4. Possible thermal candidates for DBD experiments

Compound	(%)	ΔE (keV)
$^{48}CaF_2$	.0187	4272
^{72}Ge	7.44	2038.7
$^{100}MoPbO_4$	9.63	3034
$^{116}WO_4$	7.49	2804
$^{130}TeO_2$	34	2528
$^{150}NdF_3$	5.64	3368
$^{150}NdGaO_3$	5.64	3368

depleted of these isotopes has not yet ruled out, and will be tested. The excellent thermal quality of the other crystals would make them very good candidates for DBD searches, had not be for the low natural isotopic abundance of the candidate nucleus, with the obvious exception of ^{130}Te.

3.8. Neutron background and depth of the underground laboratory

Considerable concern has been arisen recently by a claim [25] that the background due to neutron produced by cosmic rays would require "heroic efforts" for experiments located at an insufficient depth (e.g. below 5000 m.w.e.). It has however been found [26, 27] that for experiments on DBD of ^{76}Ge, muon interactions in the rocks produce a background from neutrons so far negligible with respect to that from other sources. This is also true for neutron produced by muon in the detector itself or in the shield, especially if an active shield is adopted. Some concern could come from the background from neutron produced by the radioactivity of the rock, which does not depend obviously on the depth but only on the quality of the rock. It can anyway be reduced by a suitable neutron shield. A detailed calculation is being carried out for CUORE. The background coming from neutrons produced by muons is found to be orders of magnitude lower than the one expected from the most optimistic prediction for the one coming from other sources.

4. Conclusions

While at beginning experiments on neutrinoless DBD were mainly intended as powerful tools to investigate conservation of the lepton number, they are at present regarded as an unique way to test the Majorana or Dirac nature of the neutrino. If neutrino is a Majorana particle neutrinoless DBD is, and will be, the most powerful way to determine the absolute value of its mass, which has been proved to be finite by the neutrino oscillation experiments.

The present limits (or evidence) for neutrinoless DBD would exclude, or prove, a neutrino mass of a few tenths of eV. A sensitivity superior by an order of magnitude is required to test the indication of oscillation in the inverse hierarchy hypothesis. This goal should be reached in the next decade by second generation experiments which are planned and were in some case also, at least partially, approved. To reach the sensitivity required by the direct hierarchy scheme requires an improvement of another order of magnitude, a terrible task indeed.

In closing I would like to note that experiments on DBD gave very important results also in other subjects of nuclear, subnuclear and astroparticle physics, like those on interactions of WIMPS, solar axions, rare nuclear processes etc. This will be even more true in the future experiments, which could yield results perhaps above our expectations.

References

[1] Elliott S and Engel J 2004 *J. Phys. G: Nucl. Part. Phys.* **30** 183 and references therein
[2] Aalseth C *et al* 2005 *Preprint* hep/0412300v and references therein
[3] Smirnov A 2005 Neutrino masses and mixings *this Conference*
[4] Elgoroy O *et al* 2002 *Phys. Rev. Lett.* **89** 061301
[5] Lobashov V M 2003 *Nucl. Phys.* A **719** 153
[6] Allen S W *et al* 2003 *Mon. Not. R. Astron.Soc.* **346** 593
[7] Klapdor-Kleingrothaus H V *et al* 2001 *Mod. Phys. Lett.* A **10** 2409
[8] Feruglio F *et al* 2002 *Nucl. Phys.* B **659** 359 and references therein
[9] Aalseth C E *et al* 2002 *Mod. Phys. Lett.* **17** 1475
[10] Zdesenko Y G *et al* 2002 *Phys. Lett.* B **546** 206 and references therein
[11] Bakaliorov A M *et al* 2003 *NANP2003* Results of the experiment on investigation of Germanium-76 double beta decay, Dubna, June 24, 2003
[12] Klapdor-Kleingrothaus H V *et al* 2004 *Phys. Lett.* B **584** 189
[13] Klapdor-Kleingrothaus H V *et al* 2004 *Nucl. Instrum. Methods* A **522** 367
[14] Barabash A 2005 NEMO 3 and Supernemo double beta decay experiments *this Conference*
[15] Fiorini E and Niinikosky T 1984 *Nucl. Instrum. Methods* A **224** 83
[16] Proc. of the X Int. Workshop on Low Temperature Detectors, ed F Gatti 2004 *Nucl. Instrum. Methods* A **520**
[17] Bucci C 2005 CUORE: high sensitive double beta decay cryogenic experiment *this Conference*
[18] Bellotti E 2005 GERDA, the germanium detector array for the search of neutrinoless double beta decay *this Conference*
[19] Elliott S 2005 The Majorana project *this Conference*
[20] Nakamara H 2005 MOON for double beta decays for ^{100}Mo and a proto-type detector MOON1 *this Conference*
[21] Kiel H 2005 Status and perspectives of the COBRA double beta decay experiment *this Conference*
[22] Umehara S 2005 Candles for double beta decay of ^{48}Ca *this Conference*
[23] Sinclair D 2005 SNOLAB and EXO *report to the IV SNOLAB Workshop, SNOLAB, August 15-17, 2005*
[24] Chen M 2005 SNO^{+} + SNO *report to the IV SNOLAB Workshop, SNOLAB, August 15-17, 2005*
[25] Hime A and Mei D M 2005 Muon induced background and depth requirements of underground laboratories *report to the IV SNOLAB Workshop, SNOLAB, August 15-17, 2005*
[26] Cebrian S *et al* 2005 Cosmogenic activation in Ge double beta decay experiments *this conference*
[27] Spooner N 2005 Integrated large structures for astroparticle sciences *report to the IV SNOLAB Workshop, SNOLAB, August 15-17, 2005*
[28] Cappelli S, Cebrian S, Cremonesi O and Pavan M *private communication*