Present Experimental Techniques, Results and Plans for Searches on Double Beta Decay

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Abstract. The recent results on neutrino oscillations with the consequent discovery of the existence of a finite neutrino mass has strongly stimulated the interest on neutrinoless double beta decay. I will report and discuss here the various techniques chosen or to be adopted to search for this rare event and the efforts to install underground massive experiments. The already obtained results and the hopes for the future will be also reviewed and discussed with special emphasis to those not specifically reported to this Conference.

1. Introduction

Double beta decay (DBD) was proposed 75 years ago in a beautiful paper [1] by Maria Goeppert Maier as a very rare nuclear transition from an odd/odd to an even/even nucleus (Fig.1), and considered to test the nature of neutrino by G.Racah only two years later [2]. The present impact of this process in the neutrinoless channel is due to the fundamental hypothesis suggested by Ettore Majorana [3] one year before his tragic disappearance. It refers to the symmetric theory of electron and positron and implies that the neutrino is a “Majorana particle” non-conserving lepton number, unlike the “Dirac Neutrino”. This possibility has been strongly revived by recent results of oscillation experiments which prove that the difference of the squared masses of neutrinos of different flavours is different from zero.

Even if it was always considered quite interesting as a very sensitive test of lepton conservation, there is no doubt that the large number of future planned experiments on neutrinoless DBD has been stimulated by the evidence of neutrino oscillations, also in view of the possible role of lepton non conservation in the study of the asymmetry of the Universe [4]. The sum of the two electron energies in neutrinoless DBD (I will not consider here other DBD processes) would present a peak, very sharp for detectors of good energy resolution, in correspondence to the transition energy. With the recent improvement of the resolution in many recent detectors a precise determination of the energy becomes therefore mandatory.

DBD experiments [5,6] can be carried out with geochemical or “milking” methods searching for the presence of the daughter nuclei in geological samples or in large amounts of DBD active material stored underground for long time. To reveal neutrinoless DBD one should however perform direct experiments using special DBD active materials as source and detector of DBD (source=detector) or thin sheets of DBD material interleaved with sheets of detectors (source≠detectors). One of the worst enemies in all these experiments, even if at different degrees, is the background due to radiation from the environment, the shield, the detector itself and from cosmic rays. In all experiments this last one is
presently minimized by installing the DBD detector underground as shown for most experiments in Fig. 2.

Figure 1: Double beta decay

Figure 2: Underground laboratories

The aim of the few running and of the many future experiments is to reach on the absolute neutrino mass the sensitivity of a few tens of milli electron volt indicated by the results of the neutrino oscillation experiments under the indirect hierarchy hypothesis. Reaching the few milli electron volt target predicted by the direct hierarchy hypothesis seems to be beyond any current possibility.

2. Present results

The present results of the most sensitive DBD experiments are shown in Table I, where the adopted technique and the 90% c.l. lower limits on the lifetime are reported. The extrapolation to the corresponding limits on the absolute neutrino mass in the last column depends on the theoretical evaluation and is mainly due to the determination of the nuclear matrix elements which, even if quite improved, presents still considerable differences [7,8].

Table 1: Present results on neutrinoless DBD

| Nucleus | Experiment | %  | $Q_\beta$ | Enrich | Technique | $T_{1/2}(\nu) \times 10^{22}$ | <m> |
|---------|------------|----|----------|--------|---------|------------------|------|
| 48Ca    | Elegant IV | 0.19 | 4271     | scintillator | >1.4x10^{22} | 20-28 |
| 76Ge    | IGEX      | 7.8 | 2039     | 87      | Ionization | >1.6x10^{25} | .25 – .64 |
| 76Ge    | Klapdor et al | 7.8 | 2039  | 87     | ionization | 1.2x10^{25} | .29-.81 |
| 82Se    | NEMO 5    | 9.2 | 2995     | 97      | tracking   | >1x10^{25}   | 1.7-4.5 |
| 100Mo   | NEMO 5    | 9.6 | 5034     | 95-99   | tracking   | >1x10^{24}   | .46-1.1 |
| 116Cd   | Solotvina | 7.5 | 5034     | scintillator | >1.7x10^{25} | 1.2 – 2.7 |
| 128Te   | Bernatovitz | 34  | 2529     | geochem | >7.7 x 10^{24} | .82-1.9 |
| 150Te   | Cuoricino | 55.8 | 2529    | bolometric | >2.8 x 10^{24} | .5-7 |
| 156Xe   | DAMA      | 8.9 | 2476     | 69      | scintillator | >1.2x10^{24} | .64-1.6 |
| 150Nd   | Irvine    | 5.6 | 5367     | tracking | >1.2x10^{21} | 14 - ? |

As shown by the table all results are negative apart from the claim by a subset of the Heidelberg-Moscow collaboration led by H.Klapdor-Kleingrothaus [9,10] which indicate the presence of neutrinoless DBD of $^{76}$Ge with a lifetime ranging from a previous evaluation of $T_{1/2}(\nu) = 1.2 \cdot 10^{25}$ years to a recent one of $T_{1/2}(\nu) = (2.23 \pm 0.44)(0.31) \cdot 10^{25}$ years. This result is subject to a wide and
sometimes exited debate. Referring to this result there was an animated discussion in this conference based on a recent paper by I.V. Kirpichnikov [11] who has carried out a detailed study of the peak presented by Klapdor Kleingrothaus et al to investigate if it could have been mimicked by so far unknown $\gamma$ ray peaks due to environmental radioactivity. He has exposed an unshielded Germanium detector operating on surface near a nuclear reactor. According to him the peak claimed by Klapdor Kleingrothaus et al could be due to the over position of two $\gamma$ ray lines due to environmental radioactivity and a genuine peak due to neutrinoless DBT with a lifetime of $T_{1/2}^{0\nu} = 1.8 \times 10^{25}$ years in agreement with the last claim by Klapdor Kleingrothaus. Even if this result could be debatable, since no interpretation is given to the two environmental $\gamma$ lines, it could be useful to stress the need to search for neutrinoless DBD on two or, better, three different nuclei. This is not only due to the uncertainty on the evaluation of the nuclear matrix elements and consequently on the determination of the neutrino mass. Even if a peak corresponding to the transition energy for neutrinoless DBD is found, one has to insure that it is not mimicked by some unknown process due to environmental radioactivity. Nature should not be so tricky to do that on two or three different nuclei, with different transition energy!

![Figure 3: The two spectra from H. Klapdor Kleingrothaus et al (ref.9 and 10).](image)

One can see from Table 1 that the experiments of CUORICINO and NEMO III could in principle challenge the result by Klapdor Kleingrothaus et al, but cannot anyway reject its evidence due to the uncertainties on the evaluation of the nuclear matrix elements.

I would like to describe briefly these two experiments since they are based on the two different source=detector and source=detector techniques.

**Nemo III** is a detector, operating in the Frejus tunnel. Various DBD sources are interleaved with planes of scintillators and gas detectors operating in a magnetic field (Fig. 4). This experiment gave excellent results on the two neutrino DBD in various nuclei, but also the good constraints on neutrinoless DBD of $^{82}$Se and $^{100}$Mo reported in Table I. Please note the excellent new limit of $1 \times 10^{24}$ years reached recently for neutrinoless DBD of $^{100}$Mo.

**CUORICINO** is the last of a series of experiments on DBD of $^{130}$Te carried out with the novel technique of bolometric detection of particles [12,13] The principle of these detectors is the following. When a crystal, possibly of diamagnetic and dielectric type, is kept at low temperature its heat capacity becomes very small being proportional to the cube of the ratio between the operating and Debye temperatures. As a consequence even the tiny energy delivered by particles inside the crystal gives rise to an increase in its temperature which can be measured by means of a suitable thermal sensor (a thermistor in our case). The energy resolution of these detectors, even if still in their infancy, is extremely good. In the region of X ray it is lower than 3 eV FWHM, two orders of magnitude better
than any other detector. In the region of a few MeV they are already overcoming the resolution of Germanium diodes as shown in Fig. 5 where a resolution of 3.2 keV is reported for the 5.4 $\alpha$ line of $^{210}$Po.

CUORICINO [14] is the last in a series of experiments on $^{130}$Te carried out in the Laboratori Nazionali del Gran Sasso on the reaction

$^{130}$Te $\Rightarrow$ $^{130}$Xe + 2 e$^-$ (+2 $\nu_e$)

with an isotopic abundance of 34% and a recently measured transition energy of $\sim$ 2527 keV. It consists substantially in a column of the larger experiment CUORE which is under construction in the same laboratory and it has been terminated two years ago to leave space in its dilution refrigerators of tests for CUORE (see later). It is an array of 42 natural crystals of tellurium oxide of 750 g and of 18 (four enriched) crystals of the same material of 360 grams. The total mass is 40.7 kg, by more than an order of magnitude larger than any operating cryogenic detectors. The final spectrum in the region of neutrinoless DBD is reported in Fig. 6 and shows no evidence for the peak expected for neutrinoless DBD with total statistics of 18 kg x year of $^{130}$Te. The 90 % lower limit on the lifetime is 2.8 x $10^{24}$ years corresponding to a constraint of the absolute value of the neutrino mass ranging from 0.3 to 0.7 eV on the basis of the most recent evaluations of the nuclear matrix elements.

![Figure 4: Nemo III and the spectrum of two neutrino DBD of $^{100}$Mo](image)

![Figure 5: Spectrum of $^{210}$Po](image)

![Figure 6: Spectrum of CUORICINO](image)

3. The future

A list of the future second generation experiments on DBD mainly aiming to detect or constrain the neutrinoless channel is reported in Table II. Let us consider them on the basis of the detecting technique.

Among the experiments based on the ionisation technique a special emphasis should be addressed to those with Ge diodes, initiated in 1967 with natural Germanium [15] and presently planned with enriched materials. GERDA [16] (Fig. 7) is already starting operation in LNGS with a
limited mass of natural Germanium diodes immersed in liquid argon to test this interesting shielding 
technique. It will be followed by GERDA I and II.

An intense R&D activity is going on in the USA on Majorana [Fig. 8], named after the great 
Ettore, for a planned and approved first step of a segmented array of Ge diodes. These two 
collaborations are planning to join in the future for the construction of a gigantic array with a mass of 
up to a ton of enriched Germanium.

An interesting approach, despite its scary name, is COBRA (Fig. 9) based on arrays of small 
semiconductors of CdSe operating at room temperature in the Gran Sasso Laboratory. Preliminary 
results on various DBD channels of Te and Cd isotopes have been obtained

| Isotope | A%  | Q_{bb} | G^{0n}10^{-14} | Experiments |
|---------|-----|--------|----------------|-------------|
| ^{48}Ca | 0.187 | 4.276  | 4.46           | CANDLES     |
| ^{76}Ge | 7.8  | 2.039  | 0.44           | GERDA       |
| ^{82}Se | 9.2  | 2.992  | 1.89           | MAJORANA    |
| ^{100}Mo | 9.6   | 3.034  | 3.17           | MOON        |
|         |      |        |                | SuperNEMO   |
| ^{100}Mo | 9.6   | 3.034  |                | MOON Kiev-CaMoO_{4} |
| ^{116}Cd | 7.5   | 2.804  | 3.24           | COBRA CdWO_{4} |
| ^{124}Sn | 5.6   | 2.288  | 2.75           | Sn bolometer INO |
| ^{130}Te | 34.5  | 2.529  | 2.86           | CUORE       |
| ^{136}Xe | 8.9   | 2.647  | 3.03           | EXO KAMLAND |
|         |      |        |                | BOREXINO TPC |
| ^{150}Nd | 5.6   | 3.3681 | 13.4           | S-NEMO, DCBA |

Many planned or already running experiments with test setups are based on the tracking 
technique. Two of them are to be run in Japan.

-- Moon is searching for DBD of ^{100}Mo with an array of thin sheets of enriched Molybdenum 
interleaved with planes of scintillating fibers. An interesting feature of this experiment, in the case that 
a large mass will be reached, is the possibility to detect also the interactions of solar neutrinos on 
^{100}Mo which is particularly appealing due to their low interaction energy. A first step of this 
experiment (Moon1) is already in operation in the OTO underground laboratory (Fig. 10).
DCBA for Drift Chamber Beta Ray Analysis aims to search for DBD of the same nucleus with a source of Molybdenum enriched in $^{100}$Mo in a chamber operated in a magnetic field.

A promising plan based on the tracking technique should be carried out in Europe, based on the success of NEMO III, is SUPERNEMO aiming to search for neutrinoless DBD of $^{82}$Se. This technique is the same as the one applied to NEMO II, but the structure is considerably different: plane sheets of DBD materials will be interleaved with planes of scintillators.

A new tracking technique has been proposed for NEXT: an experiment on neutrinoless DBD of $^{150}$Xe to be carried out in the Canfranc underground laboratory in Spain. It consists in TPC filled with a high pressure Xenon gas and operated with tracking and calorimetry. The peculiar aspect of a DBD event is shown in Fig. 11.

Since the beginning, scintillation was one of the standard techniques to search for DBD [5]. A promising technique adopted in Japan to search for DBD of $^{48}$Ca is CANDLES (Fig.12), an array of undoped CaF crystals with an active and passive shield. Due to the very low isotopic abundance of this rare isotope, these experiments plan a huge detecting mass starting with 300 kg as a first step to reach a final target of 3 tons.

I consider of great interest the planned use of DBD active materials dissolved in the large scintillating mass of already existing detectors for solar and reactor neutrino oscillation as first considered for Borexino. Two approaches already near completion have been presented recently. Dissolving 44 kg of Neodimium in neutrinoless DBD of $^{150}$Nd is considered in the SNO underground laboratory (SNO+). The experiment is planned to run in mid-2012 and to reach a sensitivity of $\sim$100
meV in five years of effective running time. It is interesting to note that the density of the dissolved double beta decay material is lower than the outside scintillator one and that it has therefore to be framed with special ropes (Fig. 13).

Another interesting and promising plan is Kamland-Zen in Japan where 400 kg of enriched Xenon are going to be inserted in Kamland to search for neutrinoless DBD of $^{136}$Xe. Considerable efforts are made to insert inside the scintillating liquid of Kamland the “balloon” containing the enriched Xenon (Fig. 14). The experiment is planning to start taking data in the next year.

I would like to conclude with two other second generation DBD experiments based on different techniques:

The final EXO proposal is based on the new idea to search for DBD of $^{136}$Xe by scintillation and single atom counting detecting single nuclei produced by DBD and exited by LASER as show in Fig. 15. An intense R&D activity is going on with the exciting possibility of an experiment of this type to be likely carried out in the SNO underground laboratory. The proposers are however already constructing a “classical” 200 kg liquid scintillating enriched Xenon experiment to run in the WIPP laboratory. It should start to take data soon [17].

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**Figure 13: SNO+**

**Figure 14: Kamland-Zen**

**Figure 15: EXO and the EXO scheme to detect single atoms**
As mentioned before the bolometric technique has been successfully applied already to a series of measurements of DBD of $^{130}$Te with arrays of natural tellurite leading to the construction and operation of CUORICINO, which is substantially a column of the much larger experiment CUORE (for Cryogenic Underground Observatory for Rare Events). This will consist (Fig. 16) of 19 columns of cubic crystals of 5 cm side with a total mass of about 750 kg. As mentioned before the dilution refrigerator previously housing CUORICINO has been already used to house arrays of crystals with different cleaning procedure to optimize the reduction of background in the region of neutrinoless DBD. This study will be further improved by CUORE0, which will be substantially a column of CUORE operating next year in the same dilution refrigerator, while the final large dilution refrigerator devoted to the installation of CUORE is being constructed.

**Figure 16: CUORE**

CUORE, due to its large mass, could also detect the seasonal modulation of direct interaction of WIMPS, but this would require a strong reduction of the background in the low energy region. If the shield would be made by normal lead this reduction would be jeopardized by the presence of $^{210}$Pb whose radioactivity, always present in the environment, decays with a lifetime of 22.2 years. The unexpected discovery of a Roman ship specialized in the transport of Lead and sunk near the coast of Sardinia allowed the recovery of (Fig. 17) many tons of this material, already used partially to shield CUORICINO and sufficient to internally shield entirely CUORE.

I would like to note that $^{130}$Te, even if chosen so far for its large isotopic abundance and transition energy, is not the only good candidate for the search of neutrinoless DBD. Other interesting compounds containing a DBD active nucleus have been reported. They have been all tested successfully as crystals acting as bolometers with the exception so far of compounds of Nd.

Another interesting approach of thermal detectors is their use in association with scintillation in the so called “heat plus scintillation”. This approach is being investigated in the LUCIFER R&D project recently funded by the European community. It should be considered in fact that an important contribution of the background of bolometric detectors in the region of neutrinoless DBD comes from degraded $\alpha$ particles. These particles, like nuclei recoils, deliver a large amount of heat as shown in the Dark Matter experiment based on the anticoincidence of the heat signal vs. the electromagnetic one to suppress the latter in searching for nuclear recoil. In the case of DBD one can, on the contrary, suppress the background due to $\alpha$ particles on the basis of their large delivered heat. This “scintillation vs. heat” approach is shown in Fig. 18 and it has been already applied to various crystals like ZnSe and many Molybdates. The scatter plot of a CaF$_2$ “scintillating bolometer” is shown in Fig. 19.
4. Conclusions

In concluding this report I would like to stress the continuously increasing effort in planning DBD experiments which, starting with a few units in the second half of the last century, are now reaching numbers a few tens of unities. Is this effort really worthwhile? I would like to paraphrase in this sense the philosopher (I believe Blaise Pascal) who stated that even if the probability of the existence of Paradise is low, the joy that you would get upon reaching it would be so high that it is worth it to behave well. If neutrino is a Dirac particle, nobody will ever find neutrinoless DBD. If neutrino is a Majorana particle and the hierarchy is direct, neutrinoless DBD will be perhaps found by our children or grandchildren. If neutrinos are Majorana particle and the hierarchy is an inverse one, we could find it and this will be a great joy!

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