Measurement of neutrino mass in double beta decay [DOI: 10.1051/epn:2007017]

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The long and exciting story of the neutrino started on December 4, 1930 with a famous letter “*Liebe Radioactive Damen un Herren*” addressed by Wolfgang Pauli to a Conference on Radioactivity which took place in Tübingen (?). The reason of the absence of Pauli to this conference was an unusual one : “*Unfortunately I cannot be with you due to a ball that is going to take place in Zurich in the night between the 6 and 7 of January*”.

The problem in those days came from calorimetric measurements of the β decay of ^{210}Bi where the energy delivered in the process was found to be less than half that expected. Disregarding the unpalatable possibility of non-conservation of energy, Pauli postulated in this letter the emission of a neutral particle together with the electron in the decay and named it “*neutron*” (the real neutron had not yet been discovered!). Stimulated by a conference given by Pauli in Italy, Enrico Fermi investigated in depth the process, constructed the beautiful weak interaction theory and named this new particle *neutrino* (Italian for *little neutral one*).

Neutrino is therefore a “thief” of energy and as all good thieves is hard to discover: put in other way it interacts very weakly. In fact Pauli then declared: “*I did a terrible thing tonight: I invented a particle that experimental physicists will never be able to find*”. Fortunately this pessimistic view was not true: in 1956 C.Cowan and F.Reines detected the interactions due to copious neutrino beams produced by the fission products in a nuclear reactor. This was the beginning of a series of exciting discoveries. It was first suggested and then proved that parity was violated in weak interactions and that the neutrino was spinning anti-clockwise with respect to its sense of motion, while its antiparticle, the antineutrino, was spinning clockwise (Fig.1) . A few years later it was discovered that there were two different types of neutrino: the *electronic* one associated with beta decay and the *muonic* one associated with the *muon*, a particle similar to the electron, but with a mass about 200 times larger and unstable.

We now know that another type of neutrino exists : the *tauonic* one, associated with a third particle, the *tau*. All these

▲ Fig. 1: Chirality, namely the alignment of neutrino spin towards the sense of motion

particles, named *leptons*, form therefore three families made by the three charged leptons and their neutrinos. To the particles of each family correspond obviously their antiparticles (*antileptons*), whose lepton number is -1. The three families are identified by a new quantum number named *flavour* (*electronic, muonic or tauonic*). In the Standard Model of weak interactions this number is

▲ Fig. 2: The various experiments showing neutrino oscillations, as suggested by B.Pontecorvo (center)

conserved. A very important event in fundamental physics has been the discovery in the last years of neutrino oscillations [1-4] which were first predicted almost fifty years ago by the great physicist Bruno Pontecorvo.

Let us consider as an example the neutrinos produced by the fusion processes which take place in the central region of the Sun and which are the source of the great energy produced in this and in all other stars. The copious flux of these neutrinos, which are of the electronic type, is such that their interactions, even if indeed rare, can be revealed in a very massive detector placed underground to avoid the “noise” due to cosmic rays. A pioneering experiment carried out in the United States and further searches performed in Japan, Russia, in the Gran Sasso Laboratory in Italy and more recently in Canada have clearly shown the presence of these neutrinos, but with a flux definitely lower than the expected one. This is due to the fact that solar electronic neutrinos *oscillate* inside the Sun and in their long path toward the Earth transform themselves into neutrinos of muonic or tauonic flavours. As a consequence the flux of electronic neutrinos on the Earth is lower than predicted by the so called *Solar Model*.

Neutrino oscillations have been confirmed with neutrinos produced by cosmic rays in the atmosphere, and artificially by particle accelerators and nuclear reactors (Fig.2). These oscillations, which obviously violate the conservation of the flavour number, can only occur if the difference of the squared masses of two neutrinos of different flavours is finite. This obviously means that at least one neutrino has a mass different from zero, but neutrino oscillations are unable to determine its absolute value.

The problem of the neutrino mass is crucial in fundamental physics: if it is finite the neutrino can propagate with a velocity lower than the velocity of light and the alignment of its spin (Fig.1) with respect to the direction of motion would be less than 100 % etc. Another consequence would be that the total lepton number is likely to be violated and that there is not an absolute distinction between a neutrino and an antineutrino. This possibility had been suggested in 1937 by the great physicist Ettore Majorana.

The most direct method to determine the mass of the neutrino [4,5] is the study of the deformation at the end point of the spectrum of the electron in single beta decay (Fig.3). No evidence for a finite neutrino mass has been obtained, but the present upper limits of about 2 eV are still far from what is suggested by neutrino oscillations. A new experiment carried out, as most of the previous ones, on the decay of tritium is being designed in Germany and aims to reach a sensitivity of 0.2 eV.

A more powerful, but model dependent, method to determine the mass of the neutrino comes from cosmology. Our Universe is presently embedded in a “sea” of photons decoupled from matter about 400 000 years after the Big Bang. It is the so called cosmic microwave background (CMB). We are also embedded in a sea of relic neutrinos decoupled much before, about a second after the big bang. The mass of these neutrinos would modify the distribution in space of the CMB. Recent measurements on this CMB background have set an upper limit on the neutrino masses slightly lower than that obtained in the direct measurements mentioned before, but are still far from values predicted by oscillations.

A third method to determine the effective neutrino mass is connected to a fundamental puzzle in neutrino physics: is the neutrino a Dirac or a Majorana particle (Fig.4). In the former hypothesis the neutrino would be totally different from the antineutrino, its chirality, namely the property shown in Fig.1, would be 100% and its mass most likely null. In the latter case, based on a brilliant theory suggested in 1937 by Ettore Majorana, the neutrino would not be distinct from its antiparticle, its mass finite and the lepton number would be violated. The most powerful method to investigate lepton number conservation is double beta decay (DBD), a rare nuclear process suggested by Maria Goeppert Mayer [3] in 1935, only one year after the Fermi weak interaction theory. This process (Fig.5) consists in the direct transition from a nucleus (A,Z) to its isobar (A,Z+2) and can be

▲ Fig. 3: Deformation of the beta decay spectrum due to the neutrino mass

▲ Fig. 4: Dirac and Majorana

investigated when the single beta decay of (A,Z) to (A,Z+1) is energetically forbidden or at least strongly hindered. The decay can occur in three channels

$$(A,Z+2) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu} \quad (1)$$

$$(A,Z+2) \rightarrow (A,Z+2) + 2e^- + (1,2,\dots \nu) \quad (2)$$

$$(A,Z+2) \rightarrow (A,Z+2) + 2e^- \quad (3)$$

In the first channel two antineutrinos are emitted. This process does not violate the lepton number, it is allowed by the Standard Model, and has been found in ten nuclei. We will not consider the second channel which violates the lepton number with the emission of one or more massless Goldstone particles named “Majoron”. Our interest will be devoted to the third process which is normally called *neutrinoless* DBD, even if also no neutrino is emitted in process (2). This process would strongly dominate the two neutrino channel if lepton number ...

Nucleus	Experiment	%	$Q_{\beta\beta}$	Enrich. (%)	Technique	$T_{0\nu}$	$\langle m_{\nu} \rangle$ (eV)
^{48}Ca	Elegant IV	0.19	4271		Scintillation	$>1.4 \times 10^{22}$	7-45
^{76}Ge	Heidelb-Moscow	7.8	2039	87	Ionization	$>1.9 \times 10^{25}$	0.12-1
^{76}Ge	IGEX	7.8	2039	87	Ionization	$>1.6 \times 10^{25}$	0.14-1.2
^{76}Ge	Klapdor <i>et al</i>	7.8	2039	87	Ionization	1.2×10^{25}	0.44
^{82}Se	NEMO 3	9.2	2995	97	Tracking	$>1.0 \times 10^{23}$	1.8-4.9
^{100}Mo	NEMO 3	9.6	3034	95-99	Tracking	$>4.6 \times 10^{23}$	0.7-2.8
^{116}Cd	Soltovina	7.5	3034	83	Scintillation	$>1.7 \times 10^{23}$	1.7- ?
^{128}Te	Bernatoviz <i>et al</i>	34	867		Geochemical	$>7.7 \times 10^{24}$	0.1-4.
^{130}Te	CUORICINO	33.8	2529		Bolometric	$>3.0 \times 10^{24}$	0.16-0.84
^{136}Xe	DAMA	8.9	2476	69	Scintillation	$>1.2 \times 10^{24}$	1.1-2.9
^{150}Nd	Irvine	5.6	3367	91	Tracking	$>1.2 \times 10^{21}$	3- ?

► Table 1: Present results on neutrinoless DBD and limits on neutrino mass (eV).

... is violated. From the experimental point of view, in neutrinoless DBD the two electrons would share the total transition energy since the energy of the nuclear recoil is negligible. A peak would therefore appear in the spectrum of the sum of the two electron energies in contrast with the wide bump expected, and already found, for the two neutrino DBD (Fig.6). The presence of neutrinoless DBD almost naturally implies that a term $\langle m_\nu \rangle$ called the “effective neutrino mass” is different from zero.

DBD is a very rare process both in the case of the two neutrino and of the neutrinoless mode. In the latter process its rate would be proportional to a phase space term, to the square of the nuclear matrix element and to the square of the above-mentioned term $\langle m_\nu \rangle$. While the phase space term can be easily calculated, this is not true for the nuclear matrix element whose evaluation is a source of sometimes excited debates. The calculated values could vary by factors up to two. As a consequence the discovery of neutrinoless DBD should be made on two or more different nuclei. From the experimental point of view there is an even more compelling reason to do that. In a common spectrum many peaks appear due to radioactive contaminations and many of them can hardly be attributed to a clear origin. It is not possible therefore to exclude the possibility that a peak in the region of neutrinoless DBD could be mimicked by some unknown radioactive event. Investigation of spectra obtained from different nuclear candidates where the neutrinoless DBD peak is expected in different regions would definitely prove the existence of this important phenomenon.

The value of $\langle m_\nu \rangle$ and therefore the rate of neutrinoless DBD is correlated to properties of oscillations As shown in

Fig.6 values of a few tens of units or units of meV are expected in the case of the two different ordering of neutrino masses, named “inverted” and “normal” hierarchy, respectively.

Experimental approach

Two different experimental approaches are adopted in the search for DBD [6-9]: the indirect and the direct one.

Indirect experiments

The most common indirect approach is the geochemical one. It consists in the isotopic analysis of a rock containing a relevant percentage of the nucleus (A,Z) to search for an abnormal isotopic abundance of the nucleus (A,Z+2) produced by DBD. This method was very successful in the first searches for DBD and led to its discovery in various nuclei, but could not discriminate between the various DBD modes (two neutrino or neutrinoless decay, decays to excited levels, etc.). The same is true for the *radiochemical* methods that consist in storing for a long time large masses of DBD candidates (e.g. ²³⁸U) and in searching later for the presence of a radioactive product (e.g. ²³⁸Th) due to DBD.

Direct experiments

Direct experiments are based on two different approaches (Fig.7). In the *calorimetric* one the detector itself is made of a material containing the DBD candidate nucleus (e.g. ⁷⁶Ge in a Germanium semiconductor detector or ¹³⁶Xe in a Xenon TPC, scintillator or ionization detector). In the *source ≠ detector* approach, sheets of the DBD source are interleaved with suitable detectors of ionizing particles. A weak magnetic field could also be present to eliminate various sources of background. Thin sheets have to be used to optimize the resolution in the measurement of the sum of the two electron energies.

Thermal detectors

A new approach [10-13] based on the direct detection of DBD is the use of thermal or cryogenic detectors, widely adopted also in searches for Dark Matter particles and for direct measurement of the neutrino mass in single beta decay. An *absorber* is made by a crystal, possibly of diamagnetic and dielectric type, kept at low temperature where its heat capacity is proportional to the cube of the ratio between the operating and the Debye temperatures. As a consequence, in a cryogenic set-up such as a dilution refrigerator, this heat capacity could become so low that the increase of temperature due to the energy released by

Name		%	Q _{ββ}	% E	B c/y	T (year)	Tech	<m>
CUORE	¹³⁰ Te	34	2533	90	3.5	1.8x10 ²⁷	Bolometric	9-57
GERDA	⁷⁶ Ge	7.8	2039	90	3.85	2x10 ²⁷	Ionisation	29-94
Majorana	⁷⁶ Ge	7.8	2039	90	.6	4x10 ²⁷	Ionisation	21-67
GENIUS	⁷⁶ Ge	7.8	2039	90	.4	1x10 ²⁸	Ionisation	13-42
Supernemo	⁸² Se	8.7	2995	90	1	21x10 ²⁶	Tracking	54-167
EXO	¹³⁶ Xe	8.9	2476	65	.55	1.3x10 ²⁸	Tracking	12-31
Moon-3	¹⁰⁰ Mo	9.6	3034	85	3.8	1.7x10 ²⁷	Tracking	13-48
DCBA-2	¹⁵⁰ Nd	5.6	3367	80		1x10 ²⁶	Tracking	16-22
Candles	⁴⁸ Ca	.19	4271	-	.35	3x10 ²⁷	Scintillation	29-54
CARVEL	⁴⁸ Ca	.19	4271	-		3x10 ²⁷	Scintillation	50-94
GSO	¹⁶⁰ Gd	22	1730	-	200	1x10 ²⁶	Scintillation	65-?
COBRA	¹¹⁵ Cd	7.5	2805				Ionisation	
SNOLAB+	¹⁵⁰ Nd	5.6	3367				Scintillation	

◀ **Table 2:** Future experiments on Double Beta Decay

▼ **Table 3:** Possible thermal candidates for neutrinoless DBD

Compound	Isotopic abundance	Transition energy (Kev)
⁴⁸ CaF ₂	.0187 %	4272
⁷⁶ Ge	7.44 %	2038,7
¹⁰⁰ CaPbO ₄	9.63 %	3034
¹¹⁶ CdWO ₄	7.49 %	2804
¹³⁰ TeO ₂	34 %	2528
¹⁵⁰ NdF ₃	5.64 %	3368
¹⁵⁰ NdGaO ₃

▲ **Fig. 6:** Effective neutrino mass expected in DBD experiments from neutrino oscillations. The upper and lower curves refer to the so called inverted and normal hierarchies.

a particle in the absorber can be detected and measured by means of a suitable thermal sensor. The resolution of these detectors, even if still in their infancy, is already excellent. In X-ray spectroscopy made with bolometers of a milligram or less the FWHM resolution can be as low as 3 eV, more than an order of magnitude better than in any other detector. In the energy region of neutrinoless DBD the resolution with absorbers of masses up to a kg is comparable with or better than that of Ge diodes.

Present results and future experiments

Present results

The present results [6-9] on neutrinoless DBD are reported in Table 1 with the corresponding limits on neutrino mass, where the large uncertainties on nuclear matrix elements are taken into account. It can be seen that so far no experimental group has indicated the existence of neutrinoless DBD, with the exception of a subset of the Heidelberg-Moscow collaboration led by H.Klapdor-Kleingrothaus who claim the existence of this process in ^{76}Ge . This evidence is still widely debated in the international arena.

NEMO 3 and CUORICINO

Two experiments are presently running with a sensitivity on neutrino mass comparable to the evidence reported by H.Klapdor-Kleingrothaus *et al.*: NEMO 3 and CUORICINO.

NEMO 3: this is a source $\neq$ detector experiment (Fig.8) presently running in a Laboratory situated in the Frejus tunnel between France and Italy at a depth of ~ 3800 meters of water equivalent (m.w.e). This experiment has yielded extremely good results on two neutrinos DBD of various nuclei. The limits on the neutrinoless channel of ^{100}Mo and ^{82}Se (Table 1) are already approaching the value of neutrino mass presented as evidence by Klapdor *et al.*

CUORICINO: this is at present the most sensitive neutrinoless DBD experiment running. It operates in the Laboratori Nazionali del Gran Sasso under a overburden of rock of ~ 3500 m.w.e. (Fig 9). It consists of a column of 62 crystals of natural TeO_2 to search for the neutrinoless DBD of ^{130}Te . Its mass of 40.7 kg is more than an order of magnitude larger than in any other cryogenic set-up. No evidence is found for a peak in the region of neutrinoless DBD setting a 90% lower limit of 3×10^{24} years on the lifetime of the neutrinoless DBD of ^{130}Te . The corresponding upper limit on $\langle m \rangle$ (0.16-0.9 eV) almost entirely covers the span of evidence coming from the claim of H.Klapdor-Kleingrothaus *et al.* (0.1-0.9 eV).

Future experiments

A list of proposed future experiments [5-9] is reported in Table 2 with the techniques adopted and the expected background and sensitivity. Only two of them have been approved and partially funded: GERDA and CUORE. These and a few others will be briefly described here.

GERDA and Majorana: Both these experiments are based on the “classical” detection of neutrinoless DBD of ^{76}Ge in a calorimetric approach with Germanium diodes. They are logical continuations of the Heidelberg-Moscow and IGEX experiments, respectively. GERDA, already approved in its preliminary version, is going to be mounted in the Gran Sasso Underground Laboratory. An intense R&D activity is being carried out by the Majorana collaboration in connection with the installation of this experiment. Its underground location has not yet been decided.

MOON, based on the source $\neq$ detector approach to search for neutrinoless DBD of ^{100}Mo , is to be installed in the Oto underground laboratory in Japan. The set-up will be constructed of thin sheets of enriched molybdenum interleaved with planes of scintillating fibres. The experiment is also intended to detect the low-threshold interactions of solar neutrinos on ^{100}Mo leading to ^{100}Rb .

SUPERNEMO is also a source $\neq$ detector experiment, mainly intended to search for neutrinoless DBD of ^{82}Se , to be installed in an as yet undecided underground laboratory in Europe. The system is similar to the one adopted by NEMO 3, but with a considerably different geometry.

XENON is a scintillation-based experiment to be carried out in Japan with a large mass of enriched Xenon to search for neutrinoless DBD of ^{136}Xe . Due to the large mass it will also be used in a search for interactions of Dark Matter particles (WIMPS).

EXO is also intended to search for the neutrinoless DBD of ^{136}Xe - ^{136}Ba , but with a totally new approach: to search for DBD events by detecting with the help of LASER beams single Ba^{++} ions produced by the process. The option of liquid or gaseous Xenon and the underground location has not yet been decided, ...

◀ **Fig. 7:** The two different approaches to direct search for DBD

▲ Fig. 8: NEMO 3

... but a 100 kg litre liquid Xenon experiment without Ba tagging is going to operate soon in the WIPP underground laboratory in the USA.

CUORE (Cryogenic Underground Observatory of Rare Events) is the only second generation experiment approved so far. The set-up will consist of 988 crystals of natural TeO_2 arranged in 19 columns, practically identical to that of CUORICINO, but with a total mass of about 750 kg. The experiment has already been approved by the Scientific Committee of the Gran Sasso Laboratory, by the Italian Institute of Nuclear Physics and by DOE. The basement for its installation has been prepared in Gran Sasso (Fig.9). As shown in Table 3, ^{130}Te has been chosen for CUORE due to its high isotopic abundance, but the versatility of thermal detectors will allow many other interesting, but expensive, double-beta active materials to be studied.

Conclusions

After 70 year the brilliant hypothesis of Ettore Majorana is still valid and is strongly supported by the discovery of neutrino oscillations, which implies that the difference between the squared masses of two neutrinos of different flavours is different from zero. As a consequence at least one of the neutrinos has to be massive and the measurement of the neutrino mass becomes imperative. Double 3 is a Majorana particle.

The future second generation experiments being designed, proposed and already in the case of CUORE under construction, will allow us in a few years to reach the sensitivity in the neutrino mass predicted by the results of oscillations in the inverse hierarchy scheme. ■

About the author

Ettore Fiorini is presently professor of Nuclear Physics at the University of Milano-Bicocca. His research activity in experi-

mental nuclear, particle and astroparticle physics has been carried out with various techniques such as cloud and bubble chambers, solid state and thermal detectors. He is presently spokesman of the CUORE experiment.

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▲ Fig. 9: Location of CUORICINO and of R&D for CUORE in the Gran Sasso Laboratory

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