PROCEEDINGS OF SCIENCE

Neutrino: Dirac or Majorana?

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The problem of the nature of the neutrino, namely if it is a massless Dirac particle different from its antineutrino or a Majorana particle with finite mass, is discussed. The question is related to the recent results showing the presence of neutrino oscillations clearly indicating that the difference between the squared mass of neutrinos of different flavours is different from zero. Neutrinoless double beta decay (DBD) is at present the most powerful tool to determine the effective value of the mass of a Majorana neutrino. The results already obtained in this lepton violating process will be reported and the two presently running DBD experiments briefly discussed. The future second generation experiments will be reviewed with special emphasis to those already partially approved. In conclusion the peculiar and interdisciplinary nature of these searches will be stressed in their exciting aim to discover if neutrino is indeed a Majorana particle

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Introduction

The mystery on the nature of neutrino started practically in 1937 when Ettore Majorana suggested the possibility of a certain “equality” between the neutrino and its antiparticle, the antineutrino: this would obviously violate the conservation of the lepton number. In the Dirac hypothesis on the contrary the neutrino would be totally different from its antineutrino and this would make “unnatural” the possibility of a non-zero neutrino mass. The most powerful tool to discriminate between the hypothesis of these two great physicists (Fig.1) is double beta decay (DBD) in its neutrinoless mode. This rare decay has been proposed in general only one year after the Fermi theory of Enrico Fermi by Maria Goeppert Mayer [1] (Fig.2)

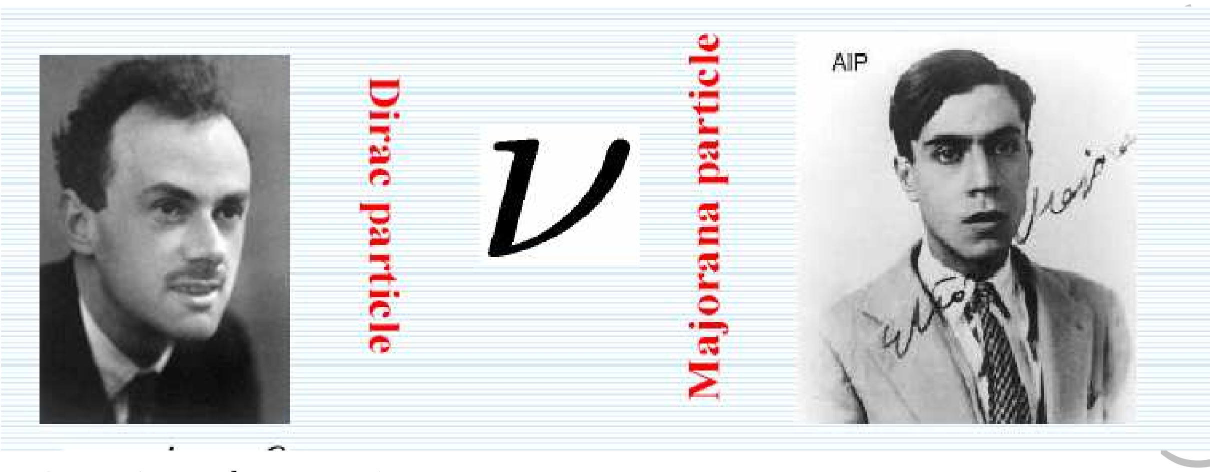


Fig.1 P.A.M. Dirac and Ettore Majorana

Fig.2 M.Goeppert Mayer and Enrico Fermi

In this first fundamental paper, published in 1935, the author was essentially interested in the nuclear physics aspect of the decay and claimed:

"From the Fermi theory of β- disintegration the probability of simultaneous emission of two electrons (and two neutrinos) has been calculated. The result is that this process occurs sufficiently rarely to allow an half-life of over 10^{17} years for a nucleus, even if its isobar of atomic number different by 2 were more stable by 20 times the electron mass"

DBD consists in the spontaneous transition from a nucleus (A,Z) to its isobar (A,Z+2) when the single beta transition to (A,Z+2) is energetically forbidden (Fig.3) or at least strongly hindered by a large change in the spin-parity states. Two electrons are emitted in three possible channels

$$(A,Z) \Rightarrow (A,Z+2) + 2\,e^- + 2\,\bar{\nu}_e \quad (1)$$
$$(A,Z) \Rightarrow (A,Z+2) + 2\,e^- + (1,2,3..\chi\ ) \quad (2)$$
$$(A,Z) \Rightarrow (A,Z+2) + 2\,e^- \quad (3)$$

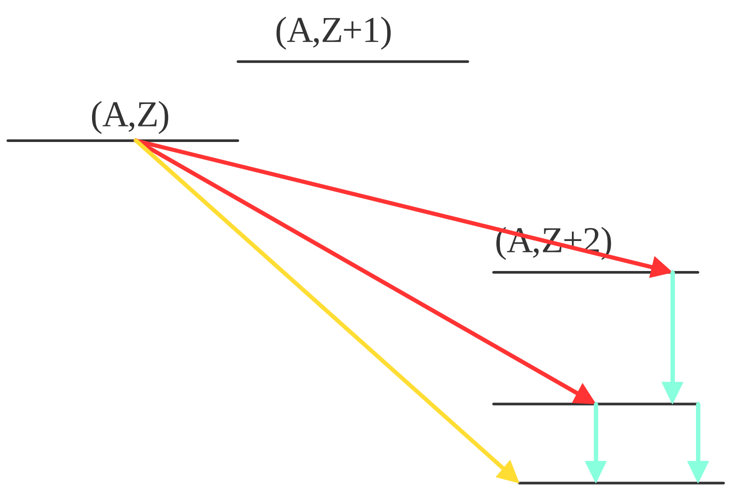


Fig.3 : The scheme of double beta decay

In the first channel two neutrinos (in fact 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" after our great Ettore. Our interest will be concentrated on the third process which is normally called "neutrinoless" DBD even if also in process (2) no neutrino is emitted. This process would strongly dominate on the two neutrino channel if lepton number is violated ; it represents therefore the strongest tool to test lepton number conservation. 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.4). The presence of neutrinoless DBD almost naturally implies that a term $<m_\nu>$ called the "effective neutrino mass" is different from zero.

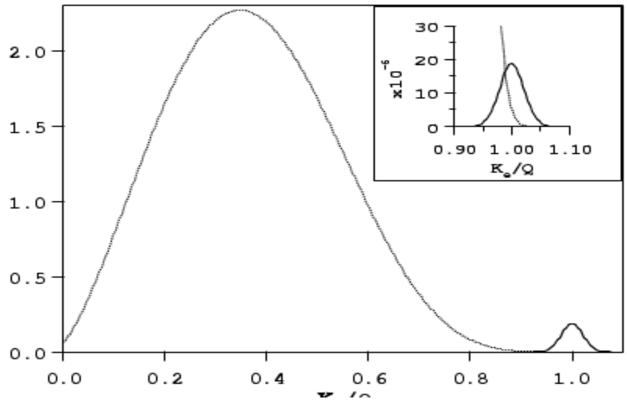


Fig.4 : The spectrum of the sum energy of the two electrons in two neutrino and neutrinoless DBD. The region of this latter process is shown in the inset.

DBD is a very rare process both in the case of the two neutrino and of the neutrinoless mode. In this second case the 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 $<m_\nu>$. While the phase space term is easy to be calculated, this is not true for the nuclear matrix element whose evaluation is a source of sometime excited debates, and for which the calculated values could vary of 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 a even more compelling reason to do that. In a common spectrum many peaks appear due to radioactive contaminations and many of them can hardly to be attributed to a clear origin. It is not possible therefore to exclude 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 neutrinoless DBD peak are expected in different regions would definitely prove the existence of this important phenomenon.

The value of $<m_\nu>$ and therefore the rate of neutrinoless DBD is correlated to properties of oscillations [2] which have been recently discovered in experiments with solar, atmospheric , reactor and accelerator neutrinos [3,4]. As shown in Fig.5 values of a few tens or units of meV are expected in the case of the two different ordering of neutrino masses named "inverted" and "normal" hierarchy, respectively.

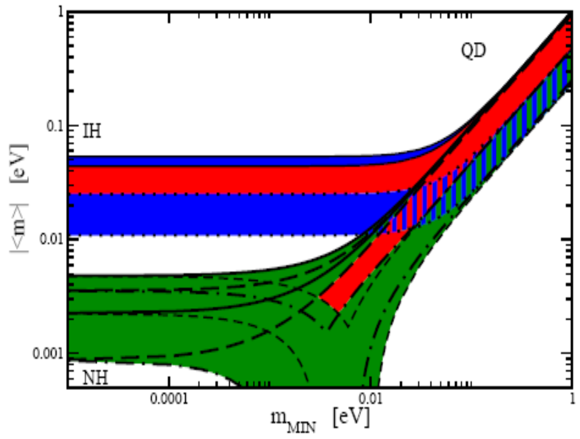


Fig.5 : The value of <m_ν > from neutrino oscillations results. The upper curve refers to a scheme of the masses of neutrinos from different flavours called "inverse hierarchy" while the lower refers to "normal hierarchy"

1. Experimental approach

There are two different experimental approaches to search for DBD : the indirect and the direct one.

1.1 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 among the various DBD modes (two neutrino or neutrinoless decay, decays to excited levels etc.). The same is true for the *radiochemical* methods consisting in storing for long time large masses of DBD candidates (e.g. ^{238}U) and in searching later the presence of a radioactive product (e.g. ^{238}Th).

1.2 Direct experiments

Direct experiments are based on two different approaches (Fig.6). In the *calorimetric* one the detector itself is made by a material containing the DBD candidate nucleus (e.g. ^{76}Ge in a Germanium semiconductor detector or ^{136}Xe in a Xenon TPC, scintillator or ionization detector). In the *source ≠ detector* approach the sheets of the DBD source are interleaved, with suitable detectors of ionizing particles. A weak magnetic field could be present and help 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.

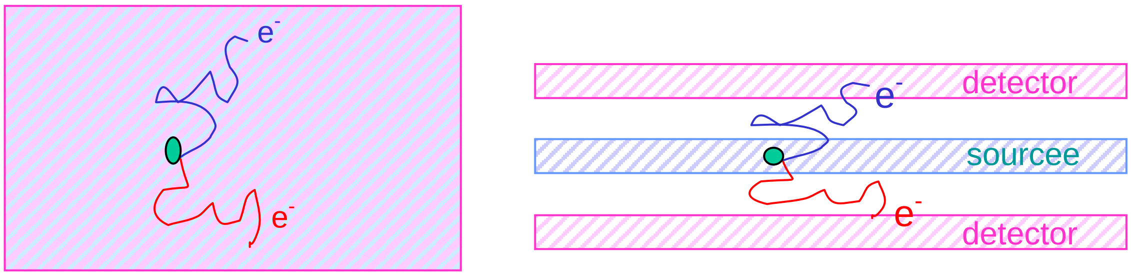


Fig.6 : The two ways to perform a direct double beta decay experiment: the "source = detector" or "calorimetric" and the "source ≠ detector one

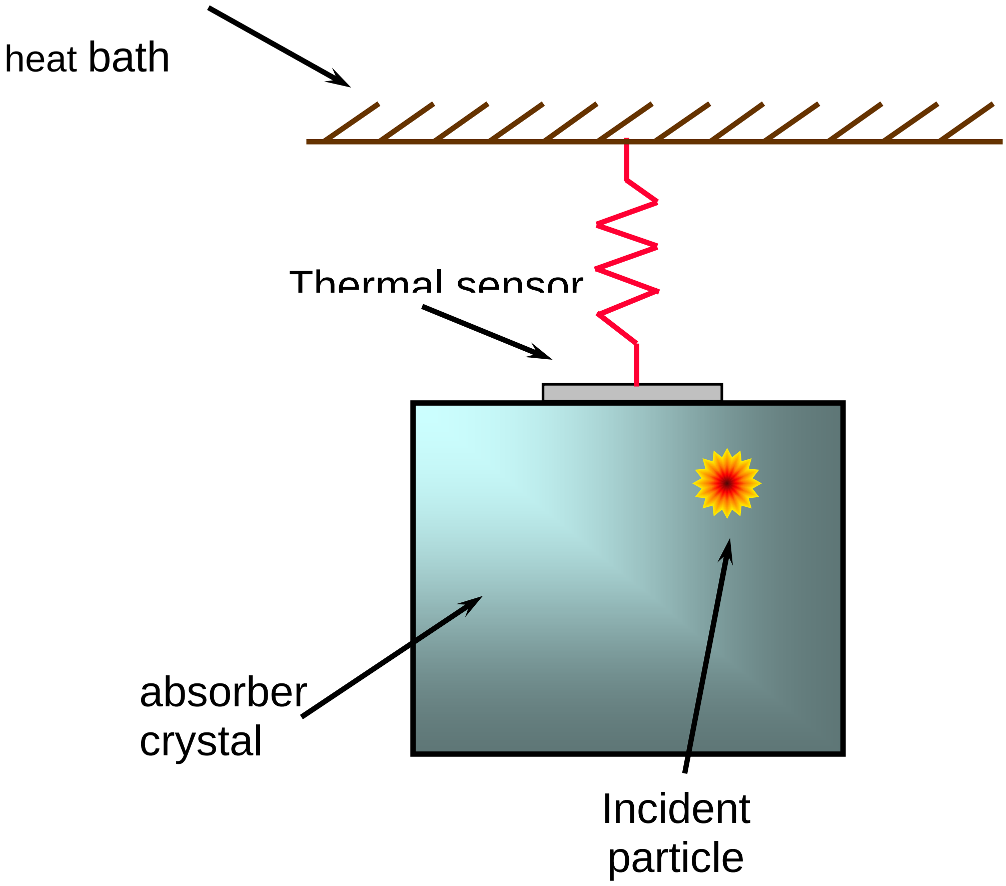


Fig.7 Scheme of a thermal detector

1.3 Thermal detectors

A new approach [5] based on the direct detection of DBD is the use of thermal or cryogenic detectors, also amply adopted in searches on Dark Matter particles and for direct measurement of the neutrino mass in single beta decay. The scheme of these detectors is shown in Fig. 7. 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 like a dilution refrigerator this heat capacity could become so low that the increase of temperature due to the energy released by 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 region of neutrinoless DBD the resolution with absorbers of masses up to a kg is comparable or better than that of Ge diodes.
In the spectrum shown in Fig.8 , obtained with a TeO_2 absorber of ~ 760 grams the FWHM resolution at 5.4 MeV is ~ 3.2 keV! .

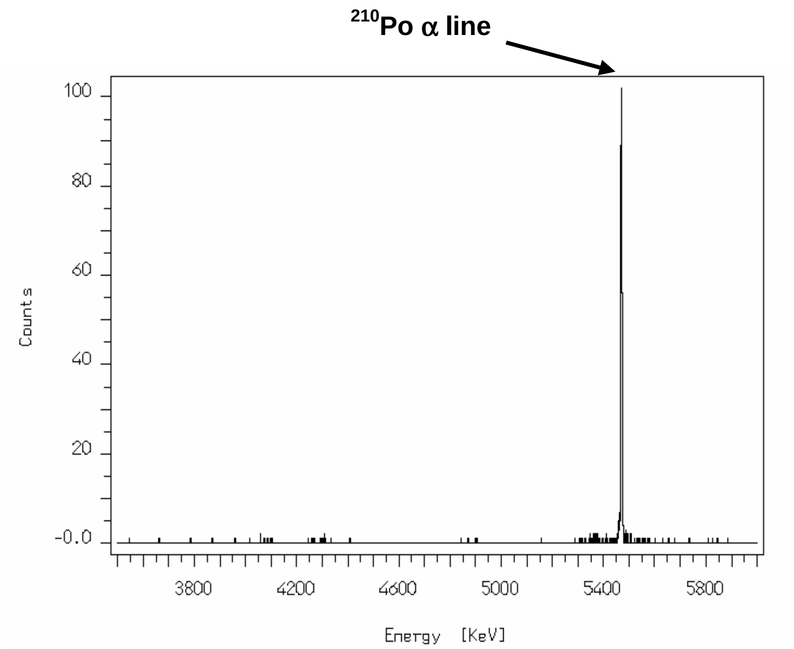


Fig.8: α spectroscopy with a 760 grams TeO_2 detector

2. Present results and future experiments

2.1 Present results

The present results [6] on neutrinoless DBD are reported in Table I 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 experiment has indicated the existence of neutrinoless DBD, with the exception of a subset of the Heidelberg-Moscow collaboration led by H.Klapdor-Kleingrothaus who claims the existence of this process in ^{76}Ge . This evidence is amply debated in the international arena.

Table I: Present results on neutrinoless DBD

Nucleus	Experiment	%	$Q_{\beta\beta}$	Enrich (%)	Technique	$T_{0\nu}$ (y)	$\langle m_\nu \rangle$
^{48}Ca	Elegant IV	0.19	4271		scintillator	$>1.4\text{x}10^{22}$	7-45
^{76}Ge	Heidelberg-Moscow	7.8	2039	87	ionization	$>1.9\text{x}10^{25}$	.12 - 1
^{76}Ge	IGEX	7.8	2039	87	Ionization	$>1.6\text{x}10^{25}$	.14 – 1.2
^{76}Ge	Klapdor et al	7.8	2039	87	ionization	$1.2\text{x}10^{25}$	.44
^{82}Se	NEMO 3	9.2	2995	97	tracking	$>1.\text{x}10^{23}$	1.8-4.9
^{100}Mo	NEMO 3	9.6	3034	95-99	tracking	$>4.6\text{x}10^{23}$	.7-2.8
^{116}Cd	Solotvina	7.5	3034	83	scintillator	$>1.7\text{x}10^{23}$	1.7 - ?
^{128}Te	Bernatovitz	34	2529		geochem	$>7.7\times10^{24}$	.1-4
^{130}Te	Cuoricino	33.8	2529		bolometric	$>2\text{x}10^{24}$	.2-1.
^{136}Xe	DAMA	8.9	2476	69	scintillator	$>1.2\text{x}10^{24}$	1.1 -2.9
^{150}Nd	Irvine	5.6	3367	91	tracking	$>1.2\text{x}10^{21}$	3 - ?

2.2 NEMO 3 and CUORICINO

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

NEMO 3 , It is a source ≠ detector experiment (Fig.9) 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 neutrino DBD of various nuclei. The limits on the neutrinoless channel of ^{100}Mo and ^{82}Se (Fig.10 and Table I) are already approaching the value of neutrino mass presented as evidence by Klapdor et al.

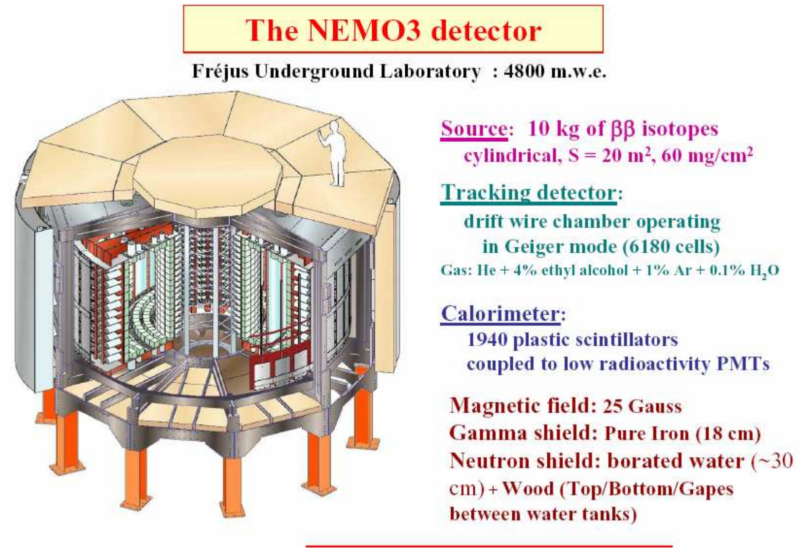


Fig.9 : Scheme and properties of NEMO 3

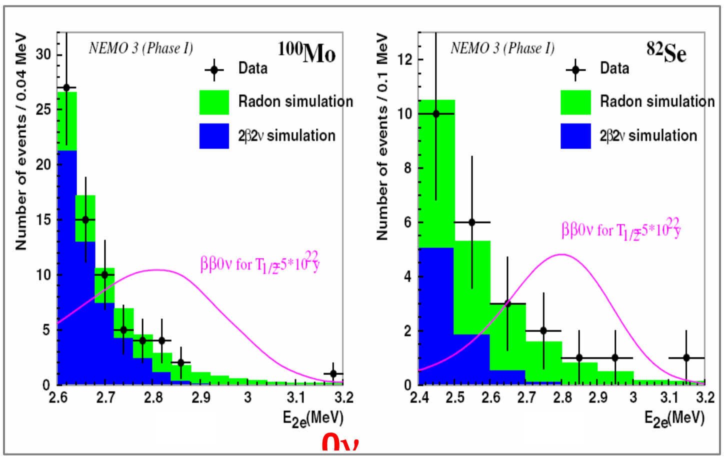
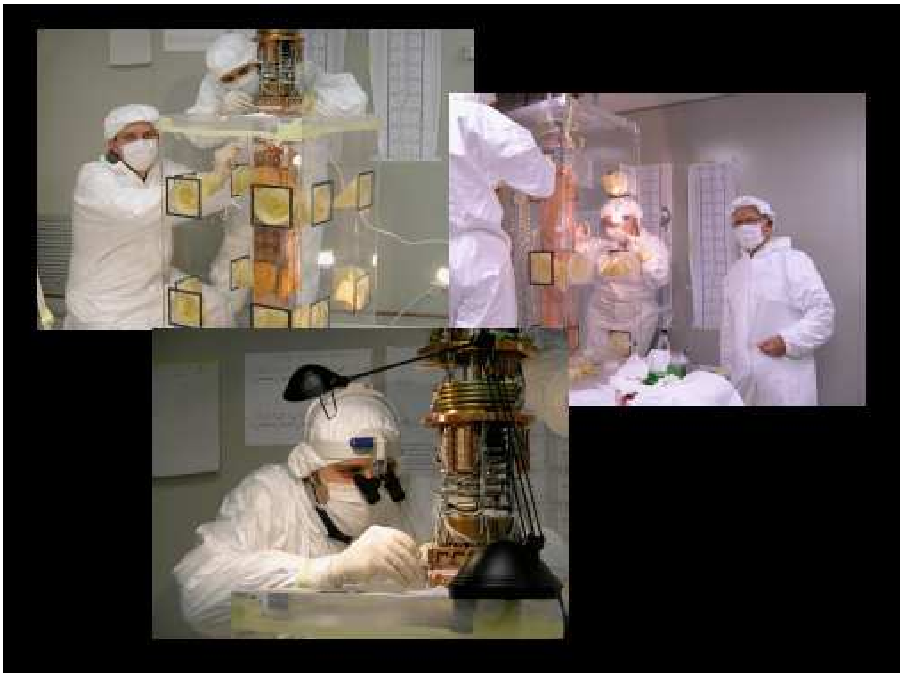


Fig. 10: Results of NEMO 3

CUORICINO Is at present the most sensitive running neutrinoless DBD experiment . It is mounted in the Laboratori Nazionali del Gran Sasso under a overburden of rock of ~ 3500 m.w.e. (Fig.11). It consists in a column of 62 crystals of natural TeO_2 to search for 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 (Fig.12). No evidence is found for a peak in the region of neutrinoless DBD (Fig.13) setting a limit that covers almost entirely the span of evidence coming from the claim of H.Klapdor Kleingrothaus et al.

Fig. 11 : The CUORICINO and CUORE installation in the Laboratorio Nazionale del Gran Sasso

[1] 

18 crystals 3x3x6 cm3 + 44 crystals 5x5x5 cm3 = 40.7 kg of TeO2
Background .18±.01 c /kev/ kg/ a
$T_{1/2}^{0}$ (^{130}Te) > 2.4x 10^{24} y $<m_{\nu}>$ .18 -.9 Klapdor 0.1 – 0.9

12: Mounting and results of CUORICINO

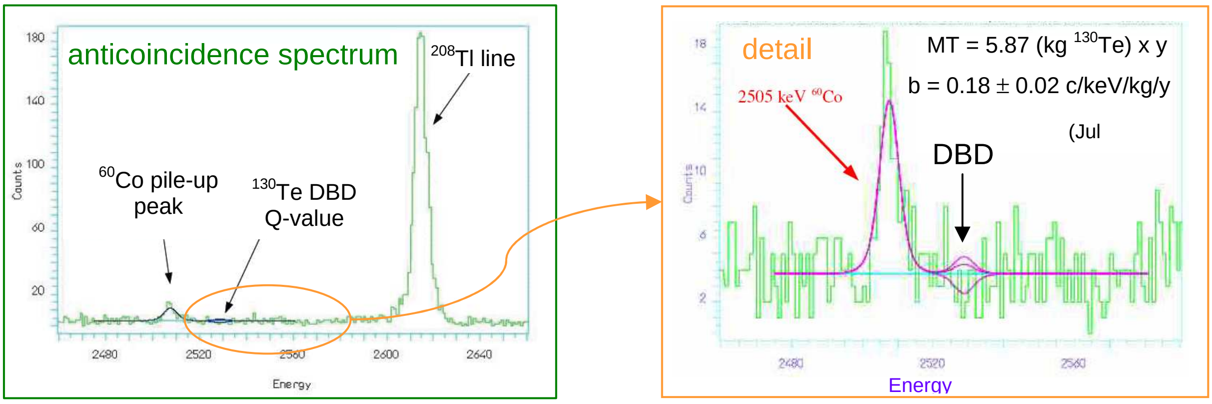


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Fig.13:The CUORICINO spectrum in the region of neutrinoless

2.3 Future experiments

A list of proposed future experiments [6] is reported in Table II with the techniques to be 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.

Table II: Future experiments on neutrinoless DBD

Name	Nucleu	%	$Q_{\beta\beta}$	%	Back c/y	T (year)	Tech	<m>
CUORE	^{130}Te	34	2533	34	3.5	$1.8x10^{27}$	Bolometric	9-57
GERDA	^{76}Ge	7.8	2039	90	3.85	$2x10^{27}$	Ionization	29-94
Majorana	^{76}Ge	7.8	2039	90	.6	$4x10^{27}$	Ionization	21-67
GENIUS	^{76}Ge	7.8	2039	90	.4	$1x10^{28}$	Ionization	13-42
Supernemo	^{82}Se	8.7	2995	90	1	$2x10^{26}$	Tracking	54-
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				Ionization	
SNOLAB+	^{150}Nd	5.6	3367				Scintillation	

GERDA and Majorana

Both these experiments (Fig.14) 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 view of the installation of this experiment: its underground location has not yet been decided.

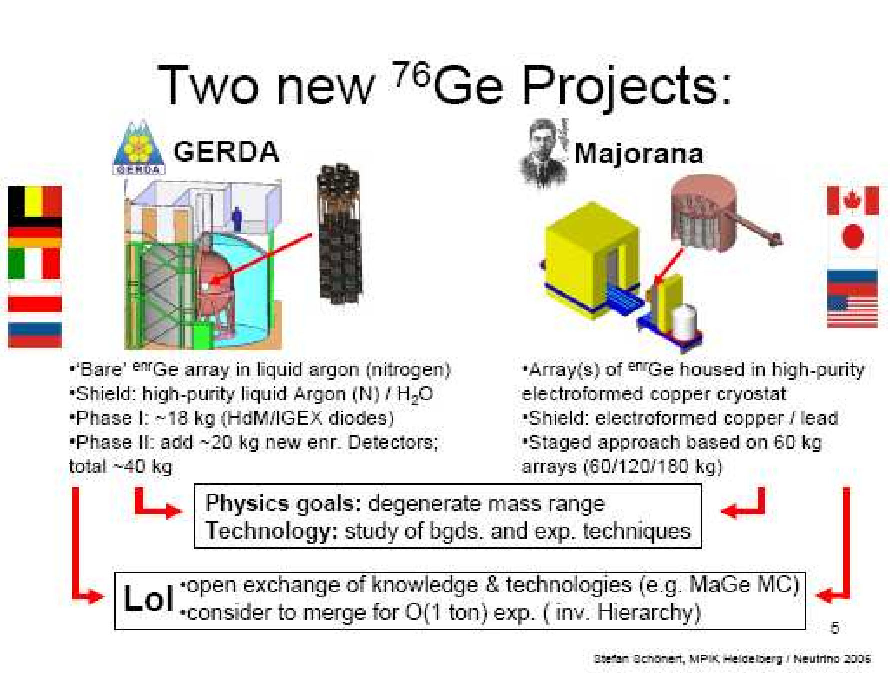

Fig. 14: GERDA and Majorana

MOON

MOON is based on the source ≠ detector approach to search for neutrinoless DBD of ^{100}Mo to be installed in the Oto underground laboratory in Japan. The set-up is made (Fig.15) of thin sheets of enriched molybdenum interleaved with planes of scintillating fibers. The experiment is also intended to detect the low threshold interactions of solar neutrinos on ^{100}Mo leading to ^{100}Rb.

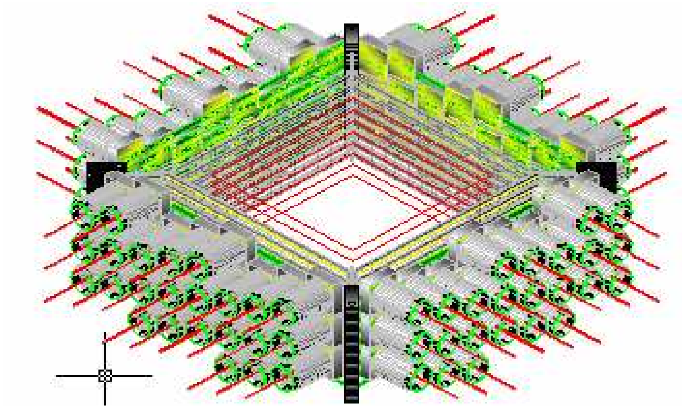

Fig.15. MOON

SUPERNEMO

SUPERNEMO is also a source ≠ detector experiment mainly intended to search for neutrinoless DBD of ^{82}Se, to be installed in a not yet decided underground laboratory in Europe.

The system is similar to the one adopted by NEMO 3 , but with a considerably different geometry (Fig.16)

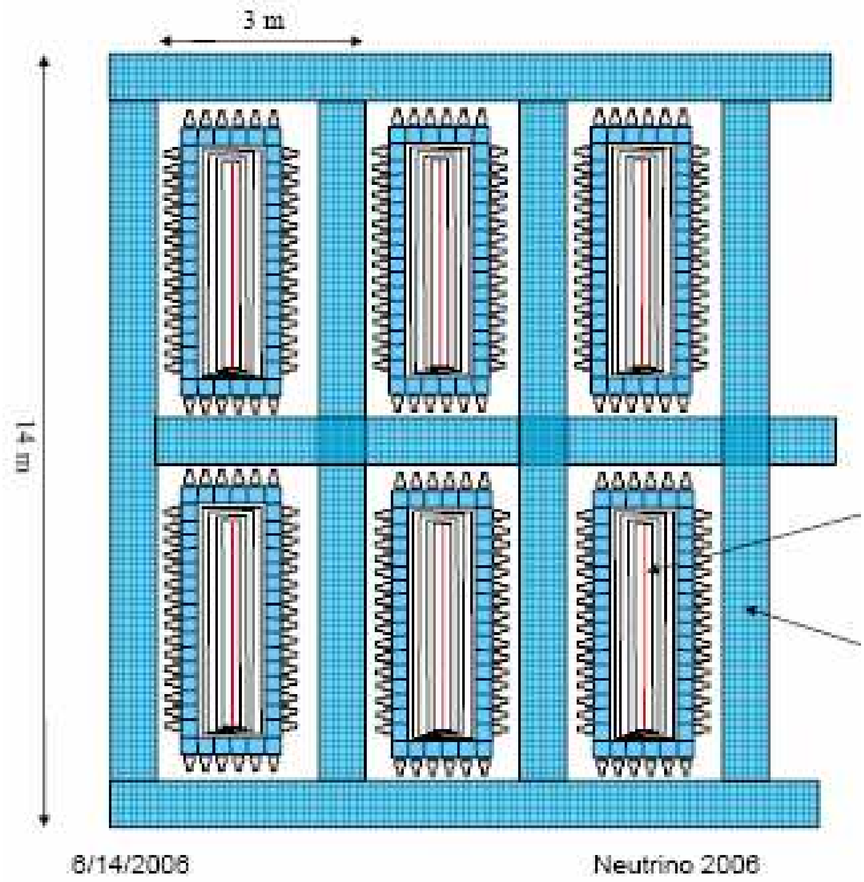

Fig. 16. SuperNEMO

XENON

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

EXO

EXO also intended to search for 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 (Fig.17) The option of liquid or gas Xenon and the underground location has not yet been decided, but a kg litre liquid Xenon experiment without Ba tagging is going to operate soon in the WIPP underground laboratory in USA.

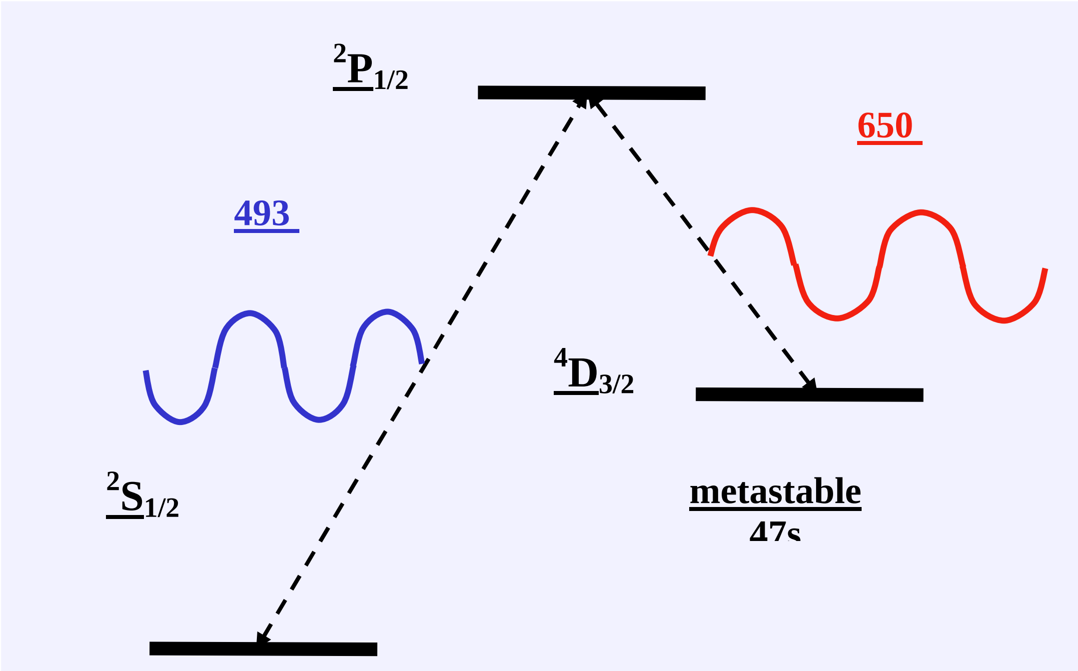

Fig. 17: Ba++ tagging in EXO

CUORE

CUORE (for Cryogenic Underground Observatory of Rare Events) will be consist in 988 crystals of natural TeO_2 arranged in 19 columns practically identical to the one of CUORICINO, with a total mass of about 750 kg (fig.18) . The experiment has already been . approved by the Scientific Committee of the Gran Sasso Laboratory and by the Italian Institute of Nuclear Physics and the basement for its installation has been already prepared in Gran Sasso (Fig.19) . As shown in Table III ^{130}Te has been chosen for CUORE due to its high isotopic abundance, but the versatility of thermal detectors allows many other interesting, but expensive, double beta active materials.

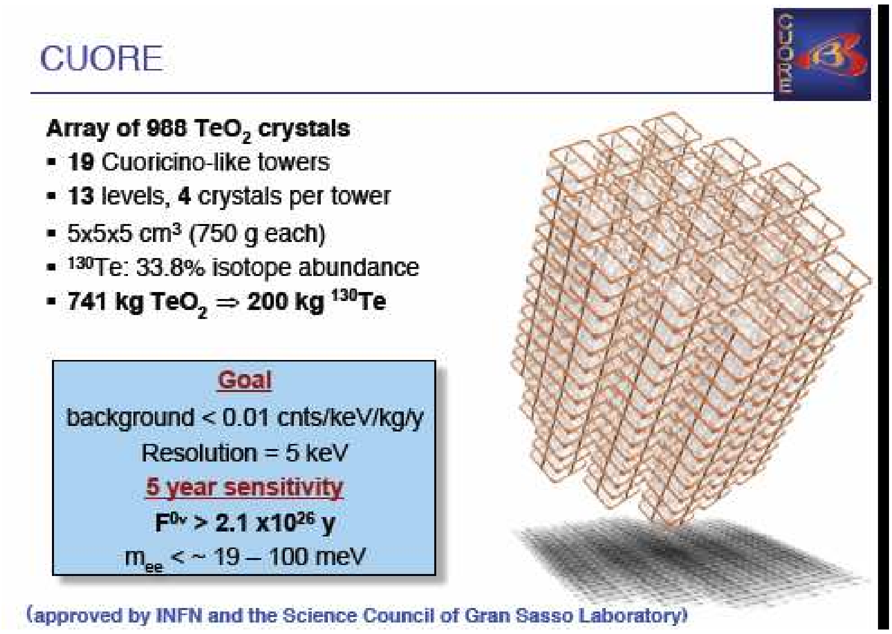

Fig.18 : CUORE

Table 3: Possible thermal candidates for neutrinoless DBD

Compound	Isotopic abundance	Transition energy
$^{48}CaF_2$	.0187 %	4272 keV
^{76}Ge	7.44 "	2038.7 "
$^{100}MoPbO_4$	9.63 "	3034 "
$^{116}CdWO_4$	7.49 "	2804 "
$^{130}TeO_2$	34 "	2528 "
$^{150}NdF_3$ $^{150}NdGaO_3$	5.64 "	3368 "

3. 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 beta decay is at present the most powerful tool to obtain this result and also to clarify if the neutrino is a Majorana particle.
The future second generation experiments being designed , proposed and already in a few case under construction will allow in a few years to reach the sensitivity in the neutrino mass predicted by the results of oscillations.
Due to their peculiar interdisciplinarity experiments on double beta decay involve different fields of physics from nuclear, subnuclear and astroparticle physics to radioactivity, material sciences , geochronology etc. It could even help in understanding the particle-antiparticle asymmetry in the Universe.
Therefore thank you Ettore!

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