Double beta Decay: Experiments and Theory Review

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With neutrino oscillations now firmly established, neutrinoless double beta decay assumes great importance since it is one of the most powerful tools to set the neutrino mass absolute scale and establish whether the neutrino is a Majorana particle. After a summary of the neutrinoless double beta decay phenomenology, the present status of the experimental search for this rare decay is reported and the prospects for next generation experiments are reviewed.

1. Introduction

The double beta decay is a second order weak transition which can be energetically favored for some even-even nuclei belonging to A even multiplets. The $(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$ double beta ($\beta\beta$-2ν) decay process is allowed by the Standard Model and has been observed for many isotopes with lifetimes longer than 10^{19} y. A more interesting process is the so-called neutrinoless double beta ($\beta\beta$-0ν) decay given by $(A, Z) \rightarrow (A, Z+2) + 2e^-$: this process violates lepton number conservation and is therefore forbidden by the Standard Model. The lifetime for the $\beta\beta$-0ν decay is expected to be longer than 10^{25} y and so far only one evidence has been reported for ^{76}Ge (see Sec. 2.1). For recent comprehensive reviews on this topic refer for example to Ref. [1].

1.1. $\beta\beta$-0ν decay and neutrino physics

Many mechanisms have been proposed for driving this decay, but the simplest one is the "mass mechanism", where a light Majorana neutrino is exchanged. Whatever is the mechanism actually causing the $\beta\beta$-0ν decay, its observation would imply that the neutrino is massive and is a Majorana particle (i.e. $\nu \equiv \bar{\nu}$). For a light Majorana neutrino mediate $\beta\beta$-0ν decay, the rate is given by $[\tau^{0\nu}_{1/2}]^{-1} = \langle m_\nu\rangle^2 F_N/m_e^2$, where m_e is electron mass and the nuclear structure factor F_N contains the nuclear matrix element and the phase space. The effective neutrino Majorana mass is given by $\langle m_\nu\rangle = |\sum_k m_k \eta_k |U_{ek}|^2|$, where m_k are the mass eigenvalues of the three neutrino mass eigenstates $|\nu_k\rangle$, η_k are the CP Majorana phases ($\eta_k = \pm 1$ for CP conservation) and U_{ek} are the elements of the electron sector of the neutrino mixing matrix. As suggested in [4] the exact mechanism causing the $\beta\beta$-0ν could be discerned by measuring the decay rates for different isotopes.

With the help of the $\Delta m^2_{ik} = |m_i^2 - m_k^2|$ and $\sin^2 2\theta_{ik} = f(|U_{ik}|^2)$ parameters determined by neutrino flavor oscillation experiments (see Ref. [2] for the latest results), it is possible to calculate $\langle m_\nu\rangle$ as a function of the unknown neutrino absolute mass scale and η_k phases [3]. From this analysis two possible scenarios can be devised for the upcoming new generation experiments aiming at a 10 meV sensitivity. (1) The $\beta\beta$-0ν decay is discovered with $\langle m_\nu\rangle \geq 10$ meV: then the neutrino is a Majorana particle and the masses are either degenerate ($m_1 \approx m_2 \approx m_3$) or follow an inverse hierarchy ($m_3 \ll m_1 \approx m_2$). If neutrinos are degenerate (for $\langle m_\nu\rangle \geq\approx 0.05$ eV) then the absolute mass scale can be established. (2) The $\beta\beta$-0ν decay is not observed and only an upper limit $\langle m_\nu\rangle \leq 10$ meV is set: then, if the neutrino is a Majorana particle, the masses must have a normal hierarchy ($m_1 < m_2 \ll m_3$).

1.2. $\beta\beta$-0ν decay and nuclear physics

To obtain $\langle m_\nu\rangle$ from the experimental observable $\tau^{0\nu}_{1/2}$ the nuclear structure factor $F_N \equiv G^{0\nu}(Q_{\beta\beta}, Z)|M^{0\nu}|^2$ must be known. While the phase space $G^{0\nu}(Q_{\beta\beta}, Z)$ can be precisely calculated, the nuclear matrix $|M^{0\nu}|$ contains the uncertain details of the nuclear part of the process. In fact there is a large spread in the nuclear matrix elements calculated by different authors with different nuclear models [5] (see also references in Ref. [1, 3]). Because of this spread also $\langle m_\nu\rangle$ is affected by large uncertainties (about a factor 3 on the average). Presently these uncertainties are a severe limitation to the potentialities of $\beta\beta$-0ν decay as a tool for neutrino physics: it has been recently suggested [6, 7] that measured $\beta\beta$-2ν decay lifetimes can be used to reduce the spread in QRPA calculations. Nevertheless, it is important to search for $\beta\beta$-0ν decay of as many as possible candidate isotopes.

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1.3. $\beta\beta$-0ν decay and CP-violation

The observation of $\beta\beta$-0ν could be used to establish CP-violation associated with Majorana neutrinos in the lepton sector due to the η_k Majorana phases. This issue has gained interest because it could provide an explanation for the observed baryon asymmetry in the Universe through the leptogenesis theory [8]. The Majorana phases could be constrained by simultaneous precise measurements of $\langle m_\nu \rangle$ and $\sum_i m_i$ (from cosmological observation) or $m_{lightest}$ (from β endpoint direct experiments). This possibility has been explored by many authors with opposite conclusions [9, 10]. Indeed the task is experimentally very challenging and maybe successful only for some values of the neutrino mixing matrix elements. The possibility of success rely also on a strong reduction of the uncertainties in the mixing matrix elements, in $\langle m_\nu \rangle$, in $\sum_i m_i$ (or $m_{lightest}$), and in the nuclear matrix elements.

1.4. Experimental approaches to $\beta\beta$-0ν

There are two approaches for direct $\beta\beta$-0ν searches. In the first approach the $\beta\beta$-0ν active source is external to the detector: the experimental configuration usually consists of foil shaped sources with two detectors (e.g. scintillators, TPCs, drift chambers ...) analyzing the electrons emerging from the foil. Using tracking detectors a background rejection is possible studying the event topology. The limits of this approach are the energy resolution and the small source mass.

In the second approach the source is internal to the detector (*calorimeter*) and only the sum energy of the two electrons is measured. The signature for $\beta\beta$-0ν decay is therefore a peak at the transition energy $Q_{\beta\beta}$. The detector can be a scintillator, a bolometer, a semiconductor diode or a gas chamber. Calorimeters can have large mass and high efficiency. Depending on the technique, high energy resolution and also some tracking are possible.

From statistical considerations, the sensitivity $\Sigma(\tau^{0\nu}_{1/2})$ of a $\beta\beta$-0ν decay search is given by $\Sigma(\tau^{0\nu}_{1/2}) \propto \epsilon\, i.a. (M t_{\rm M}/(\Delta E\, bkg))^{1/2}$, where ϵ, $i.a.$, M, $t_{\rm M}$, ΔE and bkg are the detector efficiency, the active isotope abundance, the source mass, the measuring time, the energy resolution and specific background at $Q_{\beta\beta}$, respectively. In case no background count is observed in the region of interest, the sensitivity becomes $\Sigma(\tau^{0\nu}_{1/2}) \propto \epsilon\, i.a. M t_{\rm M}$. In any experimental approach the various experimental parameters may be optimized up to some intrinsic technical limit while working on the background level usually offers the best possibility of sensitivity improvement.

The background is therefore a fundamental issue in all $\beta\beta$-0ν searches: to reduce it, all passive (e.g. heavy shielding in underground sites, material selection and purification) and active (e.g. Pulse Shape Discrimination, topology analysis through granularity and segmentation) measures must be taken. However the background caused by the high energy tail of the continuous $\beta\beta$-2ν spectrum cannot be avoided and must be minimized by improving the energy resolution.

2. Present and past experiments

In the following a selection of the most sensitive experiments is presented (see Table I for a more complete list of the best results to date for many isotopes).

2.1. ^{76}Ge experiments and the evidence for $\beta\beta$-0ν decay

The **Heidelberg-Moscow experiment** (hereafter HM) searched the $\beta\beta$-0ν decay of ^{76}Ge using five High Purity Ge semiconductor detectors enriched to 87% in ^{76}Ge. This experiment run in the Gran Sasso Underground Laboratory (Italy) from 1990 to 2003, totalling an exposure of 71.7 kg×y (i.e. 820 moles×y of ^{76}Ge). It is by far the longest running $\beta\beta$-0ν decay experiment with the largest exposure. The experiment since the end of 1995 featured PSD on four crystals to reduce background by separating Single Site Events (like $\beta\beta$-0ν decay events) from Multiple Site Events (like γ interactions): the PSD is applicable to 72% of the full data set (i.e. 51.4 kg×y). The final background at $Q_{\beta\beta}$ is about 0.11 c/keV/kg/y and it is attributed mainly to U and Th contaminations in the set-up materials. The use of Ge detectors for a calorimetric $\beta\beta$-0ν decay search was first proposed in Ref. [15] and the HM experiment is the best exploitation of this technique: it represents the Status-of-the-Art for the low background techniques and has been the reference for all last generation $\beta\beta$-0ν decay experiments. After the conclusion of the experiment, part of the collaboration (hereafter KKDC) has reanalyzed the data [16] claiming a 4σ evidence for ^{76}Ge $\beta\beta$-0ν decay with a lifetime $\tau^{0\nu}_{1/2}$ of about 1.2×10^{25} y, corresponding to a $\langle m_\nu \rangle$ of about 0.44 eV [17]. This claim has sparked a debate in the neutrino physics community [1] because the signal is indeed faint and close to other unexplained peaks.

Igex [18] is a similar experiment which run in Homestake (USA), Canfranc (Spain) and Baksan (Russia) from 1991 to 2000 with a total exposure of only 8.87 kg×y and a background at $Q_{\beta\beta}$ of about 0.17 c/keV/kg/y: its sensitivity is not enough to check the KKDC claim.

Table I A selection of the past and present experiments giving the best result per isotope to date. All given $\tau^{0\nu}_{1/2}$ ($\langle m_\nu \rangle$) are lower (upper) limits with the exception of the Heidelberg-Moscow experiment where the 99.9973% CL value is given. The spread in $\langle m_\nu \rangle$ is due to the uncertainties on the nuclear factor F_N.

isotope	**experiment**	**latest**	$Q_{\beta\beta}$	**i. a.**		**exposure**	**technique**	**material**	$\tau^{0\nu}_{1/2}$	$\langle m_\nu \rangle$
		result	**[keV]**	**nat.**	**enrich.**	**[kg×y]**			**[10^{23} y]**	**[eV]**
^{48}Ca	Elegant VI	2004[11]	4271	0.19	–	4.2	scintillator	CaF_2	0.14	7.2÷44.7
^{76}Ge	Heidelberg/Moscow	2004[17]	2039	7.8	87	71.7	ionization	Ge	120.0	0.44
^{82}Se	NEMO-3	2007[22]	2995	9.2	97	1.8	tracking	Se	2.1	1.2÷3.2
^{100}Mo	NEMO-3	2007[22]	3034	9.6	95÷99	13.1	tracking	Mo	5.8	0.6÷2.40
^{116}Cd	Solotvina	2003[12]	2805	7.5	83	0.5	scintillator	$CdWO_4$	1.7	1.7
^{130}Te	Cuoricino	2007[20]	2529	33.8	–	11.8	bolometer	TeO_2	30.0	0.16÷0.84
^{136}Xe	DAMA	2002[23]	2476	8.9	69	4.5	scintillator	Xe	12.0	1.10÷2.9
^{150}Nd	Irvine TPC	1997[14]	3367	5.6	91	0.01	tracking	Nd_2O_3	0.012	3.0
^{160}Gd	Solotvina	2001[13]	1791	21.8	–	1.0	scintillator	Gd_2SiO_5	0.013	26.0

Table II A selection of the proposed experiments. Except for CUORE and GSO all experiments use isotopically enriched material. Background *bkg* is calculated on an energy interval equal to σ_E. For all tracking experiments the quoted background is due only to the $\beta\beta$-2ν tail.

experiment	**isotope**	$Q_{\beta\beta}$	**tech.**	**i.a.**	**mass**	t_{M}	σ_E	*bkg*	$\tau^{0\nu}_{1/2}$	$\langle m_\nu \rangle$	**project**
		[keV]		**[%]**	**[kmol]**	**[y]**	**[keV]**	**[c/y]**	**[10^{28} y]**	**[meV]**	**status**
CANDLES IV+[37]	^{48}Ca	4271	scint.	2	1.8	5	73	0.35	0.3	30	R&D (III: 5 mol)
Majorana 120[26]	^{76}Ge	2039	ion.	86	1.6	4.5	2	0.1	0.07	90	R&D - reviewing
GERDA II[30]	^{76}Ge	2039	ion.	86	0.5	5	2	0.1	0.02	90÷290	funded/R&D (I: 0.3 kmol)
MOON III[42]	^{100}Mo	3034	track.	85	8.5	10	66	3.8	0.17	15	R&D (I: *small*)
CAMEO III[36]	^{116}Cd	2805	scint.	83	2.7	10	47	4	0.1	20	proposed
CUORE[34]	^{130}Te	2529	bol.	33.8	1.7	10	2	7.5	0.07	11÷57	construction
EXO[45]	^{136}Xe	2476	track.	65	60.0	10	25	1	4.1	11÷15	R&D (1.5 kmol)
SuperNEMO[44]	^{150}Nd	3367	track.	90	0.7	–	57	10	0.01	50	R&D
DCBA-F[43]	^{150}Nd	3367	track.	80	2.7	–	85	–	0.01	20	R&D (T2: *small*)
GSO[13]	^{160}Gd	22	scint.	22	2.5	10	83	200	0.02	65	proposed

2.2. Running ^{82}Se, ^{100}Mo and ^{130}Te experiments

There are presently two running experiments (Cuoricino and NEMO-3), which have chances to reach the sensitivity required to observe a $\beta\beta$-0ν signal at the level expected from the KKDC claim.

Cuoricino [19] is a calorimetric experiment using natural TeO_2 cryogenic detectors to search for ^{130}Te $\beta\beta$-0ν decay. It runs in the Gran Sasso Underground Laboratory since 2003 and consists of 62 TeO_2 crystals kept at a temperature of about 10 mK, arranged in a tower-like structure which is the base element of the future experiment CUORE (see Sec. 3.2). The total TeO_2 mass is about 41 kg. The total exposure to date is about 11.8 kg×y (i.e. 90.7 moles×y of ^{130}Te) and the measured background at $Q_{\beta\beta}$ is about 0.18 c/keV/kg/y, mainly due to U and Th contaminations on the detector and surrounding copper surfaces. This background level is obtained after applying anti-coincidence cuts between the detectors. The present 90% CL lower limit on $\tau^{0\nu}_{1/2}$ is 3.0×10^{24} y, corresponding to an upper limit on $\langle m_\nu \rangle$ of about $0.16 \div 0.84$ eV [20]. With an exposure of about 120 kg×y (i.e. 3 year running), Cuoricino would reach a 1σ sensitivity on $\langle m_\nu \rangle$ of about $0.1 \div 0.6$ eV.

NEMO-3 [21] is a tracking detector experiment running in the Frejus Underground Laboratory (France). It uses a drift chamber to analyze the electrons emitted by foils of different enriched materials. Interesting $\beta\beta$-0ν decay sensitivities are expected only for the ^{100}Mo and ^{82}Se sources. The NEMO-3 detector can reject the background by identifying γs, e^-, e^+ and αs. After measures taken in 2004 to suppress radon, the background is now about 0.5 c/kg/y (for ^{100}Mo): mostly composed by the $\beta\beta$-2ν tail (60%), ^{208}Tl in the foils (20%) and radon (20%). The data analysis using a maximum likelihood applied to 3 kinematic variables gives a 90% CL lower limit on $\tau^{0\nu}_{1/2}$ of about 5.8×10^{23} (2.1×10^{23}) y for ^{100}Mo (^{82}Se), corresponding to a limit on $\langle m_\nu \rangle$ of about $0.6 \div 2.4$

$(1.2 \div 3.2)$ eV. In 2009, the expected 90% CL sensitivity on ^{100}Mo $\tau^{0\nu}_{1/2}$ is 2×10^{24} y, corresponding to $0.3 \div 1.3$ eV for $\langle m_\nu \rangle$.

3. Future experiments

It is likely that presently running experiment will not be able to confirm or rule out the KKDC positive result: therefore this will be the task for future experiments. For a reliable confirmation, $\beta\beta$-0ν decay must be observed for different isotopes with similar $\langle m_\nu \rangle$. The KKDC claim rejection requires a negative result from either a more sensitive ^{76}Ge experiment or a much more sensitive experiment on a different isotope. All proposed next generation experiments aim at sensitivities of about 0.01 eV: whether the KKDC result is correct or not, they will have good chances to observe $\beta\beta$-0ν decay. The large sensitivity improvement (a factor 10 in $\langle m_\nu \rangle$, i.e. a factor 10^2 on $\tau^{0\nu}_{1/2}$) must be obtained by scaling up to 1 ton mass experiments and by further reducing the background. In order to perform high sensitivity searches for $\beta\beta$-0ν decay of as many different isotopes as possible, the isotope enrichment is becoming a hot topic: for many interesting isotopes large scale enrichment is still both a technical and an economical problem. A strong effort is also demanded to nuclear theory to reduce the uncertainties in the nuclear matrix evaluation.

Table II gives some informations about the more well-defined projects. Most of the projects presented here are at a very early R&D stage, especially the ones in Sec. 3.3 and 3.4, and for all of them the predicted sensitivity heavily relies on the assumed background level.

3.1. Calorimetric experiments with ionization detectors

The use of Ge ionization detectors is proposed for many future experiments because this is a well established experimental technique: it is relatively easy to scale up, it guarantees high energy resolution and it provides some background rejection by PSD and segmentation. The main drawback is the high cost for the Ge enrichment and for the detectors themselves. There is also the **COBRA** proposal [24] for using CdZnTe diode detectors, but the technique, though promising, is still very young.

The Ge detector proposals follow two opposite approaches, descending from the experience of the HM experiment and Igex. The first one attributes to the material surrounding the detector the main responsibility for the background observed in the HM experiment, and therefore proposes to eliminate all this material by suspending bare Ge crystals in a highly purified cryogenic liquid. The second approach stems from the localization of the main source of the Igex background inside the Ge crystals due to cosmogenic activity.

The **Majorana** experiment [25, 26] belongs to the second group: the final aim is a 1 ton experiment with segmented enriched Ge crystals in ultra low background cryostats. The experiment will start in 2010 and a staged approach with 60 kg detector assemblies is planned. For the first stage (Majorana 120) two 60 kg modules (114 detectors) will be installed either in the DUSEL or SNOlab underground laboratories. Even minimizing cosmic ray exposure, the expected background of about 17 c/keV/t/y (without cuts) is mainly due to cosmogenics, since the activity in the surrounding materials would be avoided by careful material screening and selection: the application of PSD, granularity and segmentation cuts would further reduce the background to about 0.25 c/keV/t/y, giving a 90% CL sensitivity of 7×10^{26} y in 5 years measuring time ($\langle m_\nu \rangle \leq 0.09$ eV). The Majorana 120 phase would be able to probe the KKDC claim. While a further enlargement to Majorana 180 is not yet settled, for a 1 ton experiment a wider collaboration is foreseen and there is already a Memorandum of Understanding with the GERDA collaboration (see below). The collaboration is presently going through a R&D activity to study the segmented detectors (SEGA), to construct a prototype multi-crystal cryostat (MEGA) and to understand and reduce the background.

The other approach is the one of Genius, GEM and GERDA.

The **Genius** experiment [27], proposed by part of the HM experiment collaboration, consists of 1 ton bare enriched Ge crystals suspended in a 12 m diameter liquid nitrogen tank. For a liquid purity of about 10^{-15} g/g for U and Th, the expected background is about 0.2 c/keV/t/y. A 10 year measurement would give a sensitivity of about 10^{28} y ($\langle m_\nu \rangle \leq 0.015 \div 0.05$ eV). This experiment could have also an interesting sensitivity for real time solar neutrino detection and for cold Dark Matter. Although the authors believes that it is no longer worth to proceed with a 1 ton experiment, given the positive result already claimed by KKDC, they set up the Genius Test Facility in the Gran Sasso Underground Laboratory, where four 2.5 kg Ge crystals have been run in liquid nitrogen [28].

Similar to Genius is the **GEM** proposal [29]: the main difference is the reduction of the amount of liquid nitrogen obtained by adding an external layer of pure water.

The new ^{76}Ge $\beta\beta$-0ν decay experiment in the Gran Sasso Underground Laboratory (also known as **GERDA**) [25, 30] is similar to Genius and GEM but has more compact dimensions. The driving idea is to scrutinize the KKDC evidence in a short time using the existing ^{76}Ge enriched detectors of the HM and Igex collaborations. The set-up consists of a liquid argon cryostat (4 m diameter) immersed in pure water tank (10 m diameter). The argon scintillation provides an additional active shielding, especially useful to reduce the effect of cosmogenic ^{60}Co in the detectors. The aim of the experiment Phase-I, planned to start in 2009, is to reduce the background to about 0.01 c/keV/kg/y (mainly detector intrinsic) and to reach an exposure of about 15 kg×y using the 20 kg of ^{76}Ge recovered from the HM experiment and Igex. If the KKDC evidence is correct, GERDA would detect a 5σ signal. In Phase-II, which is already funded, other 20 kg of enriched and segmented Ge detectors will be added. A further reduction of the background to 0.001 c/keV/kg/y and an exposure of 100 kg×y would give a 90% CL sensitivity of about 2×10^{26} y ($\langle m_\nu \rangle \leq 0.09 \div 0.29$ eV). Presently the detectors for Phase-I are being refurbished by the manufacturer and the collaboration is working on the set-up (water tank, argon cryostat and infrastructures) to be installed in the Gran Sasso Underground Laboratory. An R&D activity is in progress to prepare and test the detectors for Phase-II.

For a final 1 ton ^{76}Ge experiment there are contacts between the GERDA and Majorana collaborations for a joint experiment using the best developed and tested technique [25].

3.2. Calorimetric experiments with cryogenic detectors

The Cuoricino experiment has proved that also the cryogenic detection technique is mature for a next generation $\beta\beta$-0ν decay experiment. It is worth noting that almost all the interesting isotopes can be studied with cryogenic detectors [31, 32, 33, 42]. Cryogenic detectors have high energy resolution, can be scaled up to a 1 ton size and their background can be reduced by segmentation. Further background rejection can be achieved by hybrid detectors where, e.g., also scintillation or ionization are detected: these techniques can provide particle identification or position information [31, 32]. The drawbacks of this technique are the sensitivity to surface contaminations, the difficulty to reduce close materials and the still cumbersome ancillary equipments required for cooling the detectors.

To date, the **CUORE** (Cryogenic Underground Observatory for Rare Events) [34] is the only fully approved next generation 1 ton size $\beta\beta$-0ν decay experiment: it is being built in the Gran Sasso Underground Laboratory where it is due to start data taking in 2011. CUORE will search for $\beta\beta$-0ν decay of ^{130}Te with a detector made of about 19 towers like the one of the running Cuoricino detector. 988 natural TeO_2 detectors will make up a 740 kg granular and compact calorimeter containing 200 kg of ^{130}Te. Even if it is possible to achieve a high sensitivity just with natural Te, the possibility of introducing enriched material in the core of the detector is still an open option for a second phase. A background of about 1 c/keV/t/y can be reached by exploiting the granularity and by reducing a factor 100 the surface contaminations observed in the Cuoricino experiment. This reduction is possible with the use of specially designed advanced cleaning processes which are being tested. Presently the cryogen-free dilution refrigerator and the infrastructure in the Gran Sasso Underground Laboratory are being built, while the cryostat design is being completed. The copper for the construction has been procured and the crystal production is starting. With a background of about 1 c/keV/t/y and an energy resolution FWHM of about 5 keV, a 1σ sensitivity on $\tau^{0\nu}_{1/2}$ of about 6.5×10^{26} y can be reached in 5 years ($\langle m_\nu \rangle \leq 0.011 \div 0.057$ eV). CUORE is potentially also a good detector for cold Dark Matter and Solar Axions [35].

3.3. Calorimetric experiments with scintillators

Scintillators provide a relatively simple and well established instrument to search for $\beta\beta$-0ν decay of many interesting isotopes. They can be extremely large and, in order to reduce the background, they can be immersed in the ultra pure liquids of large solar neutrino experiments (e.g. Superkamiokande, SNO or Borex) using their photomultipliers. Their background can also be reduced by PSD. The main drawback is the poor energy resolution which makes the $\beta\beta$-2ν decay tail the main component of the background at $Q_{\beta\beta}$. Moreover photomultipliers and scintillators are often not enough radiopure for low background application.

Most noticeable are the **CAMEO** proposal [36] to immerse $CdWO_4$ crystals in Borexino or CTF, the **CANDLES** project [37] to use CaF_2 crystals in a liquid scintillator active shielding to search for $\beta\beta$-0ν decay of ^{48}Ca, in spite of its exceedingly low natural isotopic abundance, and the possible use of the Dark Matter self shielding 10 ton liquid Xe **XMASS** detector to look for ^{136}Xe $\beta\beta$-0ν decay [38]. Even more challenging are the ideas to place liquefied Xe in high pressure transparent cells in SNO [39], to dissolve Xe in Borexino [40], and to suspend scintillating nanocrystals in SNO [41].

3.4. Tracking experiments

Tracking detectors could potentially avoid all background sources with the exception of the $\beta\beta$-2ν decay tail. The main issue for this technique is therefore the energy resolution. In case a $\beta\beta$-0ν signal is detected, the reconstruction of the electron tracks would also provide a unique tool to distinguish the decay mechanism from the electron angular correlation.

The **MOON** project [42] consists of sandwiches of ^{100}Mo enriched foils, plastic scintillators, and scintillating fibers which provide the energy and position measurements. MOON would be also a solar neutrino experiment. **DCBA** project [43] proposes a Drift Chamber Beta Ray Analyser with ^{150}Nd enriched foils. There is also an Expression of Interest [44] for a **SuperNEMO** tracking detector with about 100 kg of enriched isotopes (the most interesting would be ^{150}Nd).

The **EXO** project [45] would deserve its own section because it is actually a calorimetric experiment with moderate tracking capability. It is the evolution of the Gotthard experiment [46] on ^{136}Xe, which used a high pressure Xe TPC. The EXO proposal adds the tagging of the Ba atoms produced by the ^{136}Xe decay to completely suppress all backgrounds. A single Ba^{+} ion would be detected by optical spectroscopy. Presently there are still two open options for the detector: a high pressure Xe TPC or a liquid Xe TPC where also scintillation would be detected to improve energy resolution. The second option is the preferred one because of its compactness (a 10 ton detector would have a 3 m^{3} volume), but Ba tagging requires single Ba^{+} ion extraction from liquid. Running for 5 years a 10 ton Xe detector with an energy resolution of 1% and with just the $\beta\beta$-2ν tail background, a sensitivity on $\langle m_\nu \rangle$ of about 11÷15 meV could be reached. Presently a 200 kg enriched liquid Xe TPC prototype without tagging is being installed at WIPP [45]. Running for 2 years the expected sensitivity for EXO-200 is 6.4×10^{25} y ($\langle m_\nu \rangle \leq 0.27 \div 0.38$ eV).

4. Conclusions

$\beta\beta$-0ν experiments can establish whether the neutrino is a Majorana particle and fix the absolute neutrino mass scale. Presently there is still only one experimental evidence for $\beta\beta$-0ν, which has been claimed by the Heidelberg-Moscow experiment on ^{76}Ge, but has not yet been confirmed nor ruled out. Only the Cuoricino and NEMO-3 still running experiments have some chances to confirm this result. Next generation experiments, aiming at a sensitivity on $\langle m_\nu \rangle$ of the order of 10 meV, will settle the issue: presently only the CUORE experiment is approved and being built full size.

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