ISTITUTO NAZIONALE DI FISICA NUCLEARE

Sezione di Milano

INFN/BE–00/01
10 Gennaio 2000

Neutrinoless Double Beta Decay with Xe–136 in BOREXINO and the BOREXINO Counting Test Facility (CTF)

B. Caccianiga[1] and M.G. Giammarchi[2]

[1)] Dipartimento di Fisica dell'Università di Milano, I–20133 Milano, Italy

[2)]INFN–Sezione di Milano, I–20133 Milano, Italy

Abstract

This paper discusses the methods and sensitivity for a Double Beta Decay experiment based on the Xe-136 candidate for BOREXINO or the BOREXINO Counting Test Facility. Different background assumptions and experimental configurations are studied, assuming a data taking period of one year. The related experimental problems are discussed and summary tables containing the sensitivity estimates for the various configurations are presented.

PACS: 23.40.-s; 14.60.p

*Published by **SIS–Pubblicazioni***
Laboratori Nazionali di Frascati

1 Introduction

This paper studies the feasibility of a Xe-136 based double beta decay experiment to be performed in the forthcoming BOREXINO detector for Solar Neutrino physics or in the associated Counting Test Facility. The basic of the technique requires the dissolution in large amounts of the Xe-136 double beta candidate in the sensitive volume of the detector.

The document is structured as follows: after a short description of the two detectors (§2) and of the double beta decay physics (§3 and 4), the fundamentals of the idea and the proposed experimental configurations are described in §5 and 6. §7 deals with important technical problems, such as the solubility of Xe in the BOREXINO detector and the enrichment in the required radionuclide. §8 and 9 discuss the backgrounds and the related question of the sensitivity that can be achieved in one year of data taking. After a short comment on the radiochemical approach (§10), our conclusions are drawn in §11, where the final proposals are presented.

2 The BOREXINO and CTF detectors

The Solar Neutrino BOREXINO experiment[1] [21] is located in the Hall C of Laboratorio Nazionale del Gran Sasso (LNGS, Italy) and has the main goal of real-time studying the ^{7}Be component of the solar neutrino flux. The detector is composed of 300 tons of ultrapure unsegmented liquid scintillator viewed by 2200 photomultipliers and shielded by 3300 tons of radiopure liquids (see fig. 1). Time and charge information are used to reconstruct scintillation events produced by the neutrino-induced elastic scattering reaction $\nu e \rightarrow \nu e$.

The detectability of the solar neutrino signal in BOREXINO requires extreme radiopurity of the sensitive volume and detector components; the required contamination for the scintillator is in the range of 10^{-16} g/g of ^{238}U equivalent. We refer to ref. [1] for a discussion of the BOREXINO detector, its physics program and the relevant backgrounds.

The Counting Test Facility (CTF) is a smaller-scale BOREXINO prototype[2] (also located in Hall C of LNGS), featuring $\sim$4 tons of ultrapure scintillator shielded by 1000 tons of radiopure water (fig. 2). The scintillator is enclosed in a nylon sphere ($\sim$1 m diameter, 0.5 mm thick) called the *Inner Vessel*. This detector allowed a thorough study of the radiopurity at (or close to) the level required for BOREXINO[3].

The Counting Test Facility was built and operated during the period 1993-97 and is now being restarted for a second phase of data taking, to the main goal of quality-testing the BOREXINO scintillator and purification techniques. In this second phase, the detector (which has been slightly upgraded) is called (and will be called hereafter) CTF2.

3 Introduction to Double beta decay

Double beta decay (DBD) is a process featuring an important sensitivity window to physics beyond the Standard Model [4]. While the two-neutrino DBD $(\beta\beta)_{2\nu}$

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

is an allowed, although rare, process (with a lifetime $T^{2\nu}_{1/2}$ in the range 10^{19} to 10^{24} years), the occurrence of the so-called "neutrinoless" double beta decay $(\beta\beta)_{0\nu}$ would imply lepton-number violation, as well as non-standard properties for the neutrino. In fact, in the process

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

a virtual neutrino must be exchanged between two β^- processes, which requires that the antineutrino emitted at the first interaction vertex ($n \rightarrow p + e^- + \bar{\nu}$) is then absorbed as a neutrino at the second interaction vertex ($n + \nu \rightarrow p + e^-$): for this to be possible the neutrino has to be a self-conjugated (Majorana) particle and must have a small left handed component to match the helicity needed to be absorbed. This last requirement can be provided by a Majorana mass term or explicitely by a right-handed V+A interaction; in both cases, for the process to occur the neutrino must have non-zero mass. The most general expression describing the neutrinoless double beta decay half life is:

$$\begin{aligned}[T^{0\nu}_{1/2}]^{-1} &= C^{(0)}_{mm}\frac{< m_\nu >^2}{m_e^2} + < \lambda > C^{(0)}_{m\lambda}\frac{< m_\nu >}{m_e} + < \eta > C^{(0)}_{m\eta}\frac{< m_\nu >}{m_e} + \\ &+ < \lambda >^2 C^{(0)}_{\lambda\lambda} + < \eta >^2 C^{(0)}_{\lambda\eta} + < \lambda >< \eta > C^{(0)}_{\eta\lambda}\end{aligned}$$

where $< m_\nu >$ is the effective neutrino mass expressed by $< m_\nu >= \sum |U_{ei}|^2 m_{\nu i}\phi_{ci}$ ($\phi_{ci} = \pm 1$ are CP phase terms), while $< \lambda >$ and $< \eta >$ are the effective coupling costants which describe the coupling of right-handed lepton current with right-handed and left-handed nucleonic current respectively. If one considers only the first term of the sum, that is, disregards the contribution which would arise from the existence of Right Handed, V+A currents, the transition probability reduces to:

$$[T^{0\nu}_{1/2}]^{-1} = C^{(0)}_{mm}\frac{< m_\nu >^2}{m_e^2} = G^{0\nu}|M^{0\nu}|^2\frac{< m_\nu >^2}{m_e^2} \quad (1)$$

where $G^{0\nu}$ is the phase space integral which includes the kinematics of the reaction and $|M^{0\nu}|$ is the nuclear matrix element which takes into account the initial, final and intermediate state of the nucleus in the decay.

It has also been suggested that the neutrinoless double beta decay could occur with the emission of an hypothetical massless weakly-interacting particle, called Majoron

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

In this case the transition probability would be proportional to:

$$[T^{\chi}_{1/2}]^{-1} \sim G^{\chi} |M^{0\nu}|^2 < g_{\nu\chi} >^2 \tag{2}$$

where G^{χ} is again the phase space factor, $|M^{0\nu}|$ is the nuclear matrix element and $< g_{\nu\chi} >$ is the effective coupling between the Majoron and the neutrino.

The candidates for double beta decay are the even-even nuclei for which the single beta decay is energetically forbidden. There are about 40 isotopes which satisfy this condition, among which ^{136}Xe, ^{76}Ge, ^{130}Te and ^{100}Mo. The expected theoretical shape for the two-neutrino double beta decay is shown in figure 3 in the case of ^{136}Xe. Its experimental determination is especially important to provide a valuable test of the nuclear matrix element calculations which are usually affected by large theorethical uncertainties. So far, experimental evidence for the two neutrino double beta decay $(\beta\beta)_{2\nu}$ has been estabilished (or at least indicated) for ten nuclei, among which ^{76}Ge, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{150}Nd and ^{238}U. On the other hand, the neutrinoless double beta decay (which shows up in fig. 3 as a monoenergetic line at the $Q_{\beta\beta}$ value) has never been observed and lower limits have been placed on the lifetime $T^{0\nu}_{1/2}$ of this mode by several experiments (see section §4): from these limits one can extract information on the effective neutrino mass $< m_{\nu} >$ or the Majoron coupling term $< g_{\nu\chi} >$, provided the nuclear matrix calculations are reliable enough. For example, in the assumption of a neutrinoless double beta decay driven only by the Majorana neutrino mass (i.e., disregarding the possible contribution of right handed, V+A, interactions) the limit on $< m_{\nu} >$ can be obtained inverting formula (1) and taking into account the calculated value of $C^{(0)}_{mm}$. One gets:

$$< m_{\nu} > \quad \leq \frac{m_e}{\sqrt{C^{(0)}_{mm} T^{0\nu}_{1/2}}} \tag{3}$$

Table 1 shows the estimated values of $C^{(0)}_{mm} = G^{0\nu} |M^{0\nu}|^2$ (called in some references "nuclear factor of merit " [5]) for a number of double beta decay candidates: the phase space integrals have been taken from reference [12], while the results on nuclear matrix elements come from calculations done by several authors using different techniques; the strong dependency of the obtained reults on the kind of approach used reflects the big uncertainty on the theoretical determination of this quantity and ultimately affects the

Table 1: Nuclear factor of merit calculated for different isotopes.

$C_{mm}^{(0)}(\times 10^{13}\ y^{-1})$	^{76}Ge	^{82}Se	^{100}Mo	^{116}Cd	^{128}Te	^{130}Te	^{136}Xe	^{150}Nd
$Ref.\,[6]$	1.12	4.33	2.05	–	0.336	5.34	1.18	77.4
$Ref.\,[7]$	1.18	4.20	24.9	–	0.248	4.65	1.57	53.2
$Ref.\,[8]$	–	1.82	–	–	0.145	3.13	1.13	–
$Ref.\,[9]$	0.733	1.75	0.677	0.557	0.136	3.02	1.43	–
$Ref.\,[10]$	0.142	0.938	0.000722	0.535	0.0171	1.24	0.933	–
$Ref.\,[11]$	0.19	1.30	–	–	–	–	0.248	–

reliability of the limit on the effective neutrino mass which can be set in a neutrinoless double beta decay experiment.

It is interesting to compare the predicted values for the factor $C_{mm}^{(0)}$ in the case of Xe-136 and Ge-76: from formula (3) it is in fact clear that, at least in the assumption of DBD driven only by the Majorana mass term, this factor directly influences how stringent a limit on the neutrino effective mass can be set, once a limit on the DBD lifetime has been experimentally determined. Table 1 shows that, depending on the type of calculation under consideration, the values of $C_{mm}^{(0)}$ obtained for Xe-136 are similar to or slightly bigger than those obtained for Ge-76, which translates into a potentially similar or slightly better capability of setting limits on the effective neutrino mass.

A selection of some of the most relevant experimental results on the search for double beta decay is given in §4.

4 Experimental considerations on double-beta decay

The sensitivity of an experiment planned to search for DBD critically depends on the signal detection efficiency ϵ, on the number of candidate atoms N (which in case of the calorimetric detectors is related to the mass of the detector and to the enrichment of the sample), on the data taking time t and on the background counts B per unit time in the relevant energy window. In case of no background, the absence of signal can be translated into the following limit on the half-life $T_{1/2}$ of the double beta decay process:

$$T_{1/2} > \ln 2 \times \epsilon N t / \ln 10 \text{ years} \qquad (90\%\ C.L.) \tag{4}$$

In the more realistic case of B counts of background per year in the relevant energy window, one can set a less stringent limit given by the following expression:

$$T_{1/2} > \ln 2 \times \epsilon N \sqrt{t/B} \text{ years} \qquad (68\%\ C.L.) \tag{5}$$

If a is the isotopic abundance of the double beta candidate, A its atomic number, M the sample mass and N_A the Avogadro number, the previous limit can also be expressed by:

$$T_{1/2} > \ln 2 \times \epsilon \frac{a}{A} N_A M \sqrt{t/B} \text{ years} \qquad (68\%\ C.L.) \tag{6}$$

The preceding considerations show the need to use high mass samples, possibly enriched in the DBD candidate content and to keep all kinds of background at the lowest possible level. It should be noted also that in the presence of internal background, that is, in case of contamination which increases with the sample mass itself, the limit which can be set on the half-life of the decay does not depend linearly on the sample mass, but improves only as the square root of it.

The search for DBD has been carried out both in *indirect* and *direct* ways. The *indirect* methods include the so-called *milking* technique (in which large amounts of parent nuclei are stored underground to produce appreciable numbers of daughter nuclides) and the *geochemical experiments* (where a rock containing large amount of candidate DBD parents is isotopically analized for the presence of daughter nuclei). The experimental strategies implemented for a *direct* search of the double beta decay may be broadly divided into two groups: those which focus on the calorimetric measurement of the energy released in the decay and those which are based on tracking detectors to reconstruct the decay topology. The first strategy usually has a very high efficiency in detecting the signal, thanks to the fact that the candidate DBD source is $active$ (that is, source = detector) and takes advantage of the intrinsic high energy resolution of the employed devices (bolometers, solid state detectors and so on). The second class of experiments, instead, is particularly effective in rejecting the background via topological cuts and has also the advantage of allowing the search for double beta decay of different isotopes with the same apparatus.

An important example of detector of the "calorimetric type" is the Heidelberg-Moscow experiment which is operating five enriched ^{76}Ge solid state devices with 10.96 kg active mass in the Gran Sasso underground laboratory [13]. After 28.7 kg y of data taking they measure the half-life of the two neutrino DBD to be $T^{2\nu}_{1/2} = (1.77 \pm 0.1 \pm 0.12) \times 10^{21}$ y and set the most stringent limit so far on the half-life of the neutrinoless DBD, namely, $T^{0\nu}_{1/2} > 1.1 \times 10^{25}$ y $(90\%\ C.L.)$. This last result can be translated into a limit on the Majorana neutrino mass of 0.46 eV.

The Milano-Gran Sasso experiment exploits the high energy resolution of the bolometric technique to look for the double beta decay of ^{130}Te [15]. They operate an array of 20 cryogenic detectors made up with TeO_2 crystals (340 grams each) in the Gran Sasso Underground Laboratory and have reported so far a limit for the neutrinoless DBD of $T^{0\nu}_{1/2} > 8.8 \times 10^{22}$ y $(90\%\ C.L.)$ [16].

An example of the "tracking" technique is given by the experiment NEMO-II where the DBD source is a $1m^2$ foil placed in a wire chamber which is in charge of tracing the two electrons originated in the decay. The energy and time information is obtained from two scintillator walls placed at the ends of the tracking region. This experiment has studied different istopes, such as ^{100}Mo, ^{116}Cd, ^{82}Se and ^{96}Zr, reaching limits in the range of 10^{21}-10^{22} years [14].

Table 2 summarizes the results on the neutrinoless double beta decay which were mentioned above and which are among the most significant ones. It should be underlined, though, that there are over 40 experiments presently running with many different

techniques and which have not been mentioned here.

In order to have a reference point for the discussion on the potentialities of BOREXINO and CTF2 as competitive ^{136}Xe DBD experiments, the most stringent limits obtained so far on both the $(\beta\beta)_{0\nu}$ and the $(\beta\beta)_{2\nu}$ modes in case of the ^{136}Xe isotope are also reported: the best limit obtained is due to the Gotthard experiment (see reference [17]) which consists of a cylindical copper Time Projection Chamber with an active volume of 180 liters. The experiment is performed at the Gotthard Underground Laboratory at a depth of approximately 3000 meters of water equivalent, which reduces the flux of cosmic muons in the TPC to approximately 10 per day. The detector is also shielded by 20-30 cm of lead to reduce background due to natural radioactivity from surroundings. The gas used to fill the detector is a mixture of Xenon (enriched at 63% with Xe-136) and 3.9% of methane to increase the drift velocity and suppress diffusion of secondary electrons. The operating pressure is 5 atm which gives a total of 1.46×10^{25} Xe-136 atoms in the fiducial volume. The energy resolution of the apparatus is 6.6% at 1.6 MeV; the signal reconstruction efficiency is approximately 30%, while the background rejection efficienty is greater than 98%. The experiment sets limits both on the two-neutrino and the neutrinoless double beta decay half-life: $T^{2\nu}_{1/2} > 1.6 \times 10^{20}$ y $(90\%\, C.L.)$ and $T^{0\nu}_{1/2} > 3.4 \times 10^{23}$ y $(90\%\, C.L.)$.

5 The ground-breaking work

In this paper we will be considering only the Xe-136 DBD candidate nucleus. The physical processes we are interested in are:

$$^{136}Xe \rightarrow {}^{136}Ba\ 2e\ 2\nu \qquad "two-neutrinos"\ \ DBD$$

and especially:

$$^{136}Xe \rightarrow {}^{136}Ba\ 2e \qquad "neutrinoless"\ \ DBD$$

The experimental technique involves in both cases the detection of the two electrons emitted during the decay.

For the case of the regular DBD one can approximately parametrize the expected spectrum with the analytical form:

$$\frac{dN}{dK} \sim K(T_0 - K)^5[1 + 2K + \frac{4K^2}{3} + \frac{K^3}{3} + \frac{K^4}{30}] \tag{7}$$

where K is the sum of the kinetic energies of both electrons and $T_0 = 2.479$ MeV is the $Q_{\beta\beta}$ value. This formula was actually used to obtain fig. 3 and is the Primakoff-Rosen

Table 2: Some experimental results on DBD.

Isotope	$T^{2\nu}_{1/2}\ (years)$	$T^{0\nu}_{1/2}\ (years)$	$Ref.$
^{76}Ge	$(1.77 \pm 0.1 \pm 0.12) \times 10^{21}$	$> 1.1 \times 10^{25}\ (90\%\ C.L.)$	[13]
^{130}Te	$> 5.0 \times 10^{19}\ (90\%\ C.L.)$	$> 8.8 \times 10^{22}\ (90\%\ C.L.)$	[16]
^{116}Cd	$(3.75 \pm 0.35 \pm 0.21) \times 10^{19}$	$> 5.0 \times 10^{21}\ (90\%\ C.L.)$	[14]
^{82}Se	$(1.2^{+0.3}_{-0.2} \pm 0.2) \times 10^{20}$	$> 3.6 \times 10^{21}\ (90\%\ C.L.)$	[14]
^{96}Zr	$> 1.9 \times 10^{19}\ (90\%\ C.L.)$	$> 2.4 \times 10^{20}\ (90\%\ C.L.)$	[14]
^{100}Mo	$(0.95 \pm 0.04 \pm 0.09) \times 10^{19}$	$> 6.4 \times 10^{21}\ (90\%\ C.L.)$	[14]
^{136}Xe	$> 2.1 \times 10^{20}\ (90\%\ C.L.)$	$> 3.4 \times 10^{23}\ (90\%\ C.L.)$	[17]
^{136}Xe	$> 1.6 \times 10^{20}\ (95\%\ C.L.)$	$> 3.3 \times 10^{21}\ (95\%\ C.L.)$	[18]

approximation to the best theoretical curve (see discussion in [4] pagg. 148,149).

The neutrinoless DBD on the other hand has the very simple signature of a monoenergetic line for the summed two-electrons kinetic energy. For the case of Xe-136 this signal is located at $Q_{\beta\beta} = 2.479$ MeV, as shown in 3.

The experimental technique considered in this paper consists in dissolving the candidate Xe-136 nuclei in the liquid scintillator of a BOREXINO-like detector and consequently detecting the two electrons kinetic energy by means of scintillation.

This approach, proposed by R.S. Raghavan in his 1994 PRL paper [19] [1], takes advantage of the fact that a noble gas like Xe can be used to dope a liquid scintillator without altering its chemical and optical properties. Moreover, given the fact that the solubility is very high, a sizeable number of Xe nuclei can be kept under observation by using the ultrapure liquid scintillator of the BOREXINO or CTF2 detectors. In this way a calorimetric type of search can be conducted, the source being uniformly dispersed in the detector. Finally, a subtraction of the background can potentially be conducted in a source-out/source-in approach provided the Xenon itself is sufficiently free of impurities.

6 Experimental configurations: CTF05, CTF2, BOREXINO

We will consider three main experimental configurations, called CTF05, CTF2 and BOREXINO. They can be implemented either using the Counting Test Facility or the final BOREXINO detector. We will always consider PC + PPO (1.5 gr/l) as liquid scintillator (shortly, PC) since it is the standard BOREXINO mixture.

Let us first note that the dissolution of Xenon in a spherical vessel directly exposed to an external gamma background is not the optimal choice for a DBD search, since a large fraction of the Xenon nuclei will be close to the most radioactive region of the detector. For this reason, a decoupling buffer of very high radiopurity - not containing Xenon - offers the advantage of yielding essentially the same sensitivity with a considerably smaller number of Xe-136 nuclei. This choice was made in configurations CTF05 and BOREXINO in the following list.

- **CTF05**. This configuration is considered because of the availability of a ~ 10 kg sample of Xenon already enriched (at 64%) in Xe-136 [20] (see also [18],[27]). To exploit this possibility we will consider a $r = 0.5\ m$ InnerInner Vessel immersed in the $1\ m$ radius CTF Inner Vessel. This volume is Xe-loaded and is shielded from the external water by the residual 0.5 m of scintillator (without Xe). So, this

[1] Actually the idea was already included in the 1991 BOREXINO Proposal [21].

configuration features an Inner Vessel (1 m radius) containing PC and an InnerInner Vessel (0.5 m radius) with PC+Xenon.

- **CTF2**. A 1 m radius Inner Vessel scintillator is loaded with Xe and is directly immersed in water; this is the same configuration of the previous CTF data taking. We note - however - that the new CTF data taking will be done with an additional nylon protective sheet external to the Inner Vessel. This sheet is called *the Shroud* and separates the water shielding into an external part and an internal part that contains considerably less Radon. We estimate the Radon reduction to be between 10 and 1,000 because of the Shroud.

- **BOREXINO**. In BOREXINO an InnerInner Vessel is loaded with Xenon. The radius of this InnerInner Vessel is selected to be 2.7 meters. In addition, the usual BOREXINO Inner Vessel (radius 4.25 m) is assumed to be present and full of PC (and no Xe). The dimension of the InnerInner vessel radius for this configuration (R=2.7 m) is the result of a compromise between the need to increase the shielding from the PMT γ emission (which implies the reduction of the Xe-loaded vessel radius) and the importance of having a large number of ^{136}Xe atoms. We have verified that, for our background assumptions, an InnerInner Vessel radius bigger than 2.7 m will not improve the DBD lifetime limit, but only increase the cost. This effect was already identified and discussed in [19].

The main geometrical features of the three configurations are shown in fig. 4 while the mass, cost and number of Xe-136 nuclei are summarized in table 3. Some of these quantities (solubility, cost) are actually discussed in the next paragraph.

One final comment concerning the scintillator: as stressed before we only concentrate on PC and (1.5 gr/l) PPO as a fluor. We are aware of the fact that a different fluor solution between the Xe-loaded region and the Xe-free region could improve the signal/background discrimination by pulse shape analysis techniques. However, we do not elaborate further on this.

7 Xe DBD in CTF/BOREXINO: technical problems

We will now address the main technical difficulties to be solved for the Xenon-136 procurement and dissolution in the CTF05/CTF2/BOREXINO scintillator.

The expected signal for a DBD Xe experiment depends on a number of factors we are now going to discuss in the following sub-paragraphs; the main factors are the Xe solubility in PC, the Xe-136 enrichment and the Xe diffusivity through a Nylon Vessel. They

Table 3: The three "Xenon" configurations.

Config.	PC vol/mass	Xe mass (2.14%)	Cost	Xe-136 nuclei
CTF05 (0.5m)	0.52 m^3/0.47 t	9.9 kg	9.9 k$	3.90×10^{24}
CTF05 64% enric.	0.52/0.47	9.9	available	2.80×10^{25}
CTF2 (1.0m)	4.2/3.7	79.7	79.7 k$	3.14×10^{25}
CTF2 80% enric.	4.2/3.7	79.7	6.69 M$	2.82×10^{26}
BXINO (2.7m)	82/73	1565	1.56 M$	6.17×10^{26}
BXINO 80% enric.	82/73	1565	131 M$	5.54×10^{27}

Table 4: A few Xenon properties.

Dens. (0 °C, 1 atm)	Boil. point (1 atm)	Xe-136 ab.	Sol. in PC at 15 °C
5.9 kg/m^3	166 K	8.9%	2.14% wt (at 900 mb)

determine the number of candidate DBD nuclei that are actually kept under observation in the detector as well as the Xenon cost.

7.1 Xe solubility

Xenon solubility in Pseudocumene is a critical experimental parameter that directly determines the number of nuclei under observation. The dissolution of an inert gas into a liquid follows Henry's law:

$$S = kP \tag{8}$$

where S is the solubility, P is the gas partial pressure in the gas phase and k is the proportionality constant (or solubility at 1 atmosphere partial pressure). The solubility can somehow be increased by increasing the gas phase pressure. However, in this work, we are assuming that the operating gas partial pressure is the atmospheric pressure.

Happily, an inert gas can be dissolved in an aromatic-based scintillator without appreciably altering its optical properties, so that the higher the solubility the better it is from the point of view of detecting a double beta signal.

As an indication of the solubility, it is well known that the solubility of Xenon in aromatic compounds is of the order of 2% by weight (it is actually 2.2% in the case of benzene [19]). Based on these numbers, a weighting method were developed by A. Falgiani, M. Balata and R. Scardaoni at the LNGS chemistry laboratory.

Table 5: Xenon solubility in PC at LNGS (900 $mbar$ atm. pressure).

10 °C	15 °C	20 °C	25 °C
2.25% wt.	2.14% wt.	1.97% wt.	1.89% wt.

In the weighting method, which is appropriate in case of very high solubilities, Xe is dissolved in a PC vial and the vial itself is weighted before and after the dissolution (fig. 5). The experiment is conducted in a situation in which the pressure of the gas phase in the experiment is the atmospheric pressure at LNGS (which is about 900 $mbar$).

The dissolution by bubbling of the Xe requires several minutes and the measurement is done with an analytical scale.

The weight is seen to increase up to the complete dissolution of Xe and then - after reaching a maximum - the weight decreases very slowly because of the solvent (PC) evaporation induced by the Xe flow. This effect has been measured by using a much less soluble gas (nitrogen) and applying the appropriate correction to the Xe measurement. Finally, the same Xe-dissolution procedure has been applied to other solvents (hexane, benzene) for which the Xe-solubility was known; the agreement was found to be satisfactory.

The error on the solubility determined in this way is estimated to be 10% or less. The final results, for Xe solubility in PC at the LNGS site are summarized in table 5. Since the BOREXINO operating temperature will be close to 15 °C, we will use - in the remaining of this paper - 2.14% wt. as the Xe solubility in PC at LNGS.

7.2 Xe diffusion through nylon

Xenon can diffuse out of a nylon made vessel. While this can easily be compensated by keeping the gas phase pressure (above the liquid) at a constant value, the case of enriched Xenon clearly presents a major cost consideration.

The diffusivity of a permanent gas in a polymer has an indicative value of 10^{-10} $m^2 sec^{-1}$ ([22] chapt. 4) but has a high degree of variability depending on the type of polymer and on the physical conditions. This issue was particularly important in CTF in the case of Radon, for which an intensive study was made. While we have no direct information on Xe diffusivity, the result would be very similar to the case of Radon, since for a noble gas the diffusivity has a very mild dependence on the molecular weight ([22] chapt. 2). For this reason we will consider the Radon case, as studied in CTF and in various laboratory tests.

While in general nylon gas permeability is low as compared to other polymers,

accurate Radon studies have indicated a great variability between different kinds of materials [23], even for different kinds of nylons. Moreover external conditions, such as immersion in water, has been shown to greatly increase the process (by about two orders of magnitude).

A BOREXINO internal report [24] summarizes the understanding of this problem (see also [25]). In particular it is shown that the effect can be safely neglected if the nylon is not exposed to water. This means that the only important case to be considered is the CTF2. In fact in the other cases the Xe-confining nylon is not in contact with water. For this reason, the remainder of this sub-paragraph essentially applies to the CTF2 configuration alone.

One important factor to determine the Xe partitioning in the Inner Vessel with respect to the external water is given by the relative solubilities of a noble gas in water and PC. As can be deduced from above, the solubility of Xe in PC is 2.14% by weight (or $\simeq 10^{-2}$ moles/mole), while the solubility of Xe in water is only 0.007% [26] (or $\simeq 10^{-4}$ moles/mole), so that the partition coefficient is about 10^{-2} when mole units are used [2] .

In addition to this, the mass factor needs to be considered. For the CTF2 case, 3700 kg of PC can accomodate 79.2 kg of Xe, or 582 moles. On the other hand a thousand tonnes of water are 56×10^6 moles and can accomodate 5600 moles of Xe.

This is to say that, if Xe is dissolved in a CTF2 Inner Vessel at the solubility limit, the Xe would slowly go from PC to water through the Inner Vessel to reach a final condition in which most of the Xe mass is actually in the water. Luckily, this process will take a very long time so that we can actually derive an upper limit for this effect in the case of a 1 year data taking with the CTF2 configuration.

To calculate the diffusion rate, we have considered the Rn diffusion data, as summarized in [24] and [25], according to which an effective permeation coefficient of

$$P = DS = 3.1 \times 10^{-9}\ cm^2 sec^{-1} \tag{9}$$

is a reasonable choice for Radon diffusion through a water-exposed nylon film. As mentioned before we will use the same number for Xenon.

This number can be used to establish an upper limit to the diffusion rate, according to formula (6) of [23] for the steady state diffusion:

$$\phi = DSC/d \tag{10}$$

[2] The numbers for the water refer to standard 20 °C temperature and partial pressure of 1 atmosphere. In the case of PC the effect of scaling the pressure and temperature from LNGS conditions almost cancel each other.

where C is the concentration of Xe and d is the diffusion thickness ($0.5\ mm$). So, for the CTF2 case, one has $C = 19$ kg/m^3, and $\phi = 11.7 \times 10^{-9}$ kg $m^2 sec^{-1}$. This flux will cause at most 4 kg of Xenon to leave the Inner Vessel, or 5% of the total Xenon mass.

Therefore we conclude that a maximum yearly loss of Xe because of diffusion through nylon is 5% in mass. We believe this number to be on the safe side and we will neglect this effect in the remaining.

7.3 Xe enrichment and cost

The advantage of the enrichment is very clear. Only the isotope 136 of Xe is interesting for our purpose and its natural abundance is only 8.9%. In addition, commercially available Xenon also contains a significant contamination of Krypton (about 30 ppm), which can severely affect the count rate at low (sub-MeV) energies, since Krypton-85 (present in air) has a β spectrum with 687 keV endpoint.

Xe enrichment techniques relies on ultracentrifuge or cryogenic/distillation methods and have already been used in the case of low background particle physics applications [18]. The specific case of separation of rare gases from radioactive contaminants by means of ultracentrifuge is considered in [27]. The treatment by ultracentrifuge is actually not a uniquely defined process, since it depends on the process parameters, mainly through the so called *cut*.

At low cut (0.07) no significant Xe-136 enrichment is performed. However, an important lower mass rejection is achieved, which is translated, for instance, in a very significant Krypton-85 reduction. At high cut (0.92) a significant Xe-136 enrichment is reached (and, of course a very good Krypton reduction), so that one arrives at 64% Xe-136 [27]. In short, different cut processes can lead to different Xe-136 purities, but the price will steeply increase as a function of the purity required.

First of all it has to be noted that the cost of natural commercial Xe is about 7 dollars/STP-liter (or 1,200 dollars/kg)[28]. We will assume a number of 1,000 dollars/kg in the hypotesis of a large order discount. Secondly, the cost of 50%-enriched Xe-136 is, according to a quotation currently in our hands, of 120 $/STP-liter, or 20,000 $/kg. Finally, the cost of a 80% enrichment (also quoted) is of 500 dollars/STP-liter (or 84,000 $/kg) for a large scale order.

In this memo we have considered the case of natural (no-enrichment) Xenon, the case of the available 64%-enriched sample, and the case of 80% enrichment, above which level the price will increase even more dramatically.

8 Background

As it was pointed out in §4 the sensitivity of a DBD detector is critically dependent upon the presence of background counts in the energy window where the signal is expected to fall. In CTF and BOREXINO the main foreseen sources of background are:

- Internal background
- Background from radon in the buffer liquid
- External gamma background
- Cosmic ray induced background
- Neutron induced background
- Ordinary double beta background

The following subsections contain the estimates of the background contribution from each source, evaluated for the three experimental configurations described in §6, i.e., the CTF05, CTF2 and BOREXINO setups. In particular, the number B of counts/year is given for the energy region $(0.5, Q_{\beta\beta} + \sigma)$MeV (where about 76% of the $(\beta\beta)_{2\nu}$ decay counts fall) , the $(\beta\beta)_{0\nu}$ region $(Q_{\beta\beta} \pm \sigma)$MeV and, as a reference, for the entire spectral region and the so-called neutrino window (0.25,0.8)MeV (relevant for the solar neutrino program of BOREXINO); let us recall that $Q_{\beta\beta}$=2.479 MeV is the Q value for the ^{136}Xe neutrinoless double beta decay and σ is the energy resolution at the $Q_{\beta\beta}$ value, which has been assumed (according to the light tracking Monte Carlo) to be 89 keV and 79 keV for CTF (either CTF05 or CTF2) and BOREXINO, respectively. The energy window for the study of the ordinary double beta decay has been chosen in order to keep a high percentage of the signal while rejecting a significant portion of the background coming from natural radioactivity which mainly affects the lower energy end of the spectrum. It should be also noted that the cut at 0.5 MeV preserves the peak of the $(\beta\beta)_{2\nu}$ distribution (see figure 3), thus retaining the possibility of a "shape based" discrimination between signal and background. As far as the $(\beta\beta)_{0\nu}$ decay is concerned, it is important to underline that the choice of using a small energy window (2σ), while reducing the background counts, has the drawback of lowering the signal detection efficiency ϵ to 68%. This reduces the sensitivity of the experiment, as can be easily seen from expressions $(4), (5)$ and (6).

Table 6: Internal background

Setup	All energies (ev/yr)	$(0.25, 0.8)$MeV (ev/yr)	$(0.5, Q_{\beta\beta} + \sigma)$MeV (ev/yr)	$(Q_{\beta\beta} \pm \sigma)$MeV (ev/yr)
CTF05	103	32	29	**0.11**
CTF2	823	257	233	**0.91**
BXINO	15967	4905	4526	**17**

8.1 Internal background

The contamination induced by the natural radioactivity of the scintillator itself (the so-called Internal background), has been evaluated using the GENEB Montecarlo code (see reference [29]). This code generates alphas, betas and gammas coming from the isotopes which belong to the ^{238}U and ^{232}Th chains, together with the decays of ^{40}K and propagates them through the detector. In particular, the simulation has been carried out in the hypothesis of secular equilibrium and assuming the ^{238}U, ^{232}Th and K_{nat} content in the scintillator is 10^{-16}g/g, 10^{-16}g/g and 10^{-14}g/g respectively. Furthermore, we suppose to be able of removing some of the Internal background by applying the following rejection methods:

- $\alpha/\beta\ discrimination$ technique (assumed to have a 90% efficiency in rejecting $alphas$).
- $correlated\ coincidences$ technique, in which the ^{214}Bi - ^{214}Po and the ^{212}Bi - ^{212}Po decay chains are tagged thanks to their correlation in time (this technique is assumed to have 95% rejection efficiency).
- $statistical\ subtraction$ method, in which the activity of the parent isotopes that precede the Bi-Po coincidence in the chain is deduced (and can be subtracted) from the tagged Bi-Po event rate. Also in this case a 95% efficiency in rejecting the background is assumed.

See [1] and [21] for a more complete description of background reduction techniques and cuts in BOREXINO.

The results of the simulation are summarized in table 6: the only cut which affects the background counts in the $(\beta\beta)_{0\nu}$ energy window is the $delayed\ coincidence$ one, due to the fact that only ^{214}Bi gives a relevant contribution in this energy window. This is not the case for the neutrino and the $(\beta\beta)_{2\nu}$ energy windows where all the rejection methods

Table 7: Radon in water background

Setup	All energies (ev/yr)	$(0.25, 0.8)$MeV (ev/yr)	$(0.5, Q_{\beta\beta} + \sigma)$MeV (ev/yr)	$(Q_{\beta\beta} \pm \sigma)$MeV (ev/yr)
CTF	2.5×10^7	8.3×10^5	9.9×10^5	$\mathbf{1.97 \times 10^4}$

play a very important role. It should be noted also that obviously in the case of internal background the number of counts per year increases linearly with the scintillator mass (and therefore with the Xe sample mass), thus limiting the advantages of using a large scintillator sample in order to get a bigger number of candidate DBD nuclei.

8.2 Background from radon in the buffer liquid

This background is expected to have some relevance only in the CTF2 configuration; in the other two solutions, in fact, the so-called InnerInner vessel (see §6) will help preventing Radon from reaching the innermost part of the detector, where Xenon is dissolved. Besides that, the BOREXINO and the CTF05 configurations will take advantage from the additional shielding of the scintillator outer volume (the Xenon-free one). We will therefore assume in the following that external radon does not contribute to background in BOREXINO and CTF05 and we will estimate only the possible contribution in CTF2, starting from the CTF experience. From the analysis of some of the CTF runs (n.224 and n.229 after a water extraction process, n.292 and n.296 after a distillation, see [25]) one gets the average counts/year due to external Radon in the four relevant energy windows. The results of this calculation are shown in table 7.

Of course, one expects that this kind of background will be much lower in CTF2, given the presence of the nylon Shroud, specifically designed to reduce external Radon. To parametrize the effect of the shroud, in the following we will consider a 'low', a 'high' and a 'ultrahigh" purity case, corresponding to the CTF number of background counts/year reduced by a factor 10, 100 and 1000 respectively.

8.3 External gamma background

The background counts caused by the radioactive contamination of the photomultiplier tubes has been evaluated in the CTF05, CTF2 and BOREXINO cases through a Montecarlo simulation carried out with a fast version of GENEB (called GENROX, see refer-

Table 8: Summary of external gamma background

Setup		All energies (ev/yr)	$(0.25, 0.8)$MeV (ev/yr)	$(0.5, Q_{\beta\beta} + \sigma)$MeV (ev/yr)	$(Q_{\beta\beta} \pm \sigma)$MeV (ev/yr)
CTF05	^{238}U	2628	383	2409	**62**
	^{232}Th	1569	44	1277	**266**
	^{40}K	226	0	226	**0**
CTF2	^{238}U	1.8×10^5	4.3×10^4	7.0×10^4	**474**
	^{232}Th	6.3×10^4	1.3×10^4	2.9×10^4	**2409**
	^{40}K	2.0×10^4	5.6×10^3	6.9×10^3	**0**
BXINO	^{238}U	927	0	927	**0**
	^{232}Th	401	0	401	**58**
	^{40}K	0	0	0	**0**

ence [30]), which applies a few approximations in order to produce a significant statistics of events in a reasonable amount of time. The assumed content of ^{238}U, ^{232}Th and K_{nat} in the PMT's is 112.4 μg/PM, 47.3 μg/PM,and 62.3 mg/PM , which corresponds to the measured radioactive contamination of fototubes built with high-purity glass. The results obtained from GENROX in the three configurations are summarized in table 8 where, as usual, the number of counts per year in the four energy windows is shown. In this case, we present the contribution from U,Th and K separately. It should be pointed out that the numbers shown below already take into account the background reduction obtained by applying a cut on the light center of gravity of the event, which is required to be confined within the volume where Xenon is dissolved.

8.4 Cosmic ray induced background

The Cosmic ray induced background can be divided in three main categories:

- Muon crossing the liquid buffer and producing Cerenkov light (in case of BOREXINO, also scintillator light).
- Neutrons produced by muon interactions which are captured by the buffer or by the scintillator and emit a 2.2 MeV annihilation gamma.

- Secondary products of the muon interactions into the detector which may be unstable and therefore decay in the active volume of the apparatus.

Most of the background counts induced by the sources listed above can be removed rather efficiently by recognizing the muon which has originated them: references [31] and [32] describe thoroughly the time and topological signatures which characterize a muon event in the CTF2 and in the BOREXINO geometry, respectively. It is possible to exploit these signatures to reject muons with an efficiency greater than 95%. In addition, CTF2 will feature a set of 12 PMTs situated on the bottom of the main tank and pointing upward which will further help rejecting muons crossing the detector. As for BOREXINO, the detector is equipped with a complete muon identification system consisting of an Outer part (200 PMTs mounted on the SSS sphere - see fig. 1 - pointing outward with the goal of detecting Cerenkov light emitted by the muons crossing the water shield) and an Inner part (400 PMTs pointing inward, with no light concentrators and thus able of detecting light from muons crossing the pseudocumene buffer) [1]. The combined use of the Outer and the Inner Muon Identification systems, together with the topological cuts will make BOREXINO particularly effective in recognizing muons which cross the experimental apparatus (rejection efficiency better than 99.99%, see reference [32]). Obviously, in order to be able of removing the background counts originated by the products of a cosmic ray interaction, the time between the parent and the daughter event has to be small, typically less than one second. This is the case for the neutron capture (which anyway is not dangerous for the $(\beta\beta)_{0\nu}$ search, because it affects an energy window well below the $Q_{\beta\beta}$ value), but is not true for some of the muon induced radioisotopes, such as, ^{11}Be (13.8 sec), ^{10}C (19.3 sec), ^{11}C (20.38 min) and ^{7}Be (53.3 days). The only isotopes which can give counts in the $(\beta\beta)_{0\nu}$ energy window are ^{11}Be and ^{10}C which decay β^- (endpoint E=11.5 MeV) and β^+ (endpoint E=1.9 MeV)+γ (E=0.72 MeV), respectively. The other two isotopes do not affect the $(\beta\beta)_{0\nu}$ search, because they deposit an energy much smaller than 2.479 MeV (^{11}C decays β^+ with an endpoint of 0.99 MeV + 1.02 MeV, while ^{7}Be emits a 0.478 MeV gamma). The evaluation of the event rate due to cosmogenic nuclei both in the $(\beta\beta)_{0\nu}$ and the $(\beta\beta)_{2\nu}$ energy windows requires the knowledge of the production cross-sections. This study has been carried out also in the frame of the NA54 experiment at the muon beam at CERN [33], [34] and the production cross-sections are currently under evaluation [32].

We can however already conclude, based on these studies that, for the $(\beta\beta)_{0\nu}$ search, this background will certainly be negligible with respect to the other background sources we have considered.

8.5 Neutron induced background

Another potential source of background that was recognized in [17] is due to neutrons inpinging on Xe-136 and forming ^{137}Xe nuclei through $^{136}Xe(n,\gamma)^{137}Xe$. Xe-137 is a beta emitter with 4.1 MeV endpoint and a 3.9 minutes lifetime.

In a well shielded detector, like the CTF2 or BOREXINO, the neutron flux is dominated by the muon-induced component, at the level of about 5/day in the CTF2 (and proportional numbers for CTF05 and BOREXINO). This is sufficient to derive an upper limit for the Xe-137 production since, even if all these neutrons were thermalized and absorbed, capture on H (cross section of 0.33 $barn$ and harmless gamma emitted) will compete with capture on Xe-136 ($\sigma = 0.26\ barn$). Given that the number of H atoms in bigger than the number of Xe-136 atoms by a factor of about 1,000 (in the enriched sample), we can derive an upper limit of ($5/day \times 365d/year \times 0.001$) of 2/yr in CTF2 at all energies which translates into 0.04/yr when the $Q_{\beta\beta} \pm \sigma$ window is considered.

Similar considerations can be made for BOREXINO, in which case the final number will scale to 0.8 events/yr. This background will be neglected in the following since it is negligible compared to the other background sources.

8.6 Ordinary double beta background

The limit which will be set on the neutrinoless double beta decay lifetime depends also on the number of counts from the ordinary double beta decay falling in the $(\beta\beta)_{0\nu}$ decay energy window: the smaller the energy window is (or, equivalently, the better the energy resolution is) the smaller the number of background counts which fall into it. From the expected ordinary double beta decay spectrum shape (see paragraph §3) and the CTF2/BOREXINO energy resolution one deduces that the fraction of events falling in the energy window $Q_{\beta\beta} \pm \sigma$ is $2.3 \times 10^{-4}\%$ for BOREXINO and $4.8 \times 10^{-4}\%$ for CTF2. The actual number of counts per year obviously depends on the lifetime of the ordinary double beta decay which is currently not known and on the number of decaying nuclei. The best lower limit on the lifetime has been set by the Gotthard experiment (see paragraph §4) to be 2.1×10^{20} years. Assuming this value as the actual lifetime for the decay, it is possible to calculate the number of events/year for the three experimental setups, considering both the case of non-enriched and enriched Xenon (see table 3): the results of this calculation are reported in table 9.

Besides its role as a background for the neutrinoless double beta decay, the ordinary double beta process is interesting in itself, particularly if one is able of studying the spectral shape of the two emitted electrons to experimentally determine the nuclear matrix

Table 9: Background from ordinary DBD, at 2.1×10^{20} y half-life.

Setup	All energies (ev/yr)	$(0.25, 0.8)$MeV (ev/yr)	$(0.5, Q_{\beta\beta} + \sigma)$MeV (ev/yr)	$(Q_{\beta\beta} \pm \sigma)$MeV (ev/yr)
CTF05	1.3×10^4	5.8×10^3	9.8×10^3	0.06
CTF05 64%	9.3×10^4	4.2×10^4	7.1×10^4	0.4
CTF2	1.0×10^5	4.5×10^4	7.8×10^4	0.5
CTF2 80%	9.4×10^5	4.1×10^5	7.1×10^5	4.5
BXINO	2.0×10^6	9.1×10^5	1.5×10^6	4.7
BXINO 80%	1.9×10^7	8.2×10^6	1.4×10^7	41

Table 10: Natural Xenon

Setup	Internal (ev/yr)	Ext Rn (ev/yr)	PMT (ev/yr)	$(\beta\beta)_{2\nu}$ (ev/yr)	TOT (ev/yr)	$T_{1/2} > \ln 2 \epsilon N \sqrt{t/B}$ (yr) (68% C.L.)
CTF05	0.11	0	328	0.06	328	$> \mathbf{1.02 \times 10^{23}}$
CTF2	0.93	19700 (CTF)	2883	0.5	22584	$> \mathbf{9.80 \times 10^{22}}$
	0.93	1970 (low)	2883	0.5	4854	$> \mathbf{2.13 \times 10^{23}}$
	0.93	197 (high)	2883	0.5	3081	$> \mathbf{2.66 \times 10^{23}}$
	0.93	20 (high+)	2883	0.5	2905	$> \mathbf{2.75 \times 10^{23}}$
BXINO	18	0	58	4.7	81	$> \mathbf{3.25 \times 10^{25}}$

Table 11: Enriched Xenon (64% for CTF05 and 80% for CTF2/BOREXINO)

Setup	Internal (ev/yr)	Ext Rn (ev/yr)	PMT (ev/yr)	$(\beta\beta)_{2\nu}$ (ev/yr)	TOT (ev/yr)	$T_{1/2} > \ln 2\epsilon N\sqrt{t/B}$ (yr) (68% C.L.)
CTF05	0.11	0	328	0.4	329	$> \mathbf{7.33 \times 10^{23}}$
CTF2	0.93	19700 (CTF)	2883	4.5	22589	$> \mathbf{8.80 \times 10^{23}}$
	0.93	1970 (low)	2883	4.5	4859	$> \mathbf{1.91 \times 10^{24}}$
	0.93	197 (high)	2883	4.5	3086	$> \mathbf{2.39 \times 10^{24}}$
	0.93	20 (high+)	2883	4.5	2909	$> \mathbf{2.47 \times 10^{24}}$
BXINO	18	0	58	42	118	$> \mathbf{2.41 \times 10^{26}}$

Table 12: Maximum obtainable sensitivity (no background)

Setup	$T_{1/2} > \ln 2\epsilon N t/\ln 10$ (yr) (68% C.L.)
CTF05	$> 8.04 \times 10^{23}$
CTF05 64% enriched	$> 5.79 \times 10^{24}$
CTF2	$> 6.61 \times 10^{24}$
CTF2 80% enriched	$> 5.79 \times 10^{25}$
BXINO	$> 1.27 \times 10^{26}$
BXINO 80% enriched	$> 1.14 \times 10^{27}$

elements and compare them to the predicted one. In order to do so, a good signal-to-noise ratio is necessary, together with a very well understood knowledge of the background shape under the signal. Most of the contributions to the background can be studied (and eventually subtracted) by analyzing data collected before Xenon insertion. On the other hand, the contamination which is intrinsic of Xenon is not easily disentangled from the interesting events; in particular, one of the most dangerous source of such background is ^{85}Kr which decays β with an end-point energy E=0.687 MeV (99.57% of the time) and which significantly contaminates non-enriched Xenon (see §7.3). In order to avoid the otherwise overwhelming contribution of ^{85}Kr, at least in case of non-enriched Xenon, it would be necessary to reduce the $(\beta\beta)_{2\nu}$ window to $(0.7, Q_{\beta\beta} + \sigma)$MeV at the price, of course, of cutting also a good part (42%) of the signal events.

9 Comparing background and signals: sensitivity table

The background study which has been carried out in the preceding paragraphs is needed in order to try and estimate the sensitivity of CTF05, CTF2 and BOREXINO setups to the lifetime of the neutrinoless double beta decay. **We assume a data taking period of one year**. Collecting all the information on the background contained in §8 and using the number of ^{136}Xenon atoms for each configuration as listed in table 3, one gets the limits on the $(\beta\beta)_{0\nu}$ lifetime which are collected in tables 10 and 11. In the tables, the effect of Rn-reduction induce by the Shroud in CTF2 is treated as a parameter with values 1 (no reduction), 0.1 (a factor of 10 reduction), 0.01, 0.001.

As it can be easily seen, the most annoying contribution to background in the $(\beta\beta)_{0\nu}$ energy window comes usually from the PMT radioactivity. In the ideal case of being able of completely removing the background, the best obtainable limits on the neutrinoless double beta decay lifetime can be calculated through formula (4) in §4 for the three experimental setups and in case of non-enriched and enriched Xenon. This estimate is reported in table 12.

Additional enrichment possibilities can be calculated from the above tables by simple scaling, since the $(\beta\beta)_{2\nu}$ background is never the dominant one.

10 An aside: Ba-136 production from Xe-136 DBD

For the sake of completeness, we comment on a possible radiochemical approach to DBD with Xenon-136. This approach relies on the fact that Barium-136 is produced whenever a Xe-136 DBD takes place. This method will be dominated by the two-neutrino beta decay, and, even in this case, the number of Ba-136 nuclei produced will be extremely

small.

For instance, taking the case of the enriched CTF2, one has 2.11×10^{26} Xe-136 nuclei. For a half-life of 10^{20} years, only $\sim 10^{6}$ Ba atoms will be produced in one year, corrisponding to a Ba-136 contamination of only 3×10^{-19} kg, or 5×10^{-23} gBarium/gr. Unfortunately Ba-136 is not radioactive and this concentration level is well below the sensitivity of existing analytical techniques.

11 Conclusions

It is sometimes customary to quote the sensitivity of a neutrinoless DBD experiment in terms of the effective neutrino mass alone. Formula (3), derived in the assumption that the neutrinoless double beta decay is due only to the Majorana mass term translates into:

$$< m_\nu > \ \leq \frac{(1.3 \div 3.2)}{\sqrt{T^{0\nu}_{1/2}}} \quad \text{eV} \tag{11}$$

in the case of ^{136}Xe (where $T^{0\nu}_{1/2}$ is the experimental lifetime limit expressed in units of 10^{24} years). It should be kept in mind, however, that the half-time depends in general not only on the effective mass, but also on the coupling constants of the weak hamiltonian that describe the right-handed currents, as well as on the neutrino mixing parameters (see discussion in §3 and §6 of [4]). For these reasons (and for the uncertainty in the nuclear matrix elements), the upper limit on $< m_\nu >$ has no unambiguous interpretation. It is therefore more correct to quote the sensitivity in terms of the experimentally observable half-life for the nuclide under consideration; in this view a Xe-136 study is essentially complementary to the intensively studied Ge-76 case.

The technique of high-purity liquid scintillation (CTF2/BOREXINO) can be competitive for the $T^{0\nu}_{1/2}$ of the Xe-136 DBD candidate nucleus, leading to a potentially great improvement of the present experimental limit of 3.4×10^{23} y. In particular, BOREXINO with normal Xenon can be a cost-effective route to high sensitivity DBD with Xe-136 ($T^{0\nu}_{1/2}$ limit of 3.25×10^{25} y), but the cost of an InnerInner Vessel should be added to the $\sim$ 1 million dollars cost of Xenon itself. This experimental program can be considered for BOREXINO at the end of the solar neutrino physics program.

If on the other hand CTF2/CTF05 are considered, then the enrichment must be done in order to make them competitive. In this view, also the 50% case could be interesting, as a reasonable compromise between cost and sensitivity. Needless to say, the availability of a Xe-136 sample enriched at 64% for CTF05 is a very interesting possibility.

Table 13 is a summary of the configurations which we believe are the more interesting for a Xe-136 based DBD search using the CTF/BOREXINO technology. We have

Table 13: The most interesting "Xenon" configurations.

Configuration	Enrich.	Cost	$T^{0\nu}_{1/2}$ limit (years)	Year
CTF05	64%	available	7.33×10^{23}	2002
CTF2 (ultrahigh)	50%	1.2 M$	1.54×10^{24}	2002
BXINO (2.7)	no	1.2 M$ + 2.7 m Vessel cost	3.25×10^{25}	2006

arbitrarily defined as "interesting" a configuration that simultaneously meet the following requirements:

- yields a half-life limit which is at least a factor of two greater than the present Xe-136 limit.
- has a cost which is below 2 M$.

12 Acknowledgements

We are obviously indebted to Raju S. Raghavan for the Xe-136 DBD experiment idea as well as for many helpful discussions. We also thank J. Maneira for the help in the external gamma background calculation. The solubility measurements were done by A. Falgiani, M. Balata and R. Scardaoni whose help was greatly appreciated. Finally, we thank E. Fiorini, A. Giuliani, C. Brofferio, L. Zanotti and E. Previtali for valuable discussions.

References

[1] G. Alimonti et al., to be submitted to *Astroparticle Physics*.

[2] G. Alimonti et al., *Nuclear Instr and Methods*, A **406** (1998) 411.

[3] G. Alimonti et al., *Astroparticle Physics*, **8** (1998) 141.

[4] F. Boehm and P. Vogel, *Physics of Massive Neutrinos*, (Cambridge University Press, 1987).

[5] A. Morales, *Double beta decay and neutrino masses*, Proceedings of the 6^{th} International Workshop on Neutrino telescopes, Venezia, February 22-24 1994.

[6] K. Muto et al, *Z. Phys. A*, **334** (1989) 187.

[7] T. Tomoda, *Rep. Prog. Phys.*, **54** (1991) 53.

[8] J. Suhonen et al., *Nucl. Phys. A*, **535** (1991) 509.

[9] G. Pantis et al., *Phys. Rev. C*, **53** (1996) 695.

[10] G. Pantis et al., *Phys. Rev. C*, **53** (1996) 695.

[11] E. Caurier et al., *Phys. Rev. Lett.*, **77** (1996) 1954.

[12] M. Doi et al., *Prog. Theor. Phys. Suppl.*, **83** (1985) 1.

[13] L. Baudis et al. *Phys. Lett* B **407** (1997) 219.

[14] A. Barabash, *Proc. of Neutrino 96*, ed.K. Enqvist, K. Huitu and J. Maalampi, (World Scientific, Singapore,1996) p.374.

[15] A. Alessandrello et al., *Phys. Lett.* B **433** (1998) 156.

[16] Proceedings of the DARK98 International Conference on Dark Matter, Astro and Particle Physics, Heidelberg, July 1998.

[17] J. Vuilleumier et al., *Phys. Rev.* D **48** n.3 (1993) 1009.

[18] E. Bellotti et al. *Phys. Lett* B **266** (1991) 193.

[19] R.S. Raghavan, *Phys. Rev. Lett*, **72** (1994) 1411.

[20] E. Fiorini. Private communications.

[21] BOREXINO: A Real Time Detector for Low Energy Solar Neutrinos. Ed. by G. Bellini, M. Campanella, D. Giugni and R.S. Raghavan. Milano, 1991.

[22] R.E. Treybal, *Mass Transfer Operations*, (McGraw-Hill 1987).

[23] M. Wojcik, *Nuclear Instr. & Methods B* **61** (1991) 8.

[24] L. Cadonati, C. Galbiati, M.G. Giammarchi. Memo on the effect of water on nylon (Radon diffusion). BOREXINO mail archive at http://almime.mi.infn.it.

[25] C. Galbiati. *Data taking and analysis of the Counting Test Facility of BOREXINO*. PhD. Thesis, University of Milano (1997/98).

[26] G.L. Pollack, *Physical Review A*, **23** (1981) 2660. This low solubility measurement is done using as Xe tracer the radioisotope ^{133}Xe, a gamma (81 keV) emitter with a half-life of 5.27 days.

[27] E. Bellotti et al., *Nuclear Instr. & Methods B* **62** (1992) 529.

[28] A. Falgiani, Private Communication.

[29] S. Bonetti et al., *Nuclear Instr. & Methods A* **329** (1993) 314-328.

B. Caccianiga, S. Bonetti, M.G. Giammarchi, J. Maneira, *GENEB:Generation of Neutrino and Background*, Borex Internal Report, 31 October 1997.

[30] L. Cadonati and J. Maneira, Private Communications. See also L. Cadonati *Simulation of gamma rays from PMT's in BOREXINO* and L. Cadonati *Simulation of gamma rays from the rock in BOREXINO*, both available in the internal works page of http://almime.mi.infn.it.

[31] Italian BOREXINO collaboration, *The Counting Test Facility and its results*, Status Report of the BOREXINO Project, June 6, 1996.

[32] L. Oberauer and S. Schönert, *Status Report on the BOREXINO Muon Identification System*, February 29,1997.

[33] B. Heisinger, *Doctorate Thesis*, TU-München (1998).

[34] T. Hagner, R. v. Hentig, B. Heisinger, L. Oberauer, S. Schönert, F. v. Feilitzsch, *Muon induced production of radio-instable isotopes in scintillator detectors*, to be published (1998).

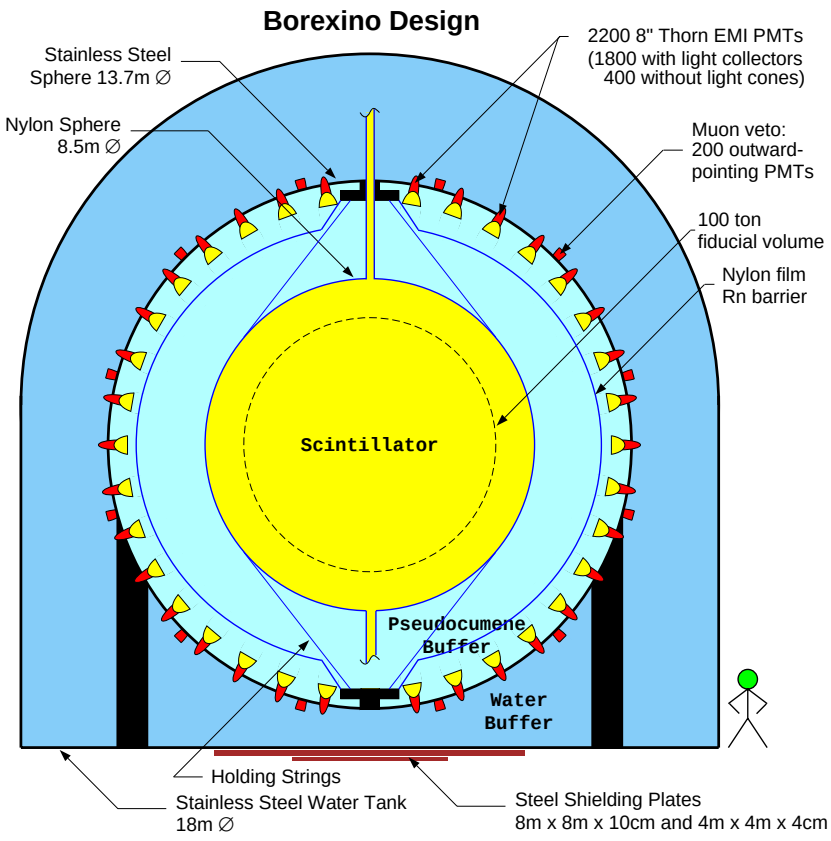

Figure 1: Schematics of the BOREXINO detector. Inside an external Water Tank (18 m diameter), a Stainless Steel Sphere (SSS) supports 2200 photomultipliers watching the internal part of the detector (plus an additional 200 PMT's viewing the water shield and acting as muon tagging). The scintillating volume is enclosed in a 8.5 m Nylon Sphere at the center (total mass of 300 tonnes) containing the 100 tonnes Fiducial Volume.

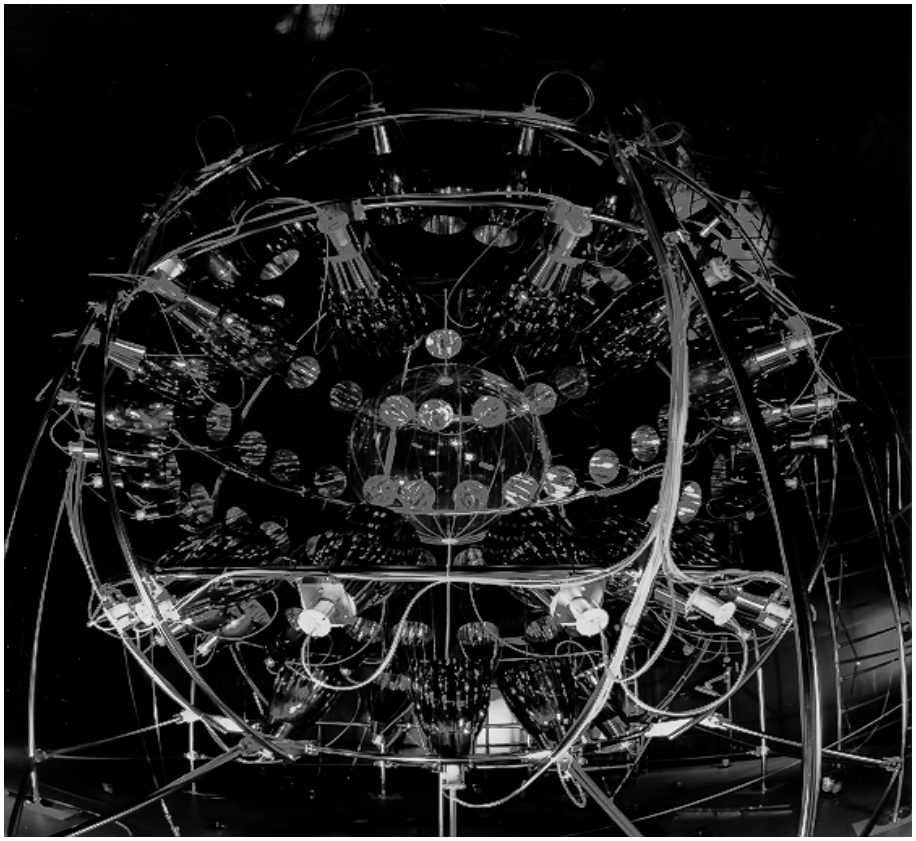

Figure 2: The Counting Test Facility experimental setup viewed from inside the CTF Water Tank (11 m diameter). The scintillator is contained in the (1 m radius) nylon balloon at the center surrounded by a steel structure which holds 100 photomultipliers.

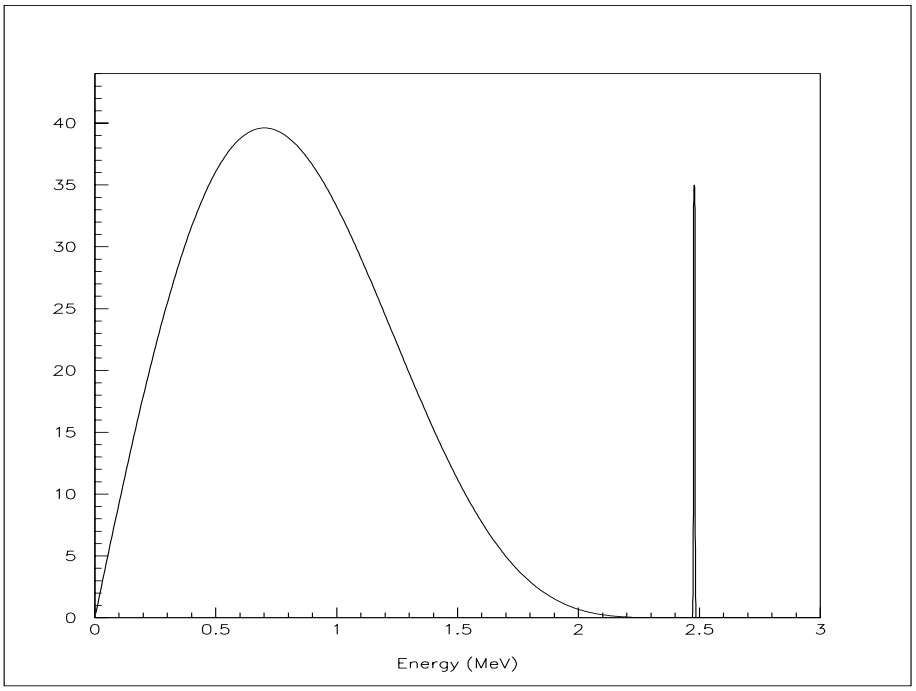

Figure 3: Double beta decay two-electron spectra for the case of Xenon-136. The vertical scale is in arbitrary units. The proportion between the neutrinoless line and $^{136}Xe \rightarrow ^{136}Ba2e2\nu$ is arbitrary as well. The $Q_{\beta\beta}$ value is 2.479 MeV.

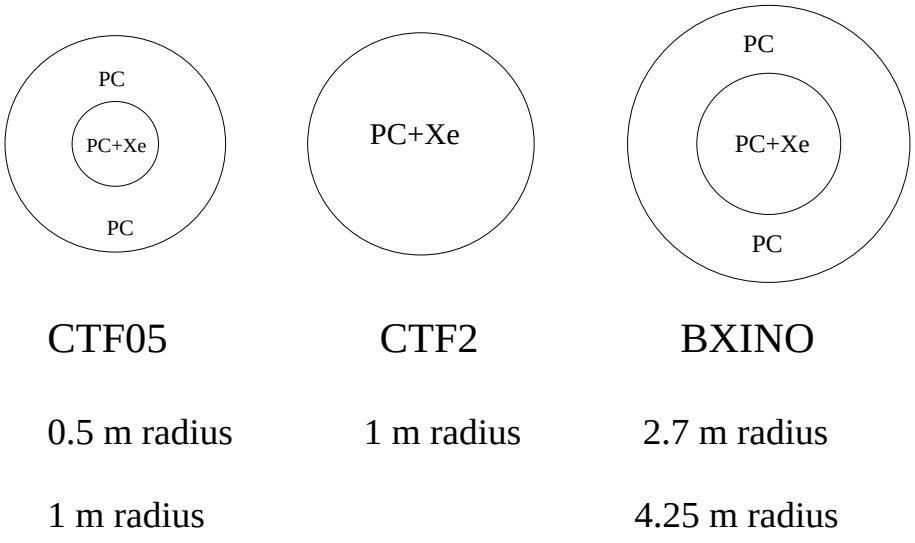

Figure 4: Geometrical features of the three considered configurations. The CTF2 configuration is the same as the CTF, with the scintillator loaded with Xenon. On the other hand, the CTF05 and BOREXINO (BXINO) configurations feature an InnerInner Vessel which contains the PC+Xe solution, while the rest of the Inner Vessel contains PC alone.

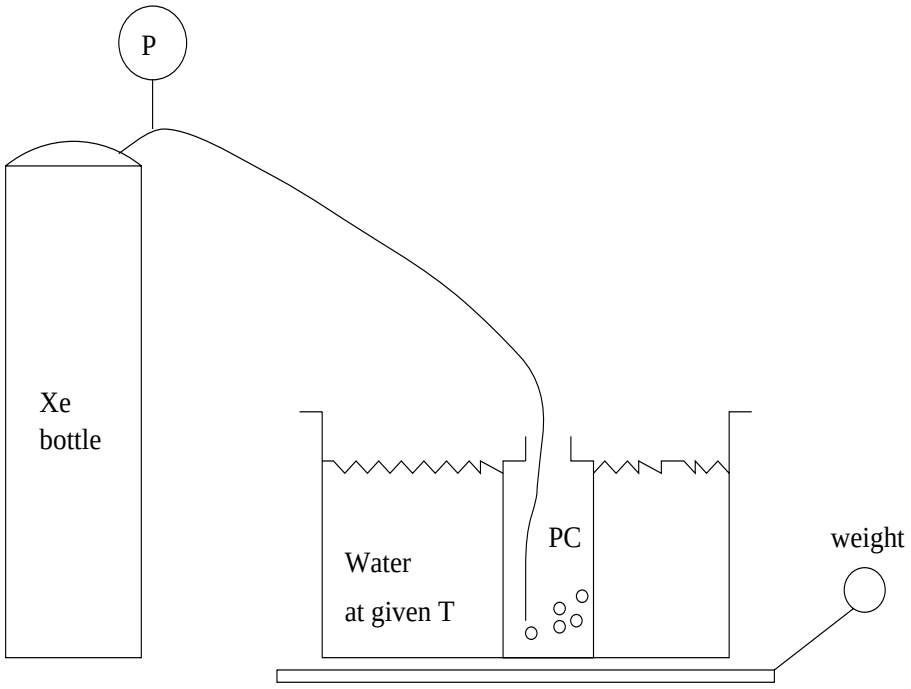

Figure 5: Dissolution of Xe in PC. The water thermostat is weighted before and during the dissolution process.