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XENON TIME PROJECTION CHAMBER FOR $\beta\beta$ DECAY

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ABSTRACT

The design of a Time Projection Chamber (TPC) filled with Xe at high pressure is described. The aim of the project is to measure the neutrino-less $\beta\beta$ decay of ^{136}Xe at the level of 10^{23} years. Guidelines for the choices operated in the project and experimental results of prototypes are presented.

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1. INTRODUCTION

Double beta decay has been investigated for almost fifty years as a very powerful tool to search for non-conservation of the lepton number. Its interest has recently been revived by the success of Grand Unified Theories and by the possibility of a finite neutrino mass [1] and of the presence of right-handed currents in weak decays [2-5]. This process involves an isotopic triplet of atomic weight A and can in principle occur in two channels

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

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

From the experimental point of view, the neutrinoless lepton not conserving mode can be discriminated against the two-neutrino one by the fact that all energy released in the process would go to the electrons. Moreover, the rate of the neutrinoless mode is expected to be roughly proportional to the fifth power of the transition energy, while the two-neutrino one would depend approximately on the tenth power. Therefore, $\beta\beta$ decay is able to reveal even a tiny violation of the lepton number and can be related to the presence of right-handed currents or to a massive Majorana neutrino.

In order to be a good candidate for searches on double beta decay, a nucleus (A, Z) has to satisfy these conditions:

- (a) single beta decay to (A, Z + 1) has to be energetically forbidden,
- (b) the transition energy has to be large (i.e. 2 ÷ 4 MeV),
- (c) its isotopic abundance has to be reasonable ($\geq 5\%$).

A large number of experiments on $\beta\beta$ decay have been carried out since 1949, and have been extensively reviewed [2-4, 6-16]. A first class of these experiments consists in the radiochemical analysis of a rock of geological age containing the isotope (A, Z) to search for an abnormal content of the nucleus (A, Z + 2). These experiments were the only ones to provide positive evidence for $\beta\beta$ decay of a few nuclei (^{82}Se , ^{130}Te and perhaps ^{128}Te), but they are obviously unable to discriminate between the neutrinoless and two-neutrino modes, at least directly. Moreover,

the possibility that the abnormal isotopic abundance of $(A, Z + 2)$ be due to events different from $\beta\beta$ decay which may have occurred during such a long geological time (10^9 years or more) has to be carefully investigated.

No evidence for any mode of $\beta\beta$ decay has been obtained so far with "direct" experiments, where the two electrons are detected and possibly measured. The only possible exception is the result by the Irvine group [11], where the two-neutrino $\beta\beta$ decay of ^{82}Se has been suggested. The rate indicated by this experiment is however an order of magnitude larger than the one obtained in geological experiments, and the effect of radioactive background has to be more carefully estimated.

In most of these "direct" experiments the $\beta\beta$ decay source has been placed, in form of plates, foils or wires, inside the detecting material (nuclear emulsion, gas of the cloud, proportional or streamer chamber etc.). Since the source has to be thin, if a good resolution in the energy of the electrons is to be achieved, the amount of beta active material cannot be very large. Moreover, if one takes into account that expected half lifetimes are of 10^{20} years or more, the background problems are impressing, even if the detector is shielded heavily against radioactivity and placed deep underground to reduce the spurious counting due to cosmic rays.

The possibility to use a $\beta\beta$ source to act at the same time as a detector has been suggested since 1960 [12], but adopted so far only in two experiments. Two CaF_2 crystals enriched in ^{48}Ca (double beta active) and ^{40}Ca (for background subtraction) have been used by the Brookhaven group [13] as scintillation detectors. Unfortunately, due to the low amount and possible contamination of the isotope, these authors could not reach a sensitivity as large as in a further experiment by the Columbia group ($2 \cdot 10^{21}$ y) [14]. A series of experiment at sea level and underground have been carried out in the last 15 years [15-17] by the Milano group using a $\text{Ge}(\text{Li})$ both as source and detector of $\beta\beta$ decay of ^{76}Ge , which is present in natural germanium in a percentage of 7.76%. The present sensitivity of the last of these experiments, which is running, is $5 \cdot 10^{22}$ years [17], the largest in all direct experiments carried out so far.

The occurrence of $\beta\beta$ decay in ^{76}Ge should be detected as a sharp peak at 2041 ± 3 KeV in the case of 0ν and as a broad enhancement at about half the above energy in the case of 2ν .

In fig. 1 a part of the energy release spectrum as measured in the ^{76}Ge experiment is shown.

Further background rejection should be achieved if, together with the energy release, other parameters (like space development of the energy release, particle charge, etc.) could be measured.

This is possible if a double beta active gaseous element, like ^{136}Xe , is used as a filling gas of a TPC eventually put into a magnetic field [18].

2. BACKGROUND AND EVENT RATE EVALUATION

^{136}Xe is a good candidate for $\beta\beta$ decay search, in fact:

- (a) $\Delta E (^{136}\text{Xe} - ^{136}\text{Cs}) = -69 \pm 8$ KeV,
- (b) $\Delta E (^{136}\text{Xe} - ^{136}\text{Ba}) = 2479 \pm 8$ KeV,
- (c) its isotopic abundance is of 8.86%.

If we assume, as plausible, that the background of spurious counts per unit mass of the detector is the same as for our present experiment on $\beta\beta$ decay in $\text{Ge}(\text{Li})$ (fig. 1), we then expect at ~ 2500 KeV, a background of

$$\sim 10^{-3} \text{ counts/KeV} \cdot \text{hour} \cdot \text{kg}(\text{Xe}).$$

Assuming an energy resolution of 75 KeV at 2500 KeV, we deduce the lifetime we can reach after one year of measurement

$$\tau_{1/2}(\beta\beta_{0\nu}) = \frac{1}{3.9} n \epsilon \sqrt{\frac{t}{R}} = 3 \cdot 10^{21} \text{ years per kilogram of xenon}$$

at 90% CL being n ($= 4 \cdot 10^{23}$) the number of $\beta\beta$ active atoms in 1 kg of xenon, ϵ ($= 0.8$) the efficiency of the apparatus for the events under observation, t ($= 1$ year) the observation period and R ($= 600$) the background rate seen during the time t .

It is evident from the above formula that one should aim at the maximum possible mass under observation.

Practical problems (uniformity of responses over large masses, insufficient knowledge of the background sources, cost, etc.) set a limit, in the case of xenon, to ~ 10 kg in a first generation experiment.

The background rate R , already minimized through standard precautions (use of low activity materials, installation in a deep underground laboratory, etc.) can be further reduced (as we will see later) using the energy deposit information obtained with very high spatial density in the TPC.

3. TIME PROJECTION CHAMBER PARAMETERS

Since we have chosen to identify the neutrinoless $\beta\beta$ decay of ^{136}Xe by the total energy release, the main parameter to be defined is the gas pressure. In fact, the events that are not fully contained in the active part of the detector are lost.

The variation of the active volume with the pressure is presented in the following table:

p (Atm)	r(sphere)cm	<u>Active</u> total volume (%)	Fiducial No. of ^{136}Xe atoms ($\times 10^{23}$)
1	72	9	3.5
5	43	54	22
10	34	69	28
20	27	79	32
30	23.5	84	34

where we considered an optimized container (i.e. a sphere of radius r) filled with 10 kg of xenon.

A pressure of at least 10 Atm and a convenient detector shape are then needed.

Very high pressures should, on the contrary, be avoided because they require very high electric fields, very small contamination of electro-negative gases, they can give recombination fluctuations and, most important, because they do not allow any background rejection based on the space and energy information provided by the TPC.

To understand this last sentence, one should recall the signal and noise characteristics.

The "true" events are made up by two electrons, emerging at wide angle. The total kinetic energy of the pair is 2479 ± 8 KeV, while the kinetic energy of each electron falls in the 0.5 - 2.0 MeV interval with 90% probability. The "background" events are mainly due to: gammas interacting via photoelectric effect (10%), compton scattering (60%), and pair production (30%).

Within the energy selection a further background rejection can then be based on:

- (a) The separation between the message left by one electron and the message left by two electrons (possible through $\Delta E/\Delta X$ if the ionization increases at the end of the range is detected).
- (b) The separation between e^+e^- and e^-e^- (possible if a magnetic field is applied).

The track of a 1.2 MeV electron generated in 10 Atm xenon is shown in fig. 2(a).

This figure is presented in the "lego-plot" format, where the binning is the TPC granularity, that we assume to be $6 \times 6 \times 6 \text{ mm}^3$ and the height of each tower is proportional to the energy deposited in each pixel of the TPC.

The increased $\Delta E/\Delta X$ on one side of the track indicates the stopping of the electron. One-bump or two-bumps ionization deposit can then be related to one-electron or two-electrons tracks. We calculated that we

can separate a one-electron event from a two-electron event in 90% of cases if $p \leq 10$ Atm, while if $p > 20$ Atm the $\Delta E/\Delta X$ method is not useful anymore (as illustrated in fig. 2(b)).

When we detect two electrons, we should be able to measure their sign. We calculated that at 10 Atm the curvature due to a 4 kG field would range from three to four times the spurious curvature due to multiple scattering, if we measure only the first 3 cm of path of each track. In the above conditions we can measure the sign of the particle in 70% of cases (since the error is dominated by multiple scattering, the requirements on TPC spatial accuracy are quite loose (~ 1 mm r.m.s.)). If $p \geq 20$ Atm the method is not applicable anymore. As a conclusion of the above discussion we can say that conflicting requirements set the operating pressure of the TPC at 10 Atm and that space accuracy is needed only at the level of 1 mm.

Energy resolutions should, on the contrary, be pushed close to the status of the art limit [19] (we assumed 75 KeV in our calculations).

With the above requirements on the TPC parameters (energy resolution, gas pressure, spatial granularity and magnetic field) the background rate R can be reduced by a factor 10, thus giving a limit (see expression A) of 10^{23} years on neutrinoless $\beta\beta$ decay for a 10 kG xenon TPC.

The design of the TPC is shown in fig. 3(a). The pressure vessel is a cylinder made of oxygen-free copper (or titanium) having length $L = 70$ cm and radius $R = 35$ cm. The TPC will look like a reduced version of the PEP4 TPC [20], obviously without any beam pipe hole. The field cage should be made with the double layer [21] technique, even if this is not a critical component since we do not measure events occurring in the outer, 4 cm thick, gas layer.

Three-dimensional view of the event should be obtained through the use of crossed cathode strips. This will limit the number of electronic channel to ~ 500 (instead of 10^4 if pads would be used) still giving

a pattern recognition power sufficient to handle signal and noise. The chamber will not have an external reference time^(*), this implies that:

- The electron recombination (due to O_2 - equivalent contamination in the gas mixture (that will be Xe + 5-10% CH_4) should be kept below 1% in the full drift length (i.e. 0.5 ppm O_2 contamination is required) to maintain the energy resolution independent from the drift path.
- The read out electronics should be of the "look-backward" type (i.e. the charge is continuously encoded and stored in a memory). As soon as the trigger-generated by some loose requirement on the TPC wires signals happens the content of the previous $n \mu s$ and of the future $n \mu s$ (n being the total drift time) is transferred to a magnetic tape.

A calibration and monitoring system should guarantee the correct behaviour of the chamber over its expected working period (~ 1 year). Among the things to be controlled, we remember: the O_2 contamination in the gas mixture (< 0.5 ppm), the temperature in the proportional region ($\Delta T < 0.3^\circ C$), the absolute gain (through internal conversion electrons of various energies) and the electronic gain (pulsing the grid).

The chamber will be operated in the Mont-Blanc underground laboratory (fig. 4).

4. PROTOTYPE RESULTS

Since we put the emphasis on energy resolution, a proportional counter has been built to begin the optimization of energy resolution and to check if the residual radioactivity in xenon (mainly due to ^{85}Kr present in commercial xenon [22]) allows the execution of the experiment.

This detector (fig. 5) is composed by a central wire ($\phi = 20 \mu m$) surrounded by a grid made of 8 wires ($\phi = 100 \mu m$) equally spaced along

(*) The possibility to use the xenon scintillation is still under investigation, but we believe that good energy resolution (through proportional multiplication) is in contradiction with big light yield.

a circle of 4 mm radius. The cathode of the counter has a 40 mm internal radius. The aim of the grid is to decouple, within certain limits, the drift and the multiplication field.

The detector can be filled up to a pressure of 10 Atm; the materials used in the construction has been chosen for their low activity. A gas purification system (fig. 6) allows to empty the detector and to recirculate the gas through "oxisorb"^(*) filters.

After several trials, a mixture of Xe + 10% CH₄ (or Ar + 10% CH₄ for comparison) has been adopted.

The amplifier scheme (shown in fig. 7) is based on the LRS TRA 1000 low noise amplifier used with a quite long (5 μ s) shaping time. The pulse height is then stored in a multichannel analyzer remotely connected to a VAX 780 computer. The detector was shielded against the soft component of the cosmic ray background using a 20 cm thick layer of low activity lead.

After setting the pressure at 6 Atm we measured the background counting rate for Ar + 10% CH₄ and Xe + 10% CH₄ and we found them comparable.

Even if we could not explore the region around 2.5 MeV, because of the limited size of the counter, we can conclude that the radioactivity does not preclude the execution of the experiment.

We then introduced an ²⁴¹Am source and we looked to the γ -spectrum (α 's were stopped in a mylar foil) using a gas gain of ~ 100 . The γ -lines and corresponding branching ratios (for branching ratios bigger than 1%) are shown in the following table:

(*) Messer-Griesheim, West Germany.

E_γ (KeV)	Br (%)
13.9	13.3
17.8	19.3
20.8	4.9
26.3	2.4

The energy distribution measured in Ar + 10% CH₄ is shown in fig. 8, while the same quantity measured in Xe + 10% CH₄ is shown in fig. 9.

The energy resolution in the two cases is almost the same. Its value can be deduced looking at the 8 KeV copper photopeak that sits on a much lower background. This peak is not present in fig. 9, because the grid potential was such to exclude ionization coming from the drift region (and the source of 8 KeV γ 's is the cathode).

Looking at fig. 10 (same as fig. 8, but on a different scale), we can fit the 8 KeV line with a gaussian having $\sigma = 1$ KeV; this resolution is dominated by the electronic noise.

5. INTERMEDIATE SOLUTION

A more detailed study of background is needed before the design of the TPC is finalized.

The most natural thing to do is to fill up the TPC vessel with a multiproportional counter (fig. 3(b)). Even with a very crude spatial resolution (assume the cell size is of 5 cm of diameter) this will allow to study the background at 2.5 MeV (both its energy distribution and from where it comes from).

Moreover, a limit on neutrinoless $\beta\beta$ decay of $\sim 10^{22}$ years can be settled using only the energy release information. This multiproportional counter can take data already in 1984 and can be operated at pressure even higher then 10 Atm.

CONCLUSIONS

A TPC project to measure the neutrinoless $\beta\beta$ decay of ^{136}Xe at the level of 10^{23} years have been described.

Further background studies require an intermediate step where a multiproportional counter is operated in the same vessel and with the same gas mixture of the final TPC. This multicell counter can, at the same time, give a first limit at 10^{22} years on neutrinoless $\beta\beta$ decay of ^{136}Xe .

We finally want to point out that the xenon TPC approach to the $\beta\beta$ decay is quite powerful because of its flexibility and of the amount of information provided.

Flexibility is important to detect background sources (changing parameters like pressure, magnetic field or eventually ^{136}Xe concentration). Space and energy deposit pattern is even more important because it can separate background from signal and, if the signal is detected, it can discriminate between ν mass induced $\beta\beta$ decay and right-handed induced $\beta\beta$ decay.

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FIGURE CAPTIONS

- Fig. 1 Counting rate versus energy deposited in 130 cc of germanium (data taken in 3700 hours).
- Fig. 2 Energy deposited by a 1.2 MeV kinetic energy electron in a TPC filled with Xe + 10% CH₄ (the three projections of the event are shown). The granularity of the TPC is assumed to be 6 x 6 x 6 mm³ and the height of each "tower" is proportional to the energy deposited in the corresponding pixel. The gas pressure is: (a) 10 Atm, (b) 20 Atm.
- Fig. 3 Sketch of the detector for $\beta\beta_{ov}$ search (see text for details): (a) the cylindrical TPC, (b) the multiproportional counter.
- Fig. 4 Sketch of the deep underground laboratory.
- Fig. 5 Proportional tube used to study the energy resolution of Xe-based gas mixtures.
- Fig. 6 The gas purification system.
- Fig. 7 The low noise preamplifier scheme.
- Fig. 8 The distribution of energy deposited by γ 's of ²⁴¹Am in the proportional tube filled with Ar + 10% CH₄ at 6 Atm.
- Fig. 9 Same as fig. 8 but with Xe + 10% CH₄ as gas mixture.
- Fig. 10 The 8 KeV γ line of copper as measured in the proportional tube filled with Ar + 10% CH₄.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Electric field lines around the anode wire of a drift tube

Fig. 5

Fig. 6

Fig. 8 ENERGY (KEV)

Fig. 7

Fig. 9 ENERGY (KEV)

Fig. 10