Possible usage of Cherenkov photons to reduce the background in a ^{136}Xe neutrinoless double-beta decay experiment

MINISTERO DELL'ISTRUZIONE, DELL'UNIVERSITÀ E DELLA RICERCA

FUTURO IN RICERCA

S. Dussoni and G. Signorelli

INFN Sezione di Pisa, Largo B. Pontecorvo 3, 56127 Pisa, Italy

INFN

SUMMARY: One of the main backgrounds in the search for ^{136}Xe nutrinoless double-beta decay (0ν$\beta\beta$) is the signal from Compton scattering of photons with energy around the decay end point at 2.458 MeV. One efficient method to exclude this background is by means of self-shielding which however results in a waste of active volume. Another proposed method is tagging the daughter barium nucleus, which relies on the capture and detection of single Ba ions to identify a Xe 0ν$\beta\beta$ decay. This is an extremely challenging task and, although feasible, presently suffers from very low efficiency.

Electrons in liquid xenon emit scintillation light at 178 nm, but liquid xenon is extremely transparent to ultra violet light. It is in principle possible to discriminate one particle events (such as the Compton background) from two particle events (double-beta decay signals) by the amount of Cherenkov radiation emitted. By identifying the Cherenkov photon content of both kind of event one can distinguish the two cases. The identification of the Cherenkov photons may be performed by looking at the different time structure of the signal with respect to the scintillation, by selecting photons with wavelengths larger than the typical Xenon scintillation light, and by the different emission topology. The efficiency of this discrimination, albeit small, can be comparable to that of barium tagging.

A proof-of-principle study of this approach is presented here together with preliminary studies on possible detectors for the two light components at different wavelengths.

Statement of the problem

Neutrinoless double beta decay (0ν$\beta\beta$) of ^{136}Xe, whose abundance in natural xenon is of ~9%, involves mainly a transition from a 0^+ state to a 0^+ state of the daughter ^{136}Ba nucleus with a Q-value of 2.479 MeV.

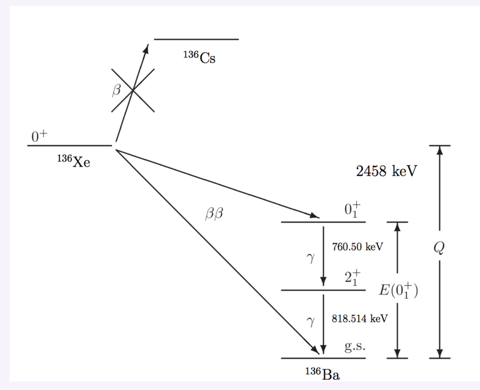
Xenon is a good candidate to observe neutrinoless double beta decay since it is at the same time an optimum detector for electromagnetic radiation, being a scintillator whose peak wavelength is 178nm.

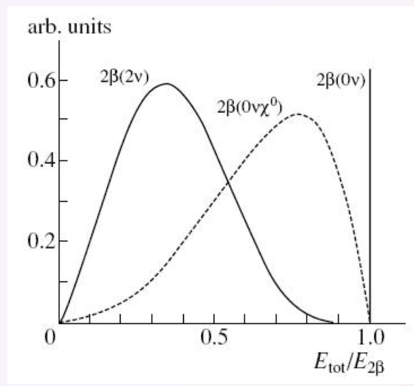
There are presently many experiments searching for 0ν$\beta\beta$ ^{136}Xe decays which make use of enriched xenon both in liquid and in gas phase [1][2] or dissolved in a liquid scintillator [6].

Its signature is a monochromatic line at an energy of 2.479 MeV which is entirely carried by the two electrons that are emitted in absence of neutrinos. The background to this process is twofold: on the one side there are events coming from the allowed double beta decay that are close to the endpoint. But the main background comes from photons entering the detector volume and releasing energy via a Xe electron which is Compton scattered, at an energy close to that of the signal. Several strategies have been proposed to reduce this background:

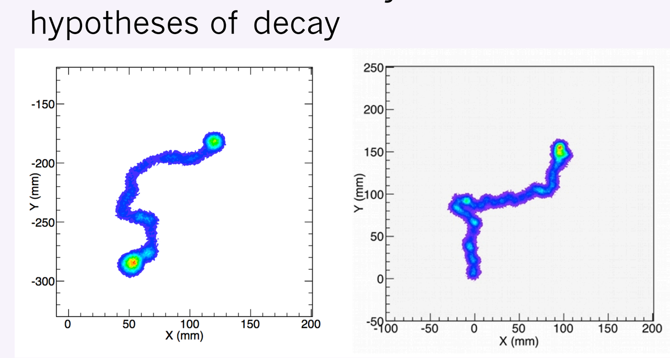
1) Self shielding by the detector itself, reducing the active volume, since photons come mainly from outside the detector volume;
2) Tagging the Compton electron by using the fact that usually a photon releases energy in several sites, i.e. distinguishing a multi-site event (likely to be induced by radioactive backgrounds) from a single-site event (signal-like) [1];
3) Tagging the electron pair. This can be done in gas xenon [2] by reconstructing the tracks of the two electrons with enhanced energy release at their endpoint, as opposed to a single ionizing electron;
4) Tagging the single barium atoms coming from the xenon neutrinoless double beta decay [3][4]. This would give the unambiguous signal of the occurrence of such a rare process, unfortunately the efficiency of such a detection is expected to be at the few percent level.

If we restrict to the case of liquid xenon we investigated the possibility to distinguish the one electron from the two electron topology by making use of their different pattern of emitted Cherenkov radiation. We do not expect to reach a high level of discrimination, nevertheless our benchmark is the percent-level efficiency of Ba ion tagging.



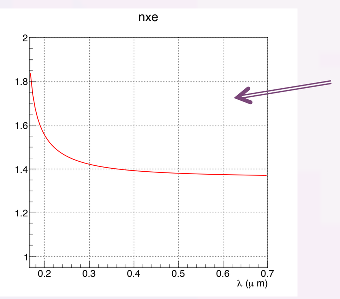


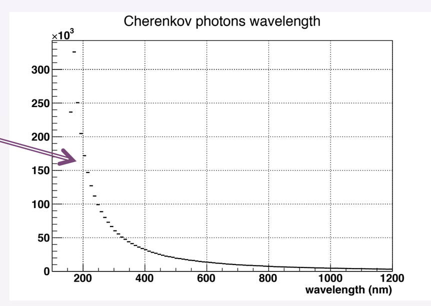
^{136}Xe double beta decay scheme and energy released undre three hypotheses of decay



Different topology of 2 electrons vs 1 electron energy release in gas xenon [2]

Liquid Xenon Properties	
Atomic Number Z	54
Density	3 g/cm^3
Boiling point	165 K
Light yield	40 000 phe/MeV
Radiation length X_0	2.87 cm
Scintillation times	4, 22, 45 ns





Liquid xenon refractive index and number of emitted Cherenkov photons as a function of the wavelength

Cherenkov emission in liquid Xenon

Liquid Xenon scintillates at 178 nm with a FWHM of 14 nm, with a light yield of roughly 40 000 photons/MeV and time constants of 4, 22 and 45 ns. Cherenkov photons are instead emitted at various wavelengths in different proportion depending on liquid xenon refractive index, with a much lower yield but with a very short time scale (1-2 ns).

Scintillation light is negligible above 200 nm, where the greatest part of Cherenkov photons are emitted (see pictures on the left). We can think of detecting the two different components by using devices (e.g. silicon photo-multipliers) which are blind respectively above and below 200 nm.

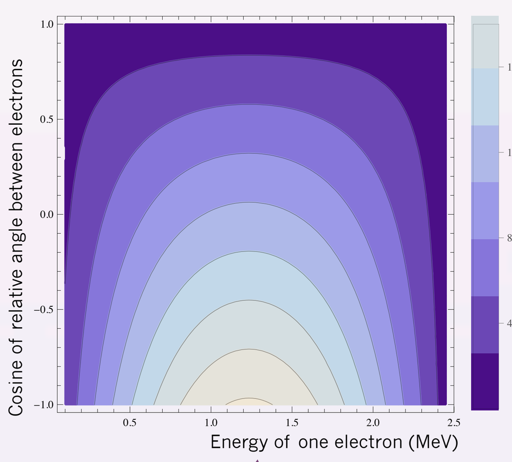
Two electrons from double beta: some lucky coincidences

The two electrons from the ^{136}Xe neutrinoless double beta decay have two nice features: their phase space is maximum at an energy of Q/2 and for a back-to-back emission [5]. They represent a bonus to distinguish one from two electrons based on (1) the amount of the emitted light and (2) the light emission topology.

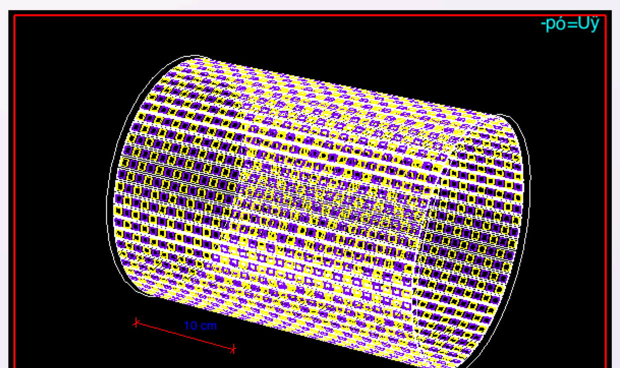
1) Cherenkov emission is a threshold process, therefore for the same total energy Q one single electron emits more Cherenkov photons than an electron pair. The difference is larger when the two electrons have an almost equal energy $Q/2$. This is exactly the experimental situation.
2) Even at this low energy, Cherenkov light retains some information on the initial direction of the emitting particle. For one single electron the light distribution is more asymmetric, while for two electrons it is more symmetric. The symmetry is larger when the two electrons are emitted back-to-back. This is exactly the experimental situation.

We used Geant4 to simulate scintillation and Cherenkov light emission from single electrons and pairs of electrons coming from a ^{136}Xe 0ν$\beta\beta$, following the correct energy-angle distribution. We simulated events in a Xe cylindrical volume of radius 7.5 cm and heigth 20 cm, covered by alternating 1 cm^2 sensors sensitive respectively to the scintillation component only or to the Cherenkov component only.

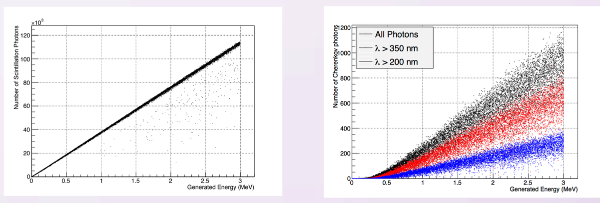
We show some sample events of single and double electrons from which the topological difference is apparent. We show also their difference in emitted light (ratio of Cherenkov vs scintillation) from which we see that two electrons emit on average 20% less Cherenkov photons, while emitting the same scintillation light.



The energy-angle distribution of the 0ν$\beta\beta$ pair peaks at Q/2 and 180°

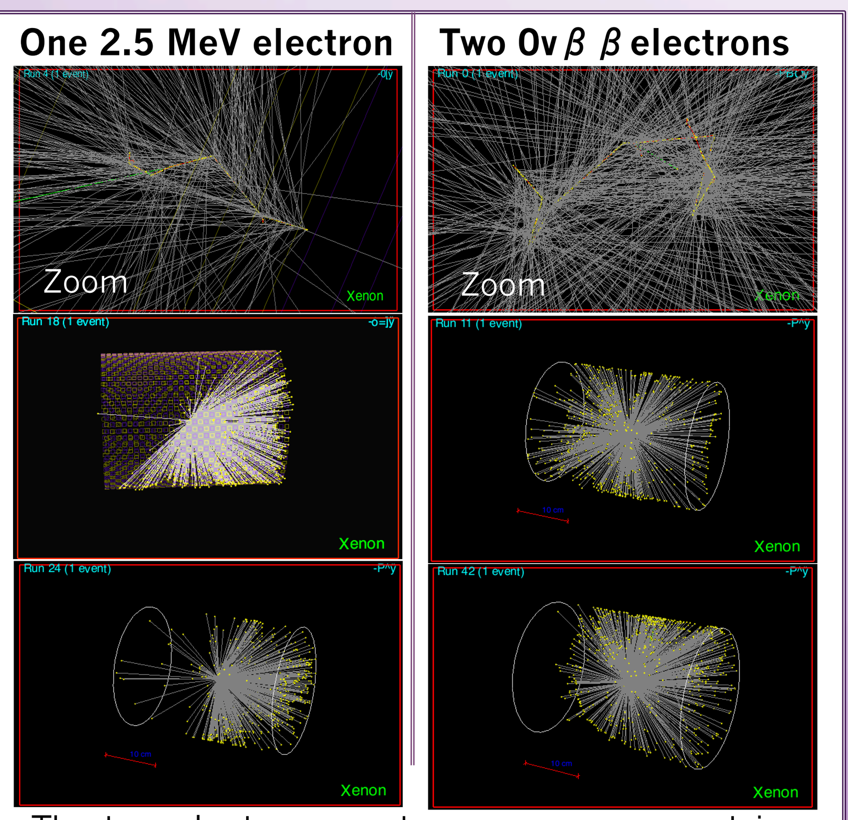


Simulated cylindrical xenon detector



Scintillation yield and Cherenkov yield with different detector wavelength threshold. Cherenkov light is much less but can be enhanced by integrating only prompt photons

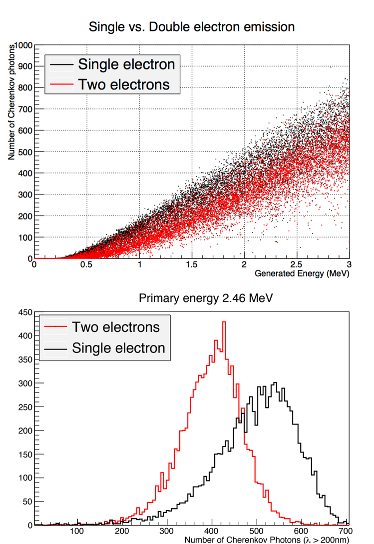
One 2.5 MeV electron | Two 0ν$\beta\beta$ electrons

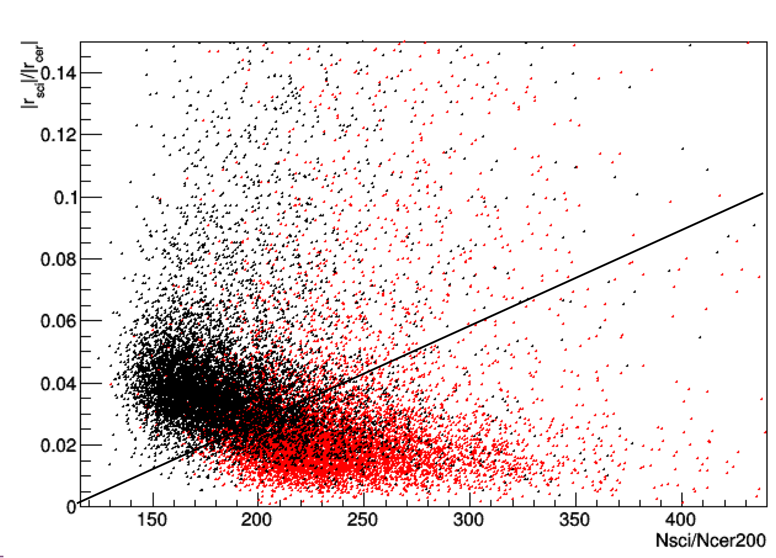


The two electron events are more symmetric

Cherenkov vs scintillation yield and topology

The plots below show the difference in Cherenkov light yield above 200 nm for one and two electrons cases. In the 2D plot a simple topological variable (the ratio of the centroid of Cherenkov vs scintillation light) is plotted against the ratio of scintillation/Cherenkov emitted photons. It is clear that a cut in this plane is effective in distinguishing the signal from the background.



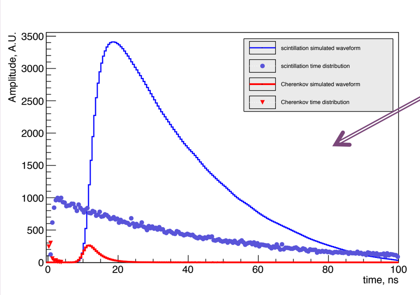


The background from a single site Compton electron has both more Cherenkov light and a less symmetric shape.

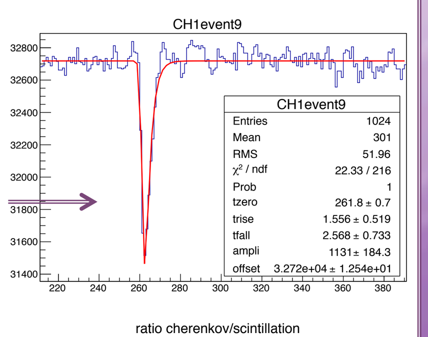
The cut in figure, for instance, retains 75% of the signal events by rejecting 90% of the background

Using the time structure of the signals

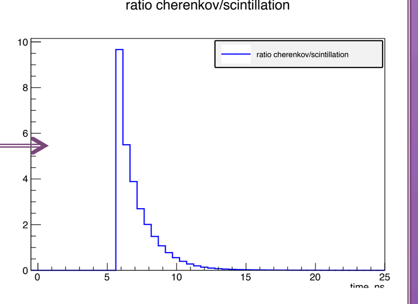
The time structure of the two signals (Cherenkov and scintillation) could also be exploited to improve the sensitivity, e.g. integrating only the initial few ns of the waveforms.



Simulation of Cherenkov (red) and scintillation (blue) light time structure before and after being detected by a SiPM with this single photon experimental response in liquid xenon



By integrating only the initial few ns of the waveform the signal from Cherenkov light is enhanced. The 1:1 ratio is reached at approximately 8 ns



Conclusion and Discussion

We showed that in principle the detection of Cherenkov light in liquid Xe detectors for ^{136}Xe 0ν$\beta\beta$ decay search could help in distinguishing the signal from Compton electrons background in the signal region.

We did not include light detection efficiency but there are presently under development VUV sensitive silicon photomultipliers with high photo-detection efficiency that could perfectly suit this application.

References:

[1] EXO-200 collaboration, *Phys.Rev.* **C89** (2014) 1, 015502
[2] NEXT-100 J. A. Hernando, *Phys. Procedia* **61** (2015) 251-253
[3] M.Danilov et al., *Phys. Lett. B* **480** (2000) 12–18
[4] EXO collaboration, *Phys. Procedia* **61** (2015) 278-282
[5] O. Ponkratenko *et al.*, *Phys.Atom.Nucl.***63**:1282-1287,2000
[6] A. Gando *et al.*, (KamLAND-Zen Coll.), Phys. Rev. C **85**, 045504 (2012).

FDFP FRONTIER DETECTORS FOR FRONTIER PHYSICS La Biodola, Isola d'Elba, Italy, May 24–30 2015

Contacts: Giovanni.Signorelli@pi.infn.it