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

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SUMMARY: One of the main backgrounds in the search for $^{136}\text{Xe}$ neutrinoless double-beta decay ($0\nu\beta\beta$) 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 $0\nu\beta\beta$ 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 composition of emitted Cherenkov radiation, 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 components at different wavelengths.

Statement of the problem

Neutrinoless double beta decay ($0\nu\beta\beta$) of $^{136}\text{Xe}$, whose abundance in natural xenon is of $\sim 9\%$, involves mainly a transition from a $0^-\text{I}$ state to a $0^-\text{II}$ state of the daughter $^{136}\text{Ba}$ 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 178 nm.

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

It is clear that a cut in this plane is effective in distinguishing the signal from the background in a double-beta decay experiment and energy released in gas xenon [2].

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 daughter 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.

Two electrons from double beta: some lucky coincidences

The two electrons from the $^{136}\text{Xe}$ neutrinoless double beta decay have two nice features: their phase space is maximum at an energy of $Q/2$ and for a certain amount of released energy the 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 $^{136}\text{Xe}$ $0\nu\beta\beta$, following the correct energy-angle distribution. We simulated events in a Xe cylindrical volume of radius 7.5 cm and height 20 cm, covered by alternating 1 cm$^2$ PMTs respectively to the scintillation component only or to the Cherenkov component only.

We show some events in which two single electrons and from which the topological pattern is apparent. We show also their difference in energy emitted (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.

Conclusion and Discussion

We showed in principle the detection of Cherenkov light in liquid Xe detectors for $^{136}\text{Xe}$ $0\nu\beta\beta$ 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 detection efficiency that could perfectly suit this application.

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 higher energy release (typically tens of MeV)

The plots below show the difference in Cherenkov light yield above 200 nm for one and two electron pairs. In the 2D plot a simple topological variable (the ratio of the centroid of Cherenkov radiation to 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.

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.

Cherenkov light is much kls but can be enhanced by integrating only prompt photons

References: