A flexible scintillation light apparatus for rare events searches

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Abstract. FLARES (a Flexible scintillation Light Apparatus for Rare Event Searches) is a project for an innovative detector technology to be applied to rare event searches, and in particular to neutrinoless double beta decay experiments. Its novelty is the enhancement and optimization of the collection of the scintillation light emitted by ultra-pure crystals through the use of arrays of high performance silicon photodetectors cooled to 120 K. This would provide scintillation detectors with $\sim 1\%$ level energy resolution, with the advantages of a technology offering relatively simple low cost mass scalability and powerful background reduction handles, as requested by future neutrinoless double beta decay experimental programs.

1. Introduction

In the Standard Model of particle physics the double beta decay, a very rare nuclear process in which a nucleus (A, Z) decays into its (A, Z+2) isobar, is allowed with the contemporary emission of 2 electrons and 2 anti-neutrinos (2νDBD). It has been observed experimentally in a dozen of isotopes with half-lives of the order 10^{18}-10^{21} years. Far more interesting is the neutrinoless double beta decay (0νDBD). The existence of the 0νDBD, a lepton number violating process, would indeed imply that neutrinos are massive Majorana fermions and could put important constraints on the absolute neutrino mass scale [1]. It is therefore evident why considerable interest has been devoted since several years to the study of this process and different experimental approaches have been screened to evaluate the best approach able to maximize the experimental sensitivity.

The 0νDBD can proceed via different mechanisms, the simplest one being the virtual exchange of a light Majorana neutrino between the two nucleons. In this case, the decay half life of the isotope ($T_{1/2}^{0\nu}$) is inversely proportional to the square of the so called effective Majorana mass $m_{\beta\beta}$:

$$\frac{1}{T^{0\nu}_{1/2}} = \frac{|m_{\beta\beta}|^2}{m_e^2} G^{0\nu} |M^{0\nu}|^2 \tag{1}$$

where m_e is the electron mass, $G^{0\nu}$ is the phase-space factor, and $M^{0\nu}$ is the 0νDBD nuclear matrix element.

Among the isotopes candidate to the 0νDBD, some isotopes are particularly interesting for the high Q-value of the transition and for their natural isotopic abundance (table 1). The high Q-value allows to have a favorable phase space factor and it is essential to get the searched peak in an energy region with a low radioactive background. Indeed, if the 0νDBD transition energy exceeds the 2615 keV γ-line of ^{208}Tl, the environmental background due to natural γs will decrease abruptly. Above this energy there are only extremely rare high-energy γs from ^{214}Bi. The other contributions to the background (α, μ, n) can instead be reduced with adequate actions as discussed in section 3.

Isotope	$Q_{\beta\beta}$ [MeV]	Isot. abund.
^{116}Cd	2.80	7.5 %
^{82}Se	3.00	8.7 %
^{100}Mo	3.03	9.6 %
^{150}Nd	3.37	5.6 %
^{48}Ca	4.27	0.19 %

Table 1. Principal double beta decay isotopes with endpoint energies above the ^{208}Tl line. Their natural isotopic abundance is also reported.

2. Experimental sensitivity

Despite the experimental signature of the 0νDBD is a well defined peak at the Q-value of the transition, the rarity of the process makes its observation very difficult. If no peak is detected, the sensitivity S is usually expressed as the process half-life corresponding to the minimum signal n that could be observed (over the background fluctuations) at a given statistical Confidence Level (C.L.):

$$S = \ln 2 \, N^{eff}_{\beta\beta} \frac{T}{n} \tag{2}$$

where $N^{eff}_{\beta\beta}$ is the effective number of nuclei under study ($N^{eff}_{\beta\beta} = N_{\beta\beta} \cdot \delta$, δ is the detection efficiency) and T is the live time.

This sensitivity formula can be applied to experiments with no spurious events in the region of interest and to experiments with background. The division between these two regimes depends on the number of background events (B [counts/keV/kg/y]) in an energy region as wide as the energy resolution (Δ [keV]) for the measurement live time (T [y]) in the whole detector mass (M [kg]). However, while equation 2 could be used in experiments in the zero background regime ($M \cdot T \cdot B \cdot \Delta \approx 0$) once chosen the C.L., for experiments with background ($M \cdot T \cdot B \cdot \Delta >> 0$) the minimum signal that can be observed depends on background fluctuations. Assuming that the number of background events is directly proportional to the detector volume (and hence to its mass) then $n = \sqrt{M \cdot T \cdot B \cdot \Delta}$ (68% C.L.) which means

$$S = \ln 2 \, N^{eff}_{\beta\beta} \sqrt{T} \sqrt{\frac{1}{M \cdot B \cdot \Delta}} \tag{3}$$

It is clear that the zero background regime is very appealing since in this case the sensitivity increase linearly with the live time and the detector mass. To work in this regime is therefore necessary to greatly reduce the background and the energy resolution to keep $M \cdot T \cdot B \cdot \Delta \approx 0$ with increasing the mass to achieve high sensitivity.

Although the energy resolution and the background are equally relevant in the determination of the detector regime, the energy resolution is of particular importance in experiments studying the 0νDBD. In fact, experiments with low energy resolution are sensitivity limited due to events of the 2νDBD tail that fall in the region of interest for the 0νDBD.

Among all the parameters, the $N_{\beta\beta}^{eff}$ is the most important since it determines the maximum sensitivity achievable. If there are not enough isotopes candidates to the 0νDBD, a high sensitivity is not reachable even if we are able to carry out experiments with excellent energy resolution and very low background.

It is therefore evident that for high sensitivity a high number of isotopes under study, a good energy resolution and low background are needed. In this context, scintillating crystals could play a primary role because:

- being solid-state detectors, scintillating crystals allow easily to maximize the detection efficiency and mass;
- scintillating crystals allow to search for 0νDBD of isotopes with high natural isotopic abundance and/or to maximize the isotopic abundance through enrichment;
- the choice of the absorber material allows to select compounds with low molecular mass and high stoichiometric multiplicity of the element containing the 0νDBD candidate;
- inorganic scintillating crystals can be grown with high level of intrinsic radiopurity to avoid background due to internal β decays;
- the background can be minimized with a proper choice of the isotope and by employing active rejection techniques as described in the next section.

Despite all those features, this approach has not exploited its full potential so far, the main reason being the relatively poor energy resolution achievable with scintillating crystals optically coupled to photomultiplier tubes. With FLARES we aim to overcome this limitation by using sensors with high quantum efficiency and increasing the crystals light yield working at low temperature.

3. The proposed technique
FLARES proposes to enhance and optimize the collection of the scintillation light emitted by ultra-pure crystals through the use of arrays of high performance silicon photodetectors cooled to 120 K.

Inorganic scintillating crystals
Many inorganic scintillating crystals exist containing different 0νDBD candidate nuclei, thus allowing a high flexibility in the choice of the source isotope. Moreover scintillators offer powerful tools for background minimization thanks to intrinsic α/β discrimination ability on the pulse shape and quenching factors for α particles (Q.F.$_\alpha$) as small as 0.2. The alpha decays belonging to the natural decay chains have Q-values in the range $\sim$5-10 MeV and therefore this quenching factor practically removes all alpha background in the 0νDBD region of interest at $\sim$3 MeV.

The use of inorganic crystals also allows to assemble large arrays of detectors with quite simple technological skills and in rather low-cost experimental setups. The use of an array of crystals allows to fully exploit the coincidence technique to further reduce the background. The 0νDBD has in fact a probability >80% to release all the energy within a single detector for crystals of hundreds of grams. Thus requiring the anti-coincidence between crystals is possible to reduce

backgrounds with higher multiplicity such as γs through Compton scattering and especially muons. To make negligible this last contribution, rare events experiments are moreover installed underground at great depths.

In many cases, the light yield and the scintillation decay time increase as the operating temperature is lowered [2]. The increase of the light yield allows to reduce the relative statistical fluctuation of the number of scintillation photons and thus to improve the energy resolution. The increase in the scintillation decay time allows instead to further increase the intrinsic α/β discrimination ability and therefore the background minimization.

In table 2 the main physical properties of $CaMoO_4$ and $CdWO_4$ scintillating crystals containing interesting 0νDBD candidate nuclei (^{100}Mo and ^{116}Cd) are listed. They are potentially good candidates for high resolution detectors because they have well known scintillation properties and offer promising light yields especially at low temperatures.

In fact, assuming to have a $CaMoO_4$ crystal at an operating temperature of 120 K, the ultimate limit for the relative FWHM energy resolution at 3 MeV can be estimated as $R_{stat}(\text{FWHM}) = \frac{2.355}{\sqrt{N_{ph} \cdot \alpha_{ph}}} = 1.03\%$ where $N_{ph} = 75000$ is the number of photons generated and $\alpha_{ph} = 70\%$ is the collection efficiency obtained by means of a dedicated Monte Carlo simulation based on the GEANT4 toolkit [4]. This evaluation is based on the hypothesis to have a device with 100% quantum efficiency and no noise. For sure it is an ideal situation but silicon drift detectors are sensors very close to these requirements.

Property	CaMoO$_4$		CdWO$_4$	
	300 K	120 K	300 K	120 K
Density [g/cm^3]	~4.3		7.9	
Emission maximum [nm]	520	~530	480	480
Light yield [ph/MeV]	~8900	~25000	~18500	~33500
Scintillation decay time [μs]	~18	~190	13	~22
Q.F.$_\alpha$ at ~5 MeV	~0.2		~0.18	
Absorption length [cm]	~60		~60	

Table 2. Properties of $CaMoO_4$ and $CdWO_4$ scintillating crystals ([4] and references therein).

Silicon Drift Detectors
Silicon drift detectors (SDDs) are solid state devices very appealing since they are characterized by quantum efficiencies ϵ_Q larger than 80% in a wide range of wavelengths [3]. As demonstrated in [4], an SDD of 1 cm^2 operated at a temperature of about 120 K and coupled to a JFET closely placed are a viable solution for reading out the light emitted by a scintillating crystal with high resolution. The expected total noise ENC associated to such an electronic chain with a shaping time of about 50 μs is ENC=3.1 e$^-$rms [5].

Expected detector performance
A prototype detector module of the FLARES experiment can be conceived as made of a $CaMoO_4$/$CdWO_4$ crystal of 500/1000 g, with two surfaces optically coupled to two arrays of N_{SDD}=20 SDDs of 1 cm^2 of area each. The attainable FWHM resolution at an energy of 3 MeV of such a device operated at 120 K can be evaluated, for example for a $CaMoO_4$ crystal, as:

$$R(FWHM) = \sqrt{R_{stat}^2 + R_{noise}^2} \cong 2.355 \sqrt{\frac{1}{\alpha_{ph} N_{ph} \epsilon_Q} + \frac{N_{SDD} ENC^2}{\alpha_{ph}^2 N_{ph}^2 \epsilon_Q^2}} = 1.15\% \qquad (4)$$

The intrinsic resolution of the scintillator was not included in this expression. It is related to several effects, like inhomogeneities due to the local variation of the light output in the scintillating crystal, variations of the reflectivity of the diffuse reflector surrounding the scintillator, as well as non-proportionalities of the scintillator response [6]. At the energies of interest for 0νDBD searches (~ 3 MeV) all these contributions can be indeed completely neglected.

4. Preliminary results

The FLARES project started at the beginning of 2015 to build a prototype scintillating detector. We are currently working on:

- Selection of a producer of high quality $CaMoO_4$ and $CdWO_4$ crystals
- Study of radioactive background within the chosen crystals
- Low temperature measurements to optimize light collection efficiency
- Test some SDDs produced at FBK in Trento for the ReDSoX project (not optimized for FLARES)
- Study of non-proportionalities of the scintillator response

Out of the different SDD geometries kindly provided by the ReDSox collaboration, the FLARES collaboration has measured two types: a square SDD of 25 mm^2 of area and an array of seven hexagonal SDDs of total area of 200 mm^2. The best results were obtained with the seven hexagonal cell array in a climatic chamber at an operating temperature of ~ 253 K. A ^{55}Fe source was directly irradiating one of the seven hexagonal SDDs. The obtained FWHM resolution on the Mn line at 5.9 keV was ~ 170 eV with a shaping time of 1 μs. The single hexagonal cell has been also optically coupled with grease to a very small CsI(Tl) cylindrical scintillator (3mm of diameter and 10mm of height). By irradiating this detector with a ^{137}Cs source, the obtained relative FWHM resolution was R$\sim 3.80\%$ at 662 keV. By scaling this result at 3 MeV energy, the 1% goal seems already to be achievable with this not optimized SDD. Further measurements are presently ongoing at low temperature (~ 100 K) and new SDDs with thin entrance window will be produced soon in order to improve the quantum efficiency at the λs of interest for FLARES (~ 500 nm).

5. Conclusion

The FLARES detector concept contains in a single device all the demanding features of an ideal 0νDBD experiment. Adequate radiopure scintillating crystals coupled to low noise SDD photodetectors result in a detector module offering high energy resolution, low cost mass scalability, isotope choice flexibility, and competitive background reduction tools. The proposed concept is therefore ideal for a high sensitivity 0νDBD experiment, since it allows the measurement of very large detector arrays in quite simple experimental setups.

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