Abstract

We present the results obtained in the development of scintillating Double Beta Decay bolometers. Several Mo and Cd based crystals were tested with the bolometric technique. The scintillation light was measured through a second independent bolometer. A 140 g CdWO$_4$ crystal was run in a 417 h live time measurement. Thanks to the scintillation light, the $\alpha$ background is easily discriminated resulting in zero counts above the 2615 keV $\gamma$ line of $^{208}$Tl. These results, combined with an extremely easy light detector operation, represent the first tangible proof demonstrating the feasibility of this kind of technique.

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I. INTRODUCTION

The evidence of a neutrino rest mass represents one of the most exciting discoveries in the field of particle physics. The discovery of the neutrinoless Double Beta Decay (0ν-DBD), however, will provide not only the ultimate answer about the nature (Dirac or Majorana) of the neutrino, but will also allow to increase the sensitivity on the neutrino mass down to a few meV. As pointed out very recently by the Members of the APS Multidivisional Neutrino Study [1], Double Beta Decay searches will play a central role in the neutrino physics of the next decade. The use of the bolometric technique offers the unique possibility to investigate different DBD nuclei with a considerably higher energy resolution, as needed for future experiments. In the case of a scintillating bolometer, the double independent read-out (heat and scintillation) will allow, thanks to the different scintillation Quenching Factor (QF) between $\alpha$ and $\gamma$, the suppression of the background events due to degraded $\alpha$-particles, the main source of background for bolometric 0ν-DBD experiments [2].

II. ENVIRONMENTAL BACKGROUND

The experimental signature of the 0ν-DBD is in principle very clear: a peak (at the $Q_{\beta\beta}$ value) in the two-electron summed energy spectrum. In spite of this characteristic imprint, the rarity of the process makes the identification very difficult. Such signals have to be disentangled from a background due to natural radioactive decay chains, cosmogenic-induced activity, and man-made radioactivity, which deposit energy in the same region as the DBD, but at a faster rate. Consequently, the main task in 0ν-DBD searches is the natural background suppression using the state-of-the-art ultra-low background techniques and, hopefully, identifying the signal. There are different sources of background for DBD experiments that can be classified in four main categories.

A. External $\gamma$ background

Environmental $\gamma$’s represent the main source of background for most of the present DBD experiments and arise mainly from the natural contaminations in $^{238}$U and $^{232}$Th. The common highest $\gamma$ line is the 2615 keV line of $^{208}$Tl, with a total branching ratio (BR) of 36 % in the $^{232}$Th decay chain. Above this energy there are only extremely rare high energy
\[ Q_{\beta\beta} \] values for various nuclei are shown in Fig. 1. \[ Q_{\beta\beta} \] values above the 2615 keV line of \(^{208}\)Tl represent the optimal starting point for a future experiment. The most interesting DBD nuclei are shown in Fig. 1.

B. Neutrons

Another important source of background is due to neutrons: low energy neutrons can induce \((n,\gamma)\) reactions in materials close (or internal) to the detectors with \(\gamma\) energies up to 10 MeV; furthermore, high energy neutrons generated by \(\mu\)-induced spallation reactions can release several MeV by direct interaction in the detectors. This contribution represents only 1% – 10% of the total background for the present DBD experiments. Unlike \(^{238}\)U and \(^{232}\)Th trace contaminations, neutrons can be, at least in principle, suppressed with suitable use of shielding/veto’s.

C. Surface contaminations

This source of background plays a role for almost all detectors, but is crucial for fully active detectors, as in the case of bolometers.
FIG. 2: Background spectrum of the CUORICINO experiment. The α-continuum extends up to the 0ν-DBD region, at 2528 keV.

α’s arising from surface contaminations located in dead layers faced to (or on) the detectors can lose part of their energy in a few microns and reach the detectors with an energy corresponding to the $Q_{\beta\beta}$ value. It is not straightforward to deal with this problem due to the fact that, unlike bulk contamination (that can be measured through HPGE detectors), the sensitivity of standard diagnostic devices can hardly reach the needed sensitivity [3]. These contaminations arise from the machining, cleaning, or passivation of the materials to be used close to the detectors, as well from Radon implantation. This α-continuum represents the main source of background for the CUORICINO DBD experiment [4], as can be deduced from Fig. 2.

D. $^{238}\text{U}$ and $^{232}\text{Th}$ internal contaminations

This source of background has to be considered very carefully for non-homogeneous (or passive) detectors, but under certain assumptions does not play a significant role for homogeneous detectors. In the case of homogeneous detectors, in fact, dangerous $\beta - \gamma$ events can be recognized through delayed α coincidences. If we discard the contribution of $^{234}\text{Pa}$ of the $^{238}\text{U}$ chain, that has $\beta - \gamma$ events with $Q_{\text{tot}}=2195$ keV, all the remaining high energy decays are shown in Fig. 3. As can be argued by the scheme, the $\beta - \gamma$ decays are preceded...
(or followed) by an α emission. Therefore, using delayed α coincidences, β − γ decays, that can mimic the 2 electron signal, are discarded. This technique can be easily applied for the 238U decay chain, while may have some problems (large death time) with the 208Tl decay. In this case the decay is preceded by the α of 212Bi with a mean time given by $T_{1/2}=3.05$ m, and it is therefore clear that this method holds only if the contaminations are not too large.

**E. Cosmogenic activity**

This source of background can affect both the detector itself and the surrounding shielding materials. Regarding the detectors, the production of long-lived radioactive nuclei depends crucially on the target material. Probably the best known cosmogenic isotope is the $^{60}$Co. This nucleus is extremely dangerous both for internal (detector) and for external (shielding) contaminations. $^{60}$Co is, unfortunately, a common contaminant of Copper, which represents the cleanest solid material available so far, often used for internal radioactive shielding by several DBD experiments. With respect to internal contamination, the background spectrum is due to the $\beta$ ($Q=318$ keV) + $2\gamma$ ($1173+1332$ keV), so that the released energy can reach the total Q-value (2824 keV). Regarding external contaminations, the background is mostly due only to the $2\gamma$'s (emitted in coincidence), with total energy of 2505 keV. Therefore a future experiment based on a nucleus with $Q_{\beta\beta} > 2505$ (and possibly also $>2824$ keV) will...
avoid this problem.

III. BOLOMETRIC LIGHT DETECTORS

The first idea of using a scintillating bolometer was suggested for solar neutrino experiments in 1989 [5]. The first light/heat measurement with α background discrimination for DBD searches was performed with a thermal bolometer and silicon photodiode by our group in 1992 [6], but was no more pursued due to the difficulties of running such a light detector at low temperatures \((\simeq 10 \text{ mK})\). The idea to use a bolometer as light detector was first developed by C. Bobin et al. [7] and then later optimized [8, 9], for Dark Matter searches. Starting from that work we developed a thermal light detector (LD) to be used for DBD search.

A bolometer is, in principle, a very simple device. It is composed of an absorber coupled with a thermometer, so that an energy release in the absorber can be detected. The temperature rise in a thermal bolometer is given by \(\Delta T \propto E/C\), where \(E\) represents the energy released into the detector and \(C\) its heat capacity. This means that a very small detector can reach a very high sensitivity (few tenths of eV); therefore a “dark” thin bolometer can absorb scintillation photons and give a measurable thermal signal. In our case, the bolometer serves primarily as a light detector and has the characteristic time constant of bolometers (20–500 ms). However it is also sensitive to every energy release (α′s, β′s, γ′s) and acts as a particle detector. Certainly large-surface bolometric LD’s cannot easily reach the threshold of PMT’s (\(\sim 1\) photoelectron i.e. 3–7 photons, tacking into account the quantum efficiency conversion), but they have two important advantages: (i) they are sensitive over an extremely large band of photon wavelength (depending on the absorber); (ii) the overall quantum efficiency can be as good as that of photodiodes. This means that the energy resolution on the scintillating light, which depends (above threshold) only on the Poisson statistical fluctuation of the emitted photons, will be better for bolometric LD’s with respect to PMT’s (see Sec. [\ref{sec:energy}]). The main characteristics of a bolometric light detector should be the easy expandability up to \(\sim 1000\) channels, and the complete reliability of the composed device (bolometer + LD) in order to have an almost 100% live time measurement. On the other hand, there is not the need to have an extremely sensitive detector, since the DBD signal lies in the MeV range.
We developed our first LD as a pure Ge disk absorber (35 mm diameter, 1 mm thick) thermally coupled with an 3x1.5x0.4 mm$^3$ Neutron Transmutation Doped Ge thermistor (thermometer). We adopted a very simple setup in which the disk is held by two PTFE supports squeezed by a screw at two opposite sides. The complete setup (see Fig. 4) was tested in the CUORE [10] R&D cryostat located deep underground in the Gran Sasso National Laboratories (Italy). The description of the Front-end electronic can be found in [11, 12].

The LD was used to test several scintillating crystals (see Sec. IV). After the encouraging results we decided to optimize the light detector.

At the working point of our bolometer, $\sim 13$ mK, the theoretical heat capacity of the Ge absorber is $\sim 0.2$ pJ/K while that of the thermistor is $\sim 32$ pJ/K. Therefore the signal height is limited practically by the thermistor itself.

We therefore decided to increase the size of the Ge absorber. The idea was to develop a large-area light detector, able to read several large scintillating crystals at the same time, lowering the number of LD’s needed to face a very large detector array. We used a 6.6 cm diameter, 1 mm thick Ge crystal (absorber) coupled with the same kind of thermistor used for the previous LD. Furthermore one side of the crystal (the one facing the scintillator) was coated with a layer of 60 nm of SiO$\text{$_2$}$ in order to increase the absorption of the scintillating photons. The new LD was mounted in the same way as the previous one. We tested the new large-area LD with a 3x3x2 cm$^3$, 140 g CdWO$_4$ single crystal (see Sec. V).
IV. RESULTS ON MOLYBDATES

Within the *standard* scintillators, an obvious possibility for DBD searches are the Molybdates, due to the high $Q_{\beta\beta}$ of $^{100}$Mo (3034 keV). The scintillation properties of these crystals, based on the $(\text{MoO}_4)^{2-}$ oxyanions, were studied only very recently [13], and further investigations are on the way. Our first aim was to see the scintillation light yield (LY) of several different samples. At that time no direct measurements were available on the particle-induced LY at temperatures lower than 77 K. Our LD was faced (simultaneously) to several small size (few grams) molybdate crystal bolometers (PbMoO$_4$, CaMoO$_4$, SrMoO$_4$) and all of them exhibited scintillation light (see Fig. 5). Due to the small size of the molybdate crystals, their energy response, as a bolometer, becomes extremely non-linear at high values. This behaviour is common for small bolometers and can be corrected using calibration sources. In our case the only calibration source used was a pure $^{238}$U solution evaporated on a small spot facing each crystal. The only “clear” peak is therefore the double $\alpha$ line of $^{238}$U at 4198 and 4151 keV. Besides this $\alpha$ decay there is the $\beta$ decay of $^{234}$Pa with an endpoint at 2.3 MeV. The induced scintillation due to the $\beta + 2\gamma$ decays of $^{234}$Th was below the threshold of the LD.

The three scatter-plots in Fig. 5 show some differences, particularly in the $\alpha$ region. Regarding the CaMoO$_4$ sample the $^{238}$U is clearly visible in the scatter plot. In the case of the PbMoO$_4$ sample, the scatter plot is dominated by an internal contamination of $^{210}$Pb, with the characteristic $\alpha$ line of $^{210}$Po at 5407 keV. The situation is not completely clear in the SrMoO$_4$ sample: this crystal shows extremely large contaminations in the $\alpha$-region and is very difficult to disentangle them due to the extreme non-linearity of the detector. Furthermore, a clear Bi-Po event ($\alpha + \beta$) is present in the spectrum (due to the slowness of the thermal detectors the two decays appear as one). Even if not exactly quantifiable due to the non-linearity of the energy scale, the power of the $\alpha$ discrimination technique is absolutely clear in Fig. 5 thanks to the different scintillation QF.

The second step could be to use larger crystals. Once we have experimentally proven that the LY is sufficient to discriminate the $\alpha$’s, we also have to show that we can build large size (hundreds of grams) bolometers with the needed high energy resolution. However other considerations need to be addressed first in order to have a good scintillating bolometer for a future high sensitivity DBD experiment.
FIG. 5: Scatter plots of Light vs Heat obtained with the three crystals. All the crystals, due to their small size, saturate the heat channel at high energies. The Heat energy scale is therefore not linearized and expressed in mV. The Y axis represents the light output (in mV) of the LD. In this case the scale is linear and direct comparison between the three crystals is possible.

PbMoO$_4$ has two disadvantages: it contains Lead and therefore the radioactive $^{210}$Pb. The only way to avoid this problem would be to use ancient lead to grow the crystal. Furthermore the mass fraction of Molybdenum within the compound will be “only” 26%.

Our sample of SrMoO$_4$ seems to be radioactively contaminated, so we can not fully judge this material. With some effort, a radiopure crystal might be grown but the cosmogenic $^{90}$Sr, in spite of its low $Q_\beta$ energy, could represent a problem, especially regarding pile-up.

CaMoO$_4$ could be a good candidate. It contains a large fraction of Molybdenum, there are several producers able to grow large crystals, and it seems to be reasonably radiopure. Unfortunately the backdraw is Ca. The 2-neutrino DBD of $^{48}$Ca, with $Q_{\beta\beta}=4271$ keV (although only 0.18% of natural isotopic abundance) will result in an unavoidable background in the 0$\nu$-DBD region of $^{100}$Mo. This background can be easily evaluated as 0.01 c/keV/kg/y.
V. EXPERIMENTAL RESULTS ON CDWO$_4$

This bolometer was tested, together with 8 CUORE bolometers, in a long background measurement during April 2005. The 3x3x2 cm$^3$, 140 g CdWO$_4$ single crystal was almost fully surrounded by a reflecting sheet oriented towards the LD that and glued, with a small spot, on the copper. It was not possible to calibrate the LD with the standard $\gamma$-sources we usually place outside the cryostat, due to its small size (it is almost transparent to $\gamma$’s, while external X-rays would not reach the cryostat inner volume). Nevertheless an estimation can be obtained by considering the resolution on the light signal. Assuming that the resolution of the LD on the scintillation peaks is only due to the statistical fluctuation of the number of photons produced in the CdWO$_4$ crystal, the LD can be calibrated. This assumption holds only if the intrinsic energy resolution of the detector is small with respect to the photon fluctuation. The intrinsic energy resolution of the LD can be evaluated by means of a heater that can inject monochromatic thermal energy $^{[14]}$ into the detector. We found in this way that the intrinsic energy resolution was negligible with respect to the width of the scintillation peaks. Therefore, assuming a Fano factor equal to 1, and plotting the energy of the photopeaks vs the energy resolution, an energy calibration (in photons) can be found as shown in Fig. 6. The number of collected photons was measured to be $\sim$ 2400 photons/MeV. Using this calibration, and assuming $\sim$ 3 eV/photon the LD can be calibrated in energy. With this method we found that the energy resolution of the LD is $\approx$ 48 eV FWHM (or 16 photons). It turns out that the baseline resolution of the LD was observed to be 1 order of magnitude smaller compared to the intrinsic statistical photon fluctuation at 2615 keV, suggesting the possibility to further increase the area of the LD for our purposes.

The energy resolution on the scintillation peak at 2615 keV is 3% FWHM. This value is similar (in some cases even better) to those obtained with NaI detectors. Furthermore this result is much better (8% FWHM) with respect to the one obtained with dedicated DBD experiments using CdWO$_4$ as a scintillator (at room temperature) read by standard PMT’s $^{[15]}$. A direct comparison between the two set-ups is, however, not straightforward. First of all the size of the crystals is different (330 g in that case). Furthermore there could be a LY increase in the CdWO$_4$ with the temperature decrease, therefore justifying our better result. But probably the explanation of our better energy resolution is due to the quantum efficiency, as explained in Sec. III the PMT’s matched for CdWO$_4$ emission have a quantum
efficiency of the order of only 18%. Furthermore the best energy resolution ever achieved with PMT’s on CdWO$_4$ scintillators is 3.7 % FWHM (at 2615 keV)\cite{16} on an extremely small sample (1 cm$^3$).

We also performed a long background run with the CdWO$_4$-LD device. Since the main aim of the run was to perform a low background measurement with 8 CUORE detectors, the device was mounted “far away” from the TeO$_2$ detectors. Because of the limited experimental volume in the cryostat, the device was mounted only partially shielded (not shielded against the dilution units itself) and not in the “best” position (the CUORE detectors are connected to a vibration decoupler that minimizes the mechanical vibrations that reach the detectors causing thermal noise). During the 417 h live time background measurement the energy resolution of the CdWO$_4$ was 25 keV. The obtained scatter plot Heat vs Light of our detector is shown in Fig. 7. A live time of 80% was achieved.

The $\alpha$-continuum is completely ruled out thanks to the scintillation detection. Moreover the background above the 2615 keV line is practically zero, demonstrating the power of this technique. Only two counts are present, above the $^{208}$Tl line, around $\sim$ 5 MeV. One of these seems to be a pile-up (it is just above an $\alpha$ line), while the second could arise from the (n,$\gamma$) reaction on $^{113}$Cd ($\sigma \simeq$ 20000 barn). Our cryostat is not shielded against thermal
FIG. 7: Scatter plot of Heat vs Light obtained in a 417 h live time background measurement. The points in the 0-300 keV (Heat) region are due to pile-up. The $\alpha$-induced background is clearly discriminated.

neutrons and taking into account the natural neutron flux in our laboratory, we expect $\sim 0.8 \gamma$ counts in the energy window 2.6 - 9 MeV.

The large number of events in the 0–300 keV region is due to the natural $\beta$ decay of $^{113}\text{Cd}$ (12.2 % i.a.) with $Q_\beta=318$ keV and $T_{1/2}=7.7\times10^{15}$ y. The expected activity can therefore be evaluated (and directly measured) and turns out to be 0.12 Hz.

Some pile-up is found in the scatter plot, especially clear in the 0-300 keV “Heat” region. This was due to the fact that “close” to the LD (and therefore close to the CdWO$_4$) a relatively intense $^{238}\text{U}$ source was present in order to calibrate other bolometers mounted in the cryostat in this run. Since the LD is a bolometer, it exhibits the same pulses whether it absorbs photons or particles. Due to the slowness of the LD some pile-up appears in the scatter plot. This pile-up can be reduced with a combined trigger (in our case the two detectors had independent triggers). In any case the problem can be avoided simply eliminating the $^{238}\text{U}$ source.

At the end of the background measurement we recognized a small failure in the electronic amplifier board of the CdWO$_4$. We fixed the problem and we performed a new energy calibration using a $^{232}\text{Th}$ source. The obtained calibration spectrum is shown in Fig. 8.
FIG. 8: Calibration spectrum of the CdWO$_4$ detector exposed to an external source of $^{232}$Th. In the inset is shown the energy resolution on the 2615 keV line.

The energy resolution at the 2615 keV line is 6 keV FWHM, which represents the typical value that can be reached with bolometers.

In the above discussion, we have shown that light measurement helps to identify the $\alpha$-induced background in thermal detector schemes. However, this technique is also extremely helpful for rejecting another “unavoidable” source of background that can take place with thermal detectors. It was observed [17] that rare heat releases induced by materials relaxations can induce thermal pulses indistinguishable with respect to particle-induced thermal pulses. It is presently not completely clear the energy scale of such events, but in any case a completely independent double read-out of the signal (heat and scintillation) will also allow one to identify such events due to the fact that they do not produce scintillation light.

VI. CONCLUSIONS

We developed a large area ($34 \text{ cm}^2$) thermal light detector for DBD searches. It is by far the largest bolometric light detector ever operated. The device is characterized by an easy construction and assembly and by an intrinsic, constant, energy resolution of the order of 16 photons FWHM. The results obtained are competitive with standard NaI scintillators.
We tested several DBD scintillating bolometers, demonstrating the feasibility of such a technique.

For the first time a DBD pilot experiment based on simultaneous detection of heat and light was performed on a large DBD scintillating crystal showing directly the feasibility and the reliability of this technique. The background that can be obtained with such detectors, provided that the $Q_{\beta\beta}$ is above 2615 keV, can easily reach levels at least 3 orders of magnitude better with respect to the present experiments. Furthermore the bolometric technique is the only one that allows one to investigate most of the DBD emitters with the required energy resolution. In the future we plan to test other molybdate crystals as well as different interesting compounds (ZnSe, ZrO$_2$).

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