Random coincidence of $2\nu2\beta$ decay events as a background source in bolometric $0\nu2\beta$ decay experiments

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Abstract Two-neutrino double $\beta$ decay can create an irre-movable background even in high energy resolution detectors searching for neutrinoless double $\beta$ decay due to random coincidence of $2\nu2\beta$ events in the case of poor time resolution. Some possibilities for suppressing this background in cryogenic scintillating bolometers are discussed. It is shown that the present bolometric detector technologies enable one to control this form of background at the level required to explore the inverted hierarchy of the neutrino mass pattern, including the case of bolometers searching for the neutrinoless double $\beta$ decay of $^{100}$Mo, which is characterized by a relatively short two-neutrino double $\beta$ decay half-life.

1 Introduction

Neutrinoless double beta ($0\nu2\beta$) decay is a key process in particle physics, since it provides the only experimentally viable possibility to test the Majorana nature of the neutrino and the lepton number conservation, establishing in the meantime the absolute scale and the hierarchy of the neutrino masses [1–3].

One of the most important goals of the next generation double $\beta$ decay experiments is to explore the inverted hierarchy of the neutrino masses. In the inverted scheme the effective Majorana ($m_\nu$) neutrino mass is expected to be in the interval $\sim 0.02$–$0.05$ eV. In order to check this range, an experimental sensitivity (in terms of half-life) for the most promising nuclei should be at the level $T_{1/2} \sim 10^{26}$–$10^{27}$ yr. This requires a detector containing a large number of studied nuclei ($\sim 10^{27}$–$10^{28}$), with high energy resolution (at most a few percent at the energy of the decay $Q_{2\beta}$), large (ideally 100 %) detection efficiency, and very low (ideally zero) radioactive background.

Besides the high-purity germanium (HPGe) detectors used to search for $0\nu2\beta$ decay of $^{76}$Ge [4, 5], cryogenic bolometers [6, 7]—luminescent [8–12] or not [13–15]—are excellent candidates to realize large-scale high-sensitivity experiments involving different isotopes with high energy resolution (a few kiloelectron volts) and detection efficiency (near 70 %–90 %, depending on the crystal composition and size).

The Cryogenic Underground Observatory for Rare Events (CUORE) cryogenic experiment [14], built on the successful Cuoricino and searching for $0\nu2\beta$ decay of $^{130}$Te with the help of TeO$_2$ detectors, is by far the most advanced bolometric search and is under construction now, while several searches (including LUCIFER [16] and AMoRE [17]), aiming to use different luminescent bolometers to search for double $\beta$ decay of $^{82}$Se (ZnSe [16, 18]), $^{116}$Cd (CdWO$_4$ [19]), $^{100}$Mo (CaMoO$_4$ [17] and ZnMoO$_4$ [20–23]), and $^{130}$Te (TeO$_2$ [24]) are in the R&D stage.

However, a disadvantage of cryogenic bolometers is their poor time resolution. This can lead to a background component at the energy $Q_{2\beta}$ due to random coincidences of lower energy signals, especially those due to the unavoidable two-neutrino double $\beta$ decay ($2\nu2\beta$) events.

The random coincidence of $2\nu2\beta$ events as a source of background in high-sensitivity $0\nu2\beta$ experiments was considered and discussed for the first time in [22]. In this work, the contribution of random coincidences (rc) of $2\nu2\beta$ events to the counting rate in the energy region of the expected $0\nu2\beta$ peak is estimated. Methods to suppress the background are discussed.

2 Random coincidence of $2\nu2\beta$ events

The energy spectra of $\beta$ particles emitted in $2\nu2\beta$ decay are related to the two-dimensional distribution $\rho_{12}(t_1, t_2)$ (see, e.g., [25] and references therein)
\[ \rho_{12}(t_1, t_2) = e_1p_1F(t_1, Z) \cdot e_2p_2F(t_2, Z) \cdot (t_0 - t_1 - t_2)^2, \]

where \( t_i \) is the kinetic energy of the \( i \)-th electron (all energies here are in units of the electron mass \( m_0c^2 \)), \( t_0 \) is the energy available in the \( 2\beta \) process, \( p_i \) is the momentum of the \( i \)-th electron \( p_i = \sqrt{m_0c^2(t_i + Z)} \) (in units of \( m_0c \)), and \( e_i = t_i + 1 \). The Fermi function \( F(t, Z) \), which takes into account the influence of the electric field of the nucleus on the emitted electrons, is defined as

\[ F(t, Z) = \text{const} \cdot p^{2s-2} \exp(\pi \eta) |\Gamma(s + i\eta)|^2, \]

where \( s = \sqrt{1 - (aZ)^2}, \eta = aZe/p, a = 1/137.036, Z \) is the atomic number of the daughter nucleus \( (Z > 0 \text{ for } 2\beta^- \text{ and } Z < 0 \text{ for } 2\beta^+ \text{ decay}) \), and \( \Gamma \) is the gamma function.

This distribution is shown for \( ^{100}\text{Mo} \) in Fig. 1.

The Primakoff–Rosen (PR) approximation for the Fermi function \( F(t, Z) \sim e/p [26] \), which is adequate for \( Z > 0 \), allows us to simplify Eq. (1) to the expression

\[ \rho_{12}^{PR}(t_1, t_2) = (t_1 + 1)^2(t_2 + 1)^2(t_0 - t_1 - t_2)^5 \]

and to obtain the formula for \( \rho(t) \) analytically:

\[ \rho^{PR}(t) = t(t_0 - t)^5(t^4 + 10t^3 + 40t^2 + 60t + 30). \]

The energy distribution for two randomly coincident \( 2\nu2\beta \) decays \( \rho_{\nu\nu}(t) \) can be obtained by numerical convolution

\[ \rho_{\nu\nu}(t) = \int_0^t \rho(t - x)\rho(x)\,dx, \]

or with a Monte Carlo method by sampling energy releases in two independent \( 2\nu2\beta \) events in accordance with the distribution (3) and adding them. The energy spectrum obtained by sampling \( 10^8 \) coincident \( 2\nu2\beta \) events for \( ^{100}\text{Mo} \) is shown in Fig. 1. (We assume here an ideal energy resolution of the detector.) This distribution can be approximated by the following compact expression,\(^1\) similar to that reported in Eq. (5):

\[ \rho_{\nu\nu}(t) = t^5(2t_0 - t)^8 \sum_{i=0}^8 a_i t^i. \]

However, the coefficients \( a_i \) are different for different isotopes; for \(^{82}\text{Se},^{100}\text{Mo},^{116}\text{Cd},^{130}\text{Te} \) (which are the nearest aims of the bolometric \( 2\beta \) experiments), they are given in Table 1. The approximation for \( ^{100}\text{Mo} \) is shown in Fig. 1.

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\(^1\)One can expect a polynomial of 21st degree because of the formulae (5) and (6).
Table 2 Counting rate of two randomly coincident $2\nu 2\beta$ events in cryogenic Zn$^{82}$Se, $^{40}$Ca$^{108}$MoO$_4$, Zn$^{100}$MoO$_4$, 116CdWO$_4$, and TeO$_2$ detectors of 100 cm$^3$ volume. Enrichment of $^{82}$Se, $^{100}$Mo, and 116Cd is assumed to be 100%, while for Te the natural isotopic abundance (34.08%) is taken. $C$ is the mass concentration of the isotope of interest, $\rho$ is the density of the material (g/cm$^3$), $N$ is the number of $2\beta$ candidate nuclei in one detector, and $B_{rc}$ is the counting rate at $Q_{2\beta}$ (counts/(keV·kg·y)) under the assumption of 1 ms time resolution of the detector.

| Isotope     | $T_{1/2}^{2\nu 2\beta}$ (yr) [27] | Detector ($\rho$)                  | $C$   | $N$                       | $B_{rc}$ |
|-------------|----------------------------------|-----------------------------------|-------|---------------------------|----------|
| $^{82}$Se   | $9.2 \times 10^{19}$             | Zn$^{82}$Se (5.65)               | 55.6% | $2.31 \times 10^{24}$    | $5.9 \times 10^{-6}$ |
| $^{100}$Mo  | $7.1 \times 10^{18}$             | $^{40}$Ca$^{108}$MoO$_4$ (4.35) | 49.0% | $1.28 \times 10^{24}$    | $3.8 \times 10^{-4}$ |
| $^{116}$Cd  | $2.8 \times 10^{19}$             | Zn$^{100}$MoO$_4$ (4.3)          | 43.6% | $1.13 \times 10^{24}$    | $2.9 \times 10^{-4}$ |
| $^{130}$Te  | $6.8 \times 10^{20}$             | 116CdWO$_4$ (8.0)                | 31.9% | $1.32 \times 10^{24}$    | $1.4 \times 10^{-5}$ |
|             |                                  | TeO$_2$ (5.9)                    | 27.2% | $0.76 \times 10^{24}$    | $1.1 \times 10^{-8}$ |

100Mo, and 116Cd, and natural abundance (34.08%) for 130Te. The time resolution of a detector is assumed as $\tau = 1$ ms. The reported rates scale linearly with the time resolution.

The background $B_{rc}$ caused by random coincidences of $2\nu 2\beta$ events has the following dependence on the energy resolution $R$, the volume of the detector $V$, and the abundance or enrichment $6$ of the candidate nuclei contained in the detector:

$$B_{rc} \sim \tau \cdot R \cdot \left(\frac{T_{1/2}^{2\nu 2\beta}}{V^2 \cdot \delta^2}\right). \quad (9)$$

One can conclude from Table 2 that the most important random coincidence background is for $^{100}$Mo due to its relatively short $2\nu 2\beta$ half-life. However, a non-negligible contribution is also expected for other isotopes for a large volume and poor time resolution of the single detectors.

Obviously, any other source of background with high enough energy can contribute due to random coincidences. For example, the presence of $^{234m}$Pa (belonging to the series of $^{238}$U) with a relatively high activity of 1 mBq/kg in 100 cm$^3$ ZnMoO$_4$ crystal will result in additional background due to random coincidence with $2\nu 2\beta$ events of $3.8 \times 10^{-5}$ counts/(keV·kg·y) at $^{100}$Mo $Q_{2\beta}$ energy. However, this contribution is much less important than that due to the $2\nu 2\beta$ decay alone. In addition, our simulations show that coincidence of $2\nu 2\beta$ signals with low energy events is not problematic, because of the quite steep shape of the $2\nu 2\beta$ spectrum near $Q_{2\beta}$. Low energy signals due to spurious sources, like microphonic noise, which can in principle contribute with a high rate, are generally easily rejected in bolometers due to pulse-shape discrimination. In conclusion, while a generic source can be reduced by careful shielding, purification of materials, improvement of the noise figure, and anti-coincidence techniques, the random coincidence of $2\nu 2\beta$ events is a background hard to suppress, as it is related to the very presence of the isotope under investigation. The possibilities for decreasing this type of background to an acceptable level are discussed in the next section.

3 Pile-up rejection in scintillating bolometers

A cryogenic bolometer [28] consists of an energy absorber (a single diamagnetic dielectric crystal in 0\nu 2\beta applications) thermally linked to a temperature sensor that in some cases may be sensitive to out-of-equilibrium phonons. The heat signal, collected at very low temperatures (typically <20 mK for large bolometers), consists of a temperature rise of the whole detector determined by a nuclear event.

The majority of the most promising high $Q_{2\beta}$-value (>2.5 MeV) candidates can be studied with the bolometric technique in the “source=detector” approach, combining high energy resolution and large efficiency [6, 7]. Ultra-pure crystals up to 100–1000 g can be grown with materials containing appealing candidates. Arrays of the single crystalline modules allow us to achieve total masses of the order of 100–1000 kg [14–16], which are necessary to explore the inverted hierarchy region.

An excellent choice for the bolometric material, as used in the Cuoricino and CUORE experiments [13, 14], consists of TeO$_2$ (tellurite) that has a very large (27% in mass) natural content of the 0\nu 2\beta candidate $^{130}$Te. In terms of background, the experience provided by TeO$_2$ searches [29] shows clearly that energy-degraded $\alpha$ particles, emitted by the material surfaces facing the detectors or by the detector surfaces themselves, are expected to be the dominant contribution in all high $Q_{2\beta}$-value candidates, for which the signal falls in a region practically free of $\gamma$ background. The $\alpha$ background component can be made negligible by using scintillating or in general luminescent (including Cherenkov light [12, 24]) bolometers. In fact, since the $\alpha$ light yield is generally appreciably different from the $\beta/\gamma$ light yield at equal deposited energy, while the thermal response is substantially equivalent, the simultaneous detection of light and heat signals, and the comparison of the respective amplitudes, represents a powerful tool for $\alpha/\beta$ discrimination and therefore for $\alpha$ background rejection [8–10]. Scintillation photons are usually detected by a dedicated bolometer, in the form of a thin slab, opaque to the emitted light and equipped
with its own temperature sensor. The light absorber, normally a Ge, Si, or Si-coated Al2O3 slab, is placed close to a flat face of the main scintillating crystal.

A wealth of preliminary experimental results [11, 18–23] show that this method is effective and that $\alpha$ rejection factors even much better than 99.9% can be achieved. Once this discrimination capability of scintillating bolometer is taken into account, a detailed background analysis, based on reasonable assumptions on internal radioactive contamination, shows that a residual background level of $\sim 10^{-4}$ counts/(keV-kg-yr) can be safely assumed [22, 23], opening the opportunity to explore the inverted hierarchy region of the neutrino mass pattern. However, the random coincidences of $2\nu2\beta$ events discussed in Sect. 2 must be kept under control. According to Eq. (8), the rate of $\alpha$-2$\nu2\beta$ events is proportional to the time resolution of the detector. Therefore, the time properties of the signal from a cryogenic detector play a crucial role in this form of background.

The large mass ($\sim 800$ g), high energy resolution ($\sim 3$–4 keV FWHM at 2615 keV) for Cuoricino and CUORE [13, 14] represent a sort of paradigm for $0\nu2\beta$ decay bolometers, inspiring other proposed experiments and related R&D activities. As temperature sensors, neutron transmutation doped (NTD) Ge elements are used, characterized by a high impedance (1–100 M$\Omega$) and a high sensitivity ($-d \log R/d \log T \sim 10$). Other promising solutions for the thermal sensors have been used [17, 30–32], but for the moment only the energy resolution and the reliability provided by NTD Ge-based bolometers seem to be compatible with a large-scale $0\nu2\beta$ experiment. In these devices, the NTD Ge thermistor is glued to the TeO2 crystal by means of a two-component epoxy. Their time resolution is strictly related to the thermal-signal risetime.

The temporal behavior of the thermal pulse, and therefore its risetime, can be understood due to a thermal model for the whole detector, described elsewhere [33–36]. The model predicts that large mass detectors with NTD Ge readout have risetimes of the order of tens of milliseconds. This is confirmed experimentally in the Cuoricino detectors, which exhibited pulse risetimes of the order of $\sim 50$ ms [13]. Similar values are expected for any cryogenic bolometers with a volume of the order of 100 cm$^3$ and based on NTD Ge thermistors. Faster risetimes could be observed if an important component of the energy reaches the thermistors in the form of athermal phonons, but this possibility depends critically on the nature of the main crystal and of the crystal-thermistor interface. The most conservative approach consists in assuming the slow risetime evaluated and observed in TeO2 bolometers.

The time resolution of the main crystal can be made substantially shorter than the risetime, taking advantage of the excellent signal-to-noise ratio expected at the $0\nu2\beta$ energy [37], which is of the order of 2000 to 1 in TeO2 crystals. (However, this high value is still to be proved for other bolometric materials relevant for $0\nu2\beta$ decay.) Even though the time resolution proved shorter by a factor of 10 with respect to the present TeO2 risetime values, and therefore around 5 ms, the background values reported in Table 2 should be multiplied by a factor 5, bringing them above $10^{-3}$ counts/(keV-kg-yr) for $^{100}$Mo. The background due to random coincidence of $2\nu2\beta$ events would then be dominant. The advantage of scintillating bolometers, which promise to keep the other sources around or below $10^{-4}$ counts/(keV-kg-yr) [22, 23], would be substantially compromised.

However, the simultaneous detection of light and heat which characterizes scintillating bolometers offers the possibility to control this problematic background source as well. In fact, a much faster risetime in the light-detector signal is expected, due to the much lower heat capacity of the energy absorber, which has now a mass of only a few grams at most. Following the bolometer thermal model [33–36], the light-detector risetime can be reduced to $\sim 1$ ms. Assuming a similar time resolution, the $2\nu2\beta$ background contribution is in the ranges shown in Table 2, due to the fast response provided by the light detector.

The above discussion is simplified: the capability to discriminate two close-in-time events cannot be reduced to a single parameter such as the detector time resolution $\tau$. In fact, it depends smoothly on the temporal distance between the two events and on the ratio between their two amplitudes as well. Furthermore, the pile-up discrimination capability is influenced by the signal-to-noise ratio in the light detector [37] and by the pulse shape and noise features. A complete analysis, the details of which will be reported elsewhere in a dedicated publication, has been performed. In this letter, we present the main results of this investigation and the most important conclusions.

An experiment based on modules of Zn$^{100}$MoO4 crystals was considered. We have used pulse shapes and noise from a real light detector, of the same type as those described in [21, 22], coupled to a ZnMoO4 scintillating crystal. The pile-up phenomenon was studied by generating light pulses with the observed experimental shape on top of experimental noisy baselines. In particular, pairs of pulses were generated with random time distances with a flat distribution up to 10 ms—in fact, the interarrival time distribution is practically constant over the [0, 10] ms range (this is the relevant time interval, since it allows us to fully explore the most problematic pile-up case, i.e., that occurring on the pulse risetime which is of the order of 3 ms). In Fig. 2, two pile-up emblematic cases (both with 3 ms time separation) extracted from the performed simulation are shown, along with a single pulse as a reference.

As a first step, we defined a 90% efficiency in accepting a pulse from the light detector as a potentially good $0\nu2\beta$
pulses generated as described above is shown in Fig. 3. More quantitatively, the same procedure that retains 90 % of genuine single pulses rejects 80 %–90 % of piled-up pulses when their sum amplitude is in the region of \(Q_{2\beta}\) and the difference between the arrival times of the two pulses covers uniformly the interval \([0, 10]\) ms. For example, the analysis of the sample reported in Fig. 3 excludes 83 % of piled-up pulses when accepting 90 % of good pulses. The other two indicators provide equivalent or even better results. However, we prefer here to consider conservatively the results obtained with the method of the risetime, as this parameter is an intrinsic property of each signal that does not require the comparison with a standard shape. This comparison in fact implies a delicate synchronization between the single pulse and the standard-shape pulse; this topic will be discussed in the aforementioned more complete work.

The results of the simulation show that the contribution to the background of the piled-up events is substantially equivalent to that obtained when assuming a time resolution \(r\) of 1 ms in Eq. (9) (since 80 %–90 % of the pulses are rejected in the region of \(0\nu\beta\) decay inside a pile-up relevant range of 10 ms), and therefore confirming the evaluation for ZnMoO4 reported in Table 2.

We can thus conclude that light detectors at the present technological level are compatible with next-generation \(0\nu\beta\) decay experiments based on ZnMoO4 crystals with background in the \(10^{-4}\) counts/(keV·kg·y) scale, confirming that this class of experiments has the potential to explore the inverted hierarchy region of the neutrino mass pattern [22, 23].

### 4 Conclusions and prospects

Random coincidence of \(2\nu\beta\) events is an irremovable background source in large-scale \(2\beta\) experiments using detec-
tors with slow response time, such as large mass cryogenic bolometers with NTD Ge readout.

Advancement of time resolution of cryogenic detectors plays a key role in suppressing the background. However, we have shown that the present technology is already compatible with searches at the sensitivity frontier. For further improvements, experimental efforts should be concentrated on the time properties of the light signal, which are potentially much faster than the heat pulses of a scintillating bolometer. Achieving a time resolution below 0.1 ms could potentially much faster than the heat pulses of a scintillating bolometer. Achieving a time resolution below 0.1 ms could make the background totally negligible, even for the difficult case of $^{100}$Mo. This performance could be obtained by using sensors that are sensitive to out-of-equilibrium phonons or intrinsically fast [30–32].

A more direct way to decrease the pile-up effect is to reduce the volume of the main absorber (and increase correspondingly the number of array elements), on which the random coincidence rate depends quadratically, as shown in Eq. (9). Cryogenic detectors with space resolution could allow one to reduce the background further.

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References

1. F.T. Avignone III, S.R. Elliott, J. Engel, Rev. Mod. Phys. 80, 481 (2008)
2. A. Giuliani, Acta Phys. Pol. B 41, 1447 (2010)
3. W. Rodejohann, Int. J. Mod. Phys. E 20, 1833 (2011)
4. H.V. Klapdor-Kleingrothaus et al., Eur. Phys. J. A 147, 12 (2001)
5. C.E. Aalseth et al., Phys. Rev. D 65, 092007 (2002)
6. E. Fiorini, T.O. Niinikoski, Nucl. Instrum. Methods Phys. Res. A 224, 83 (1984)
7. A. Giuliani, J. Low Temp. Phys. (2012). doi:10.1007/s10909-012-0576-9
8. L. Gonzalez-Mestres, D. Perret-Gallix, Nucl. Instrum. Methods Phys. Res. A 279, 382 (1989)
9. A. Giuliani, S. Sanguinetti, Mater. Sci. Eng., R Rep. 11, 1 (1993)
10. A. Alessandrello et al., Phys. Lett. B 420, 109 (1998)
11. S. Pirro et al., Phys. At. Nucl. 69, 2109 (2006)
12. T. Tabarelli de Fatis, Eur. Phys. J. C 65, 359 (2010)
13. E. Andreotti et al., Astropart. Phys. 34, 822 (2011)
14. C. Arnaboldi et al., Nucl. Instrum. Methods Phys. Res. A 518, 775 (2004)
15. F. Alessandria et al., arXiv:1109.0494v1 [nucl-ex]. Accessed 2 September 2011
16. A. Giuliani et al., in Proceedings of the Fifth International Conference Beyond 2010, Cape Town, South Africa, 1–6 February 2010, ed. by H.V. Klapdor-Kleingrothaus, I.V. Krivosheina, R. Viollier (World Scientific, Singapore, 2011), p. 256
17. S.J. Lee et al., Astropart. Phys. 34, 732 (2011)
18. C. Arnaboldi et al., Astropart. Phys. 34, 344 (2011)
19. L. Gironi et al., Opt. Mater. 31, 1388 (2009)
20. L. Gironi et al., J. Instrum. 5, 11007 (2010)
21. J.W. Beeman et al., J. Low Temp. Phys. (2012). doi:10.1007/s10909-012-0573-z
22. J.W. Beeman et al., Phys. Lett. B 710, 318 (2012)
23. J.W. Beeman et al., Astropart. Phys. (2012). doi:10.1016/j.astropartphys.2012.02.013
24. J.W. Beeman et al., Astropart. Phys. 35, 558 (2012)
25. V.I. Tretyak, Yu.G. Zdesenko, At. Data Nucl. Data Tables 61, 43 (1995)
26. H. Primakoff, S.P. Rosen, Rep. Prog. Phys. 22, 121 (1959)
27. A.S. Barabash, Phys. Rev. C 81, 035501 (2010)
28. A. Giuliani, Physica B 280, 501 (2000)
29. M. Pavan et al., Eur. Phys. J. A 36, 159 (2008)
30. A. Fleischmann et al., AIP Conf. Proc. 1185, 571 (2009)
31. G. Angloher et al., Astropart. Phys. 31, 270 (2009)
32. C. Nones et al., J. Low Temp. Phys. 151, 871 (2008)
33. J. Zhang et al., Phys. Rev. B 57, 4472 (1998)
34. A. Alessandrello et al., Czechoslov. J. Phys. 46-S5, 2893 (1996)
35. M. Pedretti et al., Physica B 329–333, 1614 (2003)
36. L. Foggetta et al., Astropart. Phys. 34, 809 (2011)
37. H. Spieler, Semiconductor Detector Systems (Oxford University Press, London, 2005)
38. T. Fazzini et al., Nucl. Instrum. Methods Phys. Res. A 410, 213 (1998)