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Rejection of randomly coinciding events in $Li_2^{100}MoO_4$ scintillating bolometers using light detectors based on the Neganov–Luke effect

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Abstract Random coincidences of nuclear events can be one of the main background sources in low-temperature calorimetric experiments looking for neutrinoless double-beta decay, especially in those searches based on scintillating bolometers embedding the promising double-beta candidate ^{100}Mo, because of the relatively short half-life of the two-neutrino double-beta decay of this nucleus. We show in this work that randomly coinciding events of the two-neutrino double-beta decay of ^{100}Mo in enriched $Li_2^{100}MoO_4$ detectors can be effectively discriminated by pulse-shape analysis in the light channel if the scintillating bolometer is provided with a Neganov–Luke light detector, which can improve the signal-to-noise ratio by a large factor, assumed here at the level of ~750 on the basis of preliminary experimental results obtained with these devices. The achieved pile-up rejection efficiency results in a very low contribution, of the order of $\sim 6 \times 10^{-5}$ counts/(keV·kg·y), to the background counting rate in the region of interest for a large volume (~90 cm^3) $Li_2^{100}MoO_4$ detector. This background level is very encouraging in view of a possible use of the $Li_2^{100}MoO_4$ solution for a bolometric tonne-scale next-generation experiment as that proposed in the CUPID project.

1 Introduction

The double-beta (2β) decay is an extremely rare nuclear transition in those even-even nuclides where ordinary beta decay is either forbidden by conservation of energy or highly suppressed by a large spin change. While the two-neutrino mode of the decay ($2\nu2\beta$), being allowed in the Standard Model of particles (SM), was observed experimentally after long-time efforts (see, e.g., reviews [1,2]), the neutrinoless double-beta ($0\nu2\beta$) decay violates lepton number conservation [3–5] and is therefore forbidden in the framework of the SM. The process is considered as a unique way to investigate properties of neutrino and test many other hypothetical effects beyond the SM implying lepton number non conservation. The study of $0\nu2\beta$ decay can establish the Majorana nature of neutrino, help determine the scale of the neutrino mass, the neutrino-mass hierarchy and the Majorana CP-violating phases, check possible contribution of hypothetical right-handed currents admixture to weak interaction, the existence of Nambu–Goldstone bosons (majorons), and many other new-physics effects [6–8].

Despite almost seventy years of experimental activity, the $0\nu2\beta$ decay has not been observed yet. The most sensitive experiments give half-life limits on the level of 10^{24}–10^{26} years (see reviews [9–13], and the recent KamLAND-Zen results [14]), which correspond to effective Majorana neutrino mass limits on the level of $\langle m_\nu \rangle \sim 0.1 - 1\,\mathrm{eV}$. The next-generation experiments should explore the inverted region of the neutrino mass ($\langle m_\nu \rangle \sim 0.02 - 0.05\,\mathrm{eV}$) and develop a technology to go towards the normal-hierarchy mass scale ($\langle m_\nu \rangle \sim 0.01\,\mathrm{eV}$). The experimental sensitivity requested to explore the inverted-hierarchy region (for the nuclei with the highest decay probability) is on the level of $\lim T_{1/2} \sim 10^{26} - 10^{27}$ years. The sensitivity requirements are even much stronger taking into account certain problems

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of nuclear-matrix-element calculation accuracy and a possible quenching of the axial vector coupling constant (g_A) [4].

In light of the foregoing, cryogenic scintillating bolometers look very promising detectors for the next generation $0\nu2\beta$ experiments thanks to their high energy resolution (a few keV), 80–90% detection efficiency, and excellent particle identification ability [15–17]. The isotope ^{100}Mo is one of the most promising 2β nuclei taking into account the high energy of the decay ($Q_{2\beta}$ = 3034.40(17) keV [18]), the comparatively high natural isotopic abundance (δ = 9.744(65)% [19]), and the possibility of isotopical separation by centrifugation in a large amount. The recent calculations of nuclear matrix elements for the $0\nu2\beta$ decay of ^{100}Mo give comparatively "short" half-life in the range of $T_{1/2}^{0\nu2\beta} \approx (0.7-1.7)\times10^{26}$ y [20–23] (for an effective Majorana neutrino mass equal to 0.05 eV, assuming the standard value of the axial vector coupling constant $g_A = 1.27$, and using the recent calculations of the phase-space factor from Ref. [24]).

The availability of molybdenum-containing scintillators to be operated as cryogenic scintillating bolometers is an important practical advantage of ^{100}Mo. Recently, lithium molybdate (Li_2MoO_4) crystal scintillators were successfully tested as scintillating bolometers [25,26]. Subsequently, a technique to grow large-volume, high-quality Li_2MoO_4 crystal scintillators with low radioactive contamination – embedding also enriched ^{100}Mo – was developed in the framework of the LUMINEU [27,28] and ISOTTA [29] projects with outstanding results [30,31]. This makes this material very promising for $0\nu2\beta$ experiments with ^{100}Mo.

However, random coinciding events, especially of the $2\nu2\beta$ decay of ^{100}Mo, can produce background due to the poor time resolution of cryogenic detectors [32,33]. This effect can be a major source of background in the region of interest on the level of $\sim10^{-3}$ counts/(keV·kg·y) [34], depending on the detector volume and performance, and on the data-analysis approach. As it was demonstrated in [34] the rejection efficiency substantially depends on the time properties and signal-to-noise ratio of the detector. Here we analyze the advantages of a cryogenic light detector operated with Neganov–Luke amplification [35,36] to reject pile-up signals in a Li_2MoO_4-based scintillating bolometer.

2 Neganov–Luke light detectors

In scintillating bolometers for $0\nu2\beta$ search, employed in the LUMINEU [27] and LUCIFER [37] projects, the light emitted by the scintillating crystal is detected and measured by an auxiliary bolometer, consisting of a pure Ge wafer, working as light collector and energy absorber. The wafer is coupled to a neutron transmutation doped (NTD) Ge thermistor, serving as a temperature sensor. Details on these light detectors can be found in Refs. [38,39]. In this work, we will consider Ge wafers with a diameter of 44 mm and a thickness of 0.17 mm, as those used by the LUCIFER and LUMINEU collaborations in their pilot experiments. In general, the performances of these light detectors present a significant spread, due to a difficult reproduction of the thermal couplings among detector elements, but they are always largely sufficient to separate α and β particles in the region of interest for $0\nu2\beta$ decay of ^{100}Mo (around 3034 keV), exploiting their different light yields [30,32].

An average-performance detector based on the NTD Ge technology in the LUMINEU or LUCIFER context, in optimized noise conditions, has typically a baseline width of the order of $\sim$100 eV rms, even if occasionally much better values – around 40–50 eV rms – are observed [38,39]. We will take conservatively the former value for the discussion that will follow. The light collected in a Li_2MoO_4 scintillating bolometer corresponds to an energy deposition in the light detector of about 1 keV when 1 MeV total energy is released by electrons in the scintillator. In previous tests with this compound, lower values were observed (of the order of 0.4 keV/MeV [26] or 0.7 keV/MeV [30]), but recently it was possible to obtain systematically light yields close to $\sim$1 keV/MeV thanks to an improved crystal quality [31]. The signal in the light detector induced by a $0\nu2\beta$ event corresponds therefore to about 3 keV energy. Consequently, a typical signal-to-noise ratio (defined as the ratio of the signal amplitude to the standard deviation of the noise baseline) of light detectors operated with Li_2MoO_4 crystal scintillators is $\sim$30 [34].

The signal-to-noise ratio in the light channel can be enhanced by a large factor by exploiting the Neganov–Luke effect [35,36], keeping essentially the same light-detector structure and materials and especially the same temperature sensor. The latter point is of great importance in view of a large scale experiment like that proposed by the CUPID group of interest [40], since the NTD Ge readout is very simple and involves only well-established room-temperature electronics with easy channel multiplication [41].

The Neganov–Luke effect consists in a heat-mediated voltage-assisted measurement of the charge developed in a semiconductor detector by impinging radiation. It enables the detection of very small amount of charges, down to a few electron-hole pairs, with much better sensitivities with respect to the conventional readout based on charge-sensitive amplifiers. To this aim, the semiconductor bolometric absorber is provided with electrodes on its surface, which are used to apply an electric field in the absorber volume. The work done by the fields on the drifting charges can be detected in form of heat by NTD Ge thermistors. In the case of our 44-mm-diameter Ge disk, the electrodes are a set of concentric Al rings deposited on one surface by evaporation with a shadow mask. The rings are electrically connected by

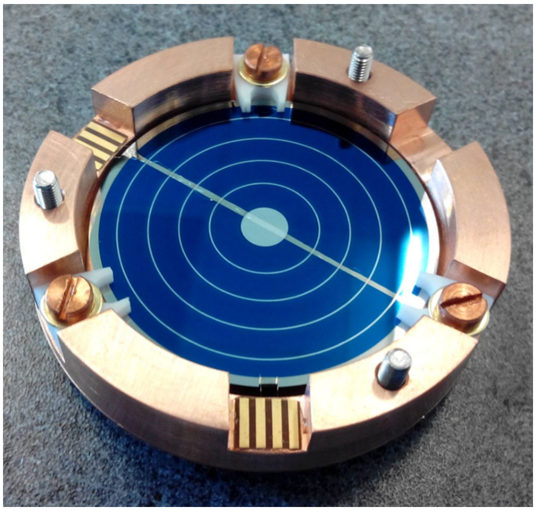

Fig. 1 A Neganov–Luke light detector fabricated at CSNSM. It consists of a 44-mm-diameter Ge disk provided with a set of concentric Al electrodes with a pitch of about 3.7 mm and coated with a 70-nm-thick SiO antireflective film (*blue color* area). The NTD Ge thermistor for the temperature readout is visible in the *lower* part of the photograph as a small chip attached at the Ge disk close to the edge. The visible uncoated diametrical band allows for contacting the annular electrodes

means of ultrasonic wedge bonding with an alternate pattern. This allows applying a given voltage drop between any couple of adjacent rings and producing an electric field parallel to the surface. A photograph of the device is shown in Fig. 1. The use of a ring structure, instead of a peripheral and central electrode only, enables to increase the charge-collecting electric field for a given applied voltage and to decrease the path length of the charges towards the electrodes, implying a lower trapping probability.

Several Neganov–Luke light detectors, with different inter-electrode pitches and adding in some samples a SiO antireflective coating with a thickness of 70 nm [42], were fabricated, tested and characterized. One of these devices has been used succesfully to detect the tiny Cherenkov light emitted by a TeO_2 crystal [43], in the framework of a R&D activity for an improvement of the $0\nu2\beta$ detectors used in the CUORE experiment [44] and designed to be used in its proposed evolution CUPID [40]. In general, we have shown that it is possible to apply safely ∼50 V to the electrode structure discussed above and shown in Fig. 1, without the development of leakage currents. Often, it is possible to reach ∼100 V. The signal amplification achievable on LED pulses in the infrared range is spectacular, of the order of ∼30. The baseline noise remains almost constant under signal Neganov–Luke amplification, with a slight increase observed sometimes in the high-voltage range (50–100 V).

Of course, it is important to understand and control the noise sources which contribute to the baseline fluctuations. These are mainly due to parasitic effects, like vibrations (which induce temperature fluctuations of Ge wafer), micro-

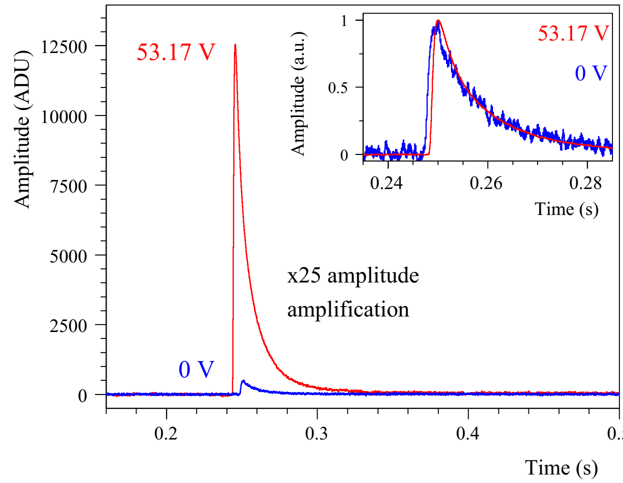

Fig. 2 Comparison of light-detector pulses (in ADC unit) induced by the absorption of a flash of light emitted by a LED (wavelength 1.45 µm) with (53.17 V label, alluding to the voltage value applied between two adjacent Al rings) and without (0 V label) Neganov–Luke effect. In the inset: the two pulses are normalized in amplitude in order to emphasize the factor ∼20 improvement of the signal-to-noise ratio

phonic noise (generated by the readout-wire mechanical oscillations), and, to a minor extent, intrinsic noise of the thermistor (Johnson and 1/f noise) and of the preamplifier. Our rejection method could take advantage of a mitigation of these contributions, which however are not amplified by the Neganov–Luke effect, as discussed above. A more dangerous noise source that we have observed is related to the aforementioned leakage currents developed at high voltages. The associated fluctuations can contribute significantly to the noise and the Neganov–Luke effect amplifies them along with the signal. This sets an intrinsic upper limit to the achievable gain in terms of signal-to-noise ratio.

The best results obtained up to now is an improvement of the signal-to-noise ratio of ∼20 with respect to the performance in absence of Neganov–Luke effect, as shown in Fig. 2. We are confident however that this figure can be largely improved, as these results are very preliminary and an extensive optimization work is still to be done in terms of electrode configuration, deposition procedure and noise control. We will assume in the following that a gain of 25 can be obtained, close to what already achieved and rather conservative with respect to the potential of this technology.

We would like to stress that the improvement in terms of signal-to-noise ratio obtained by the Neganov–Luke effect cannot increase the light-detector energy resolution beyond the limit set by the photon statistics. At the ^{100}Mo $0\nu2\beta$ characteristic energy, about 1450 scintillation photons are collected by the light detector, as ∼3 keV is the total energy contained in the corresponding scintillation pulse. (The light emission from Li_2MoO_4 has an intensity maximum at ∼600 nm [30], which corresponds to a photon energy of

2.07 eV.) A poissonian standard deviation of ∼40 photons is therefore expected, corresponding to an intrinsic limit on the energy resolution of $\sigma \approx 80$ eV. This however plays no role in our following discussion about pile-up rejection, which requires as much as possible noise-free pulses and is not affected by an energy-resolution loss due to the granularity of the energy carriers.

3 Generation of randomly coinciding events

In order to discriminate random coincident events in scintillating bolometers, it is possible to exploit pulse-shape analysis either in the heat or in the light channel signals. The formers are slower but feature a much better signal-to-noise ratio. Even if light signals can provide a significant discrimination with the state-of-the-art light detectors [33], heat signals are superior in terms of rejection efficiency [34] as their larger signal-to-noise ratio (typically of the order of $\sim 10^3$) prevails. The rationale of using Neganov–Luke light detectors is to exploit the ten-time faster light signals in terms of rise-time with a signal-to-noise ratio that approaches that of the heat channel.

We have investigated the rejection efficiency that can be obtained with this light-detector technology, and consequently the final background rate in the region of interest due to random coincidences of two-neutrino 2β decay, assuming a single module consisting of a cylindrical $Li_2^{100}MoO_4$ crystal with a diameter of 44 mm and a height of 60 mm, coupled to a Neganov–Luke light detector like the one described in the previous section (an array of single modules with these features will be tested in the framework of the CUPID R&D program). Assuming 100% enrichment, such a crystal contains 9.4×10^{23} ^{100}Mo nuclei. The consequent random-coincidence background rate B_{rc} amounts to [33]:

$$B_{rc}\left[\text{counts}/(\text{keV}\cdot\text{kg}\cdot\text{y})\right] \approx 3.37\times10^{-4}\cdot[T_R/1\,\text{ms}], \quad (1)$$

where T_R is the pulse-pair resolving time. The assumption underlying this formula is that two signals separated by an interval shorter than T_R will be analysed as a single pulse with an amplitude given by the sum of the two individual ones, while they will be recognized as double if the time separation is longer than T_R.

Ten thousands of noise baseline samples and a scintillation reference pulse were used to generate sets of single and randomly coincident pulses. The noise samples were acquired by a real Neganov–Luke light-detector baseline with a sampling frequency of 20 kSPS. In order to build the scintillation reference pulse, we took 40 individual scintillation pulses (sampled with 1 kSPS) from an ordinary light detector based on a Ge disk instrumented with an NTD Ge thermistor, in a setup similar to that described in Ref. [30]. We stress that this device is identical to those equipped with Al rings to exploit the Neganov–Luke effect. The light detector was coupled to a 240 g Li_2MoO_4 scintillating bolometer. The scintillation pulses used to build the reference pulse corresponded to γ and β events with energies in the 1.5–2.6 MeV range in the Li_2MoO_4 scintillator. The reference pulse was obtained by fitting the average pulse built on these 40 individual light signals and therefore it represents faithfully the shape of a scintillation signal. The phenomenological fitting function is a sum of three exponentials with three free amplitudes and three free time constants. It is not based on a detector-response model, but it represents very accurately the pulse shape. The rise-time of the reference pulse (defined as the time to change the pulse amplitude on the front edge from 10% to 90% of its maximum) is $\tau_{\text{rise}} \approx 3$ ms, while the decay time (the time to change the pulse amplitude on the pulse decay from 90% to 30% of its maximum) is $\tau_{\text{decay}} \approx 14$ ms.

To generate randomly coinciding light signals corresponding to overlapping heat signals (assuming 1 keV/MeV light-to-heat ratio as discussed above) in the region of the ^{100}Mo $Q_{2\beta}$ value, the amplitude of the first pulse A_1 was obtained from the $2\nu2\beta$ distribution of ^{100}Mo, while the amplitude of the second pulse was chosen so that the total pulse energy was $Q_{2\beta} + \Delta E$, where ΔE is a random component in the energy interval $[-5, +5]$ keV [33]. Ten thousands of single pulses and ten thousands of coinciding signals were randomly generated in the time interval from 0 to $3.3 \cdot \tau_{\text{rise}}$. The choice of the factor 3.3 is arbitrary. It garantees that pulses separated by a longer interval are recognized as double with 100% efficiency, as discussed below. As far as this condition is respected, the final results on the rejection efficiency do not depend on the value of this factor.

An example of light signal obtained with an ordinary cryogenic light detector, with a signal-to-noise ratio around 30 as discussed above, is given in the upper panel of Fig. 3. As discussed in the previous section, we assume that a light detector based on Neganov–Luke effect can improve this value up to 25 times, leading to a signal-to-noise ratio of 750. A single pulse in these conditions is also shown in Fig. 3 (lower panel).

4 Results and discussion

The mean-time method was applied to discriminate randomly coincident events. The mean-time parameter $\langle t\rangle$ was calculated for each pulse $f(t_k)$ by using the following formula:

$$\langle t\rangle = \sum f(t_k)\cdot t_k / \sum f(t_k),$$

where the sum is over time channels k, starting from the start of a pulse and up to a certain time.

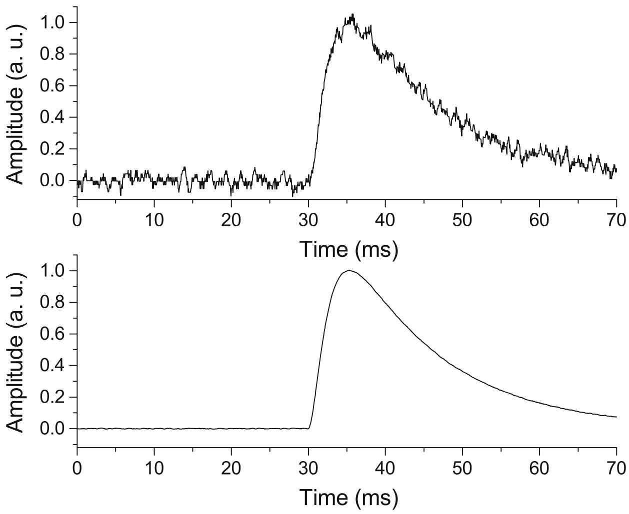

Fig. 3 Examples of generated light pulses with signal-to-noise ratio 30 (*upper panel*) and 750 (*lower panel*)

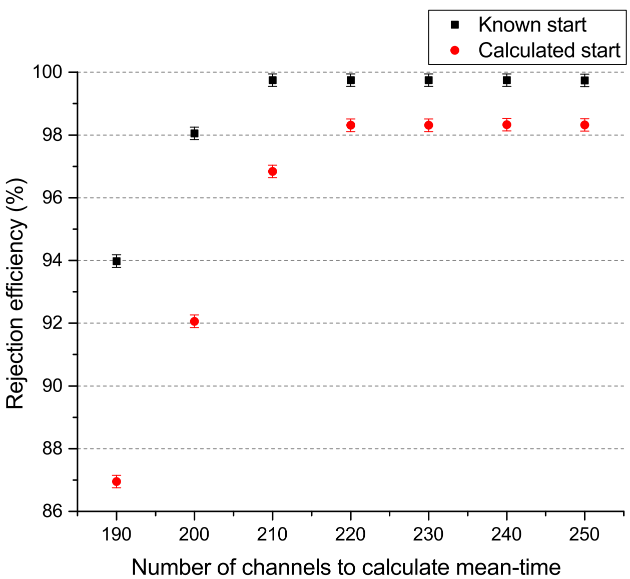

Fig. 4 Dependence of the rejection efficiency of the mean-time method on the number of channels to calculate the mean-time parameter $\langle t \rangle$. The analysis was performed for the Li_2MoO_4 light signals with 3 ms rise-time and the signal-to-noise ratio 750 under two conditions of the signal-origin determination: (*squares*) start positions of the signals known from the generation procedure; (*circles*) start positions found by the pulse profile analysis. One channel is 0.05 ms

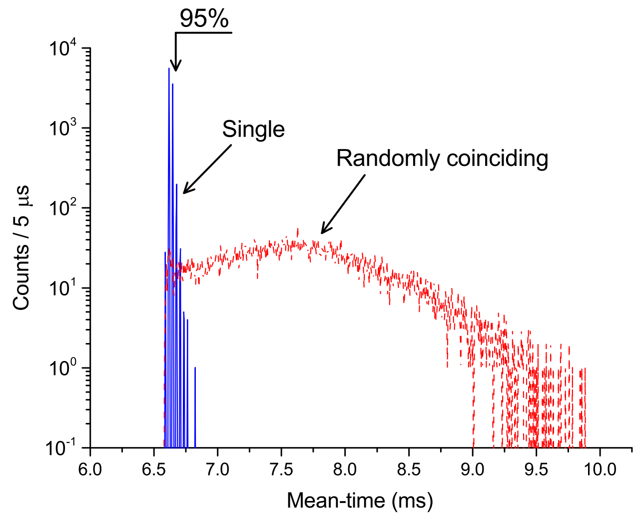

Fig. 5 Distribution of the mean-time parameter for single and randomly coinciding light pulses with a rise-time $\tau_{\rm rise} = 3$ ms and signal-to-noise ratio 750. The rejection efficiency of randomly coinciding pulses, separated by time intervals equally distributed in the range $[0 - 3.3 \cdot \tau_{\rm rise}]$, is 98.3% under the requirement to accept 95% of single events. The signal origin is determined by the pulse-profile analysis

Table 1 Rejection efficiency of randomly coinciding $2\nu2\beta$ events achievable by pulse-shape discrimination using light signals for different signal-to-noise ratios (without and with Neganov–Luke effect) and two conditions of the signal origin determination: start of the signals known from the generation procedure and start position found by the pulse-profile analysis

Channel, rise-time	Signal-to-noise ratio	Start position	Rejection efficiency (%)
Light, 3 ms	30	Known	98.4 ± 0.2
		Found	86.3 ± 0.2
	750	Known	99.8 ± 0.2
		Found	98.3 ± 0.2

The number of channels used to calculate the mean-time parameter was optimized to achieve an as-high-as-possible rejection efficiency, defined as the number of rejected coinciding events divided by the number of randomly generated events in the time interval $3.3 \cdot \tau_{\rm rise} \sim 10$ ms in the light channel. We have verified that when two pulses are separated by an interval longer than ∼10 ms (corresponding to about three times the light-signal rise-time) they are recognized as double with 100% efficiency. An example of the mean-time method optimization is presented in Fig. 4. The rejection efficiency reaches its maximum when the mean-time parameter is calculated from the signal origin to approximately 220–250 channels corresponding roughly to $\sim\tau_{\rm decay}$.

The distributions of the mean-time parameters for single and pile-up events, generated for a light detector with a signal-to-noise ratio of 750, are presented in Fig. 5. The rejection efficiency of randomly coinciding pulses, under the requirement to detect 95% of single events, is 98.3%.

The rejection efficiencies computed by the simulations are presented in Table 1, where the results obtained with an ordinary light detector are also given for comparison.

The dependence of the rejection efficiency on the signal-to-noise ratio obtained using the mean-time method for the Li_2MoO_4 light signals was studied for start positions of the signals found by our algorithm (as in a real experiment), and using the exact signal start positions known from the generation procedure (to estimate the maximum achievable

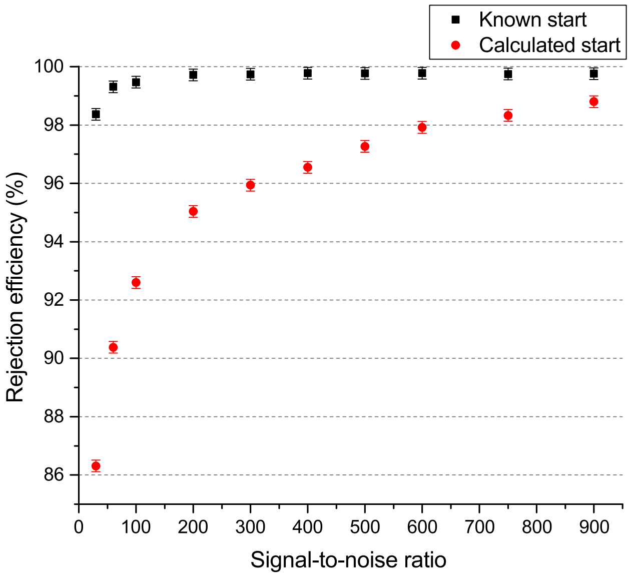

Fig. 6 Dependence of the rejection efficiency on the signal-to-noise ratio obtained using the mean-time method for Li_2MoO_4 light signals under two conditions of the signal-origin determination: (*squares*) start positions of the signals known from the generation procedure; (*circles*) start positions found by the pulse profile analysis

efficiency). The results are shown in Fig. 6. The rejection efficiency depends remarkably on the accuracy of the pulse-origin determination, which is substantially improved by the high signal-to-noise ratio provided by the Neganov–Luke light-detection technology.

In order to translate the rejection efficiencies reported in Table 1 into background rate levels, we use Eq. (1) with $T_R = 10$ ms and multiply the resulting value by the complement to 1 of the rejection efficiencies reported in Table 1 for the reconstructed pulse-origin case. We obtain 4.6×10^{-4} counts/(keV·kg·y) and 5.6×10^{-5} counts/(keV·kg·y) for an ordinary and a Neganov–Luke effect light detector, respectively. It is interesting to compare these values with 1.1×10^{-4} counts/(keV·kg·y), which is the background rate estimated for a similar-volume $Zn^{100}MoO_4$ scintillating bolometer and using the heat channel to perform pulse-shape discrimination [34]. It is clear that with an ordinary light detector the heat signals provide a better discrimination. The situation changes drastically in favour of the use of the light signals if a Neganov–Luke amplifying technology can be implemented.

We remark that, in order to obtain the background rate achievable with our rejection method, we have to insert $T_R \approx 0.17$ ms in Eq. (1). In other terms, the combination of a Neganov–Luke light detector with the mean-time pulse-shape analysis technique allows achieving an effective pulse-pair resolving time of the order of only ∼0.17 ms in large-volume Li_2MoO_4 scintillating bolometers.

5 Conclusions

Background caused by pile-up events in Li_2MoO_4 cryogenic scintillating bolometers, in particular by random coincidences of the two-neutrino 2β events of ^{100}Mo, can be effectively suppressed by pulse-shape discrimination of signals from light detectors based on the Neganov–Luke effect. An advantage of the Neganov–Luke light detectors coupled to Li_2MoO_4 crystal scintillators is a high signal-to-noise ratio, up to a level of 750, as assumed in this paper on the basis of experimental results on prototypes of Neganov–Luke light detectors. The application of the mean-time pulse-shape discrimination reduces the random-coincidence background down to $\sim 5.6 \times 10^{-5}$ counts/(keV·kg·y), with a remarkable pile-up rejection efficiency of 98.3% in a 0–10 ms time interval, which corresponds to the typical resolving time for a light signal. A high signal-to-noise ratio is a crucial characteristic for a cryogenic light detector in order to achieve a high discrimination efficiency of pile-up events, mostly because this increases the accuracy of the pulse-origin determination, on which the efficiency depends substantially.

In a heat-energy window of 5 keV, in agreement with the energy resolution of the bolometric technique, we expect therefore a background contribution from random coincidences of two-neutrino 2β events inferior to 1 counts/(ton·y). As extensively discussed in the context of the CUPID project and in general of next-generation $0\nu2\beta$ decay experiments [17,32,40], the dominant background in ^{100}Mo-based detectors is in fact due to $2\nu2\beta$ decay, with reasonable assumptions on all the other background sources (material radiopurity and gamma, neutron and muon external radiation). Therefore, our work addresses the most critical aspect of the Li_2MoO_4 technology in terms of background and shows that it is compatible with a full exploration of the inverted-hierarchy region of the neutrino mass pattern if implemented in a large-scale next-generation experiment.

We remark that the temperature and the electronic readouts for the Neganov–Luke light detectors here described are identical to those used presently in CUORE, making the present approach particularly attractive for CUPID. We stress also that, in case of an array of hundreds of bolometers as that proposed in CUPID, the voltage to be applied to the light-detector electrodes can be delivered with only a pair of wires from room temperature to the cryogenic experimental space, since the electrode pairs of all the light detectors can be connected in parallel at the array level.

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