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The CUPID neutrinoless double-beta decay experiment

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ABSTRACT

Neutrinoless double-beta decay ($0\nu\beta\beta$) is a key process to address some of the major outstanding issues in particle physics, such as the lepton number conservation and the Majorana nature of the neutrino. The next-generation of experiments aims at covering the Inverted-Ordering region of the neutrino mass spectrum, with sensitivities on the half-lives greater than 10^{27} years. Among the exploited techniques, low-temperature calorimetry has proved to be a very promising one, and will keep its leading role in the future thanks to the CUPID experiment. CUPID will search for the neutrinoless double-beta decay of ^{100}Mo. By deploying Li_2MoO_4 scintillating crystals enriched in ^{100}Mo and cryogenic light detectors, CUPID will perform simultaneous readout of heat and light signals, allowing for particle identification, and thus a powerful rejection technique for α background. To meet the new sensitivity target, the CUORE readout system must be upgraded. The readout system for each channel will consist of a pre-amplifier, a Programmable Gain Amplifier (PGA), a low-pass filter (Bessel filter) and a Digital AcQuisition System (DAQ). Finally, there is a pulser to generate thermal stabilization energy in the crystals. The motivation and expected performance of the technical upgrades are described in the context of the goals of the CUPID experiment.

1. Introduction

The CUPID (CUORE Upgrade with Particle IDentification) experiment will aim to detect neutrinoless double-beta decay ($0\nu\beta\beta$) using a large and modular low-temperature calorimeter consisting of multiple crystals, each containing a nuclide that decays into double-beta ($2\nu\beta\beta$). The energy released by the particles in the crystals can be detected through thermistors.

The $0\nu\beta\beta$ decay is a rare second-order process, theorized to occur if neutrinos are Majorana fermions, meaning that the neutrino and its antiparticle are identical. If detected, the $0\nu\beta\beta$ decay should appear as a peak at the Q-value of the $2\nu\beta\beta$ summed electron energy spectrum ($Q_{\beta\beta}$). In order to detect this rare decay, pile-up and background events must be mitigated. This result will be achieved by employing the very promising bolometric technique embedding a $2\nu\beta\beta$ decay isotope, the ^{100}Mo, and by using background and pile-up rejection techniques.

An important role in the detection of these events is played by the readout system, which must acquire signals for years and be stable to thermal variations. An additional concern is the noise introduced by the electronics, which must be negligible compared to other noise sources in the experimental setup.

The focus of this work is to present both the CUPID experimental setup and all the upgrades that will help detect the $0\nu\beta\beta$ decay, in particular the readout system that acquires and digitizes the thermistor signals.

2. Experimental setup

The experimental setup is very similar to the CUORE experiment, which is still taking data. The CUPID experiment will use the same cryostat developed for CUORE, which is located at the Laboratori Nazionali del Gran Sasso (LNGS), Italy, and is capable of reaching temperatures down to less than 10 mK.

For the CUPID experiment, 1596 scintillating Li_2MoO_4 crystals (LMOs) will be grouped into 57 towers of 14 tiers [1] and enriched in ^{100}Mo, an isotope with a $2\nu\beta\beta$ half-life decay of $T^{1/2} = 7.1 \cdot 10^{18}$ yr and $Q_{\beta\beta} = 3034$ keV.

The impinging particles release energy in the scintillating LMOs leading to phonons vibrations and photons emission. The phonons vibration is translated into an increase in temperature that is read by a Germanium Neutron Transmutation Doped thermistor (Ge-NTD) [2]. On the other hand, the scintillation light is absorbed in a thin bolometric slab of Ge facing the LMO, acting as a light detector, that is also equipped with Ge-NTD for the readout. In total, each LMO will have two light sensors and one heat sensor when stacked in towers, for a total of 1596 heat and 1710 light channels.

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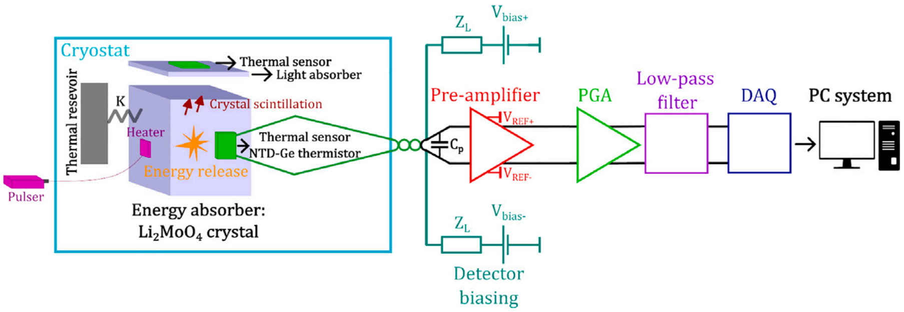

Fig. 1. CUPID readout system.

3. Background and pile-up rejection

Thanks to the promising double-beta decay isotope, the γ events will be automatically suppressed in the Region of Interest (ROI), since the last natural radioactive line has a lower energy than $Q_{\beta\beta}$. The α events will be distinguished from the β events by observing the ratio between the emitted light energy and the emitted heat energy, which is different for α and β events in the ROI, thus allowing α/β discrimination.

Pile-up rejection due to $2\nu\beta\beta$ decays will also be improved by using the light channel. Since light signals have a faster rise time ($\sim$ 1 ms) compared to heat signals ($\sim$ 10 ms), reading the fast light signals will help reduce the $2\nu\beta\beta$ pile-up in the ROI. To further improve pile-up rejection, the light Ge absorber will be equipped with two electrodes that apply an electric field across the slab, applying the so-called "Neganov-Luke" amplification which leads to an increase in signal-to-noise ratio.

With these improvements in pile-up and background suppression, the CUPID experiment will aim to achieve a $\sim 10^{-4}$ counts/(keV kg yr) background level in the ROI [1], which is about two orders of magnitude lower compared to the CUORE experiment. Furthermore, the estimated CUPID sensitivity to the $0\nu\beta\beta$ half-life will be larger than 10^{27} years, which will correspond to an upper limit on the effective neutrino mass of $12-20$ meV.

4. Signal amplification and acquisition

Fig. 1 shows the overall readout system used in the CUPID experiment. The electrical signals come from the various thermistors attached to the crystals and the light absorbers (the Ge slabs) inside the cryostat. Long cables connect the thermistor to the front-end electronics, which will be located outside the cryostat and operate at ambient temperature.

A dedicated detector bias circuit provides current to the thermistor to control its resistance. Load resistors can range from 2 GΩ to 70 GΩ, while the bias can range from 0 V to ±55 V (more choice and greater range if compared to CUORE [3]).

There will also be a high precision, thermally stable (on the order of ppm/°C) pulse generator connected to a heater (a resistor) that produces stabilization energy pulses with a resolution on the order of 20 eV FWHM at 1 MeV.

The electrical signal coming from the thermistor passes through a differential voltage pre-amplifier with a selected pair of Junction Field Effect Transistors (JFETs) at the inputs. The pre-amplifier features ultra-low input white noise JFETs (the CUORE input JFETs are optimized for low parallel noise and have more than twice the input white noise [3]) and a renovated network topology designed around these input devices, achieving an input white noise of $\sim 1.3-1.4\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$ (shown in Fig. 2) and $\lesssim 5\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$ @ 1 Hz. The input JFETs also have fixed voltages and currents at any temperature, resulting in high gain stability. The outputs of the pre-amplifier are connected to a Programmable Gain Amplifier (PGA), which can amplify the signal at four different levels. The PGA outputs are then filtered by a low pass filter, which is a 6-pole programmable (24 Hz to 2.5 kHz) Bessel anti-aliasing filter. The analog signal is then digitized by a Digital AcQuisition System (DAQ), which is based on a Field Programmable Gate Array (FPGA) with System on Chip, has programmable frequency acquisition (up to 24 kHz) and a high-resolution (to minimize signal-to-noise ratio degradation at low amplifier gains) 24-bit ADC for digital conversion. Finally, the digitized signals are sent to a PC system via an optically coupled standard Ethernet interface.

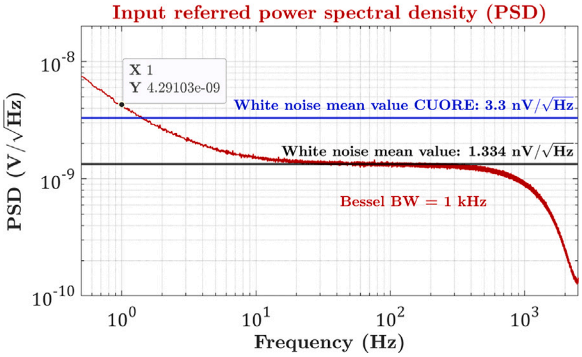

Fig. 2. CUPID pre-amplifier input referred power spectral density (new measurement on a pre-amplifier prototype). In the plot are shown the mean white noise (for both the CUPID and the old CUORE pre-amplifier) and the noise at 1 Hz.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Davide Trotta reports travel was provided by National Institute of Nuclear Physics Milan-Bicocca Branch. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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