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Research paper

An active noise cancellation technique for the CUORE Pulse Tube cryocoolers

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ABSTRACT

The Cryogenic Underground Observatory for Rare Events (CUORE) experiment at Gran Sasso National Laboratory of INFN searches for neutrinoless double beta decay using TeO_2 crystals as cryogenic bolometers. The sensitivity of the measurement heavily depends on the energy resolution of the detector, therefore the success of the experiment stands on the capability to provide an extremely low noise environment. One of the most relevant sources of noise are the mechanical vibrations induced by the five Pulse Tube cryocoolers used on the cryogenic system which houses the detectors. To address this problem, we developed a system to control the relative phases of the pulse tube pressure oscillations, in order to achieve coherent superposition of the mechanical vibrations transmitted to the detectors. In the following, we describe this method and report on the results in applying it to the CUORE system.

1. Introduction

In the last two decades rare event searches have sharply accelerated. The determination of the nature of the neutrino and the search for dark matter are crucial for our understanding of new physics beyond both the well established Standard Model of particle physics [1] and the Lambda Cold Dark Matter cosmological model [2]. Although the experimental techniques substantially differ, these searches share the common need for large mass detectors. Indeed the only way to maximize the probability of detection is to increase the number of source/target nuclei that are under investigation.

Among the available detection techniques, the bolometric approach offers an intrinsically high energy resolution, but suffers from a limited scalability to high masses due to cryogenic constraints. In order to provide the necessary cooling power at millikelvin temperatures for a ton-scale detector, a custom cryogenic apparatus exploiting dilution refrigeration is needed. The dilution process requires a 4 K environment which can be maintained by using either a liquid He (LHe) bath or mechanical cryocoolers, such as Pulse Tubes (PTs) [3]. Although the use LHe has proved to be a limiting factor in the scalability of cryogenic experiments – both in terms of cost and duty cycle – in past years it has been preferred over the cryogen-free approach due to burden of mechanical vibrations caused by cryocoolers.

In the following we describe an innovative technique which has been developed for the CUORE experiment to drastically suppress the noise induced by the PTs. The implementation of this technique will ease the development of large cryogen-free systems for future rare events searches. First, we introduce the CUORE experiment (Section 2) and its PT cryocoolers (Section 3). Next, we illustrate the technique developed (Section 4) and describe the analysis method (Section 5). Finally, we report the results obtained for the CUORE system (Section 6).

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2. The CUORE challenge

CUORE is a ton-scale experiment that searches for neutrinoless double beta decay of ^{130}Te ($0\nu\beta\beta$ [4]). This is accomplished using TeO_2 crystals operating as cryogenic bolometers with a total mass of 742 kg (~ 206 kg of ^{130}Te). The detector consists of 988 crystals arranged into 19 identical structures called "towers". Each tower hosts 52 bolometers arranged in 13 floors.

The CUORE cryostat has been designed to house this ton-scale detector and to maintain it at about 10 mK continuously for 5–10 years. To face this unprecedented challenge, a large custom cryogen-free cryostat has been designed [5]. Five PT cryocoolers cool down to 35 K and 3.5 K respectively 980 kg and 7400 kg of material, mainly copper plates and vessels and ^{210}Pb-depleted archaeological lead shielding [6]. A high-power (3 μW at 12 mK) ^{3}He/^{4}He Dilution Unit (DU) then provides cooling power to cool to around 10 mK the 1519 kg of the detector structure with its shielding vessel - mostly copper and TeO_2 crystals.

In order to minimize the detector noise, the entire experimental volume – about one cubic meter – must be kept in optimal and stable experimental conditions, which means in an exceptionally low radioactive background and a low mechanical vibration environment. To address the former requirement, all the materials used in CUORE meet strict radio-purity criteria and underwent different types of cleaning procedures ([7] and references therein). To cope with the latter requirement, a special suspension has been designed to mechanically decouple the detector structure from the rest of the cryostat. The suspension insulator has been custom designed from Minus-K technology and acts as a mechanical low pass filter for vibrations, with a cut-off frequency of about 0.5 Hz in both the vertical and horizontal directions [9]. Moreover, the whole CUORE infrastructure itself has been designed to be isolated from external sources of vibrations by means of four elastomeric dampers.

3. The CUORE PTs

A Pulse Tube is a cryocooler whose cooling power is provided by means of ^{4}He gas isoenthalpic expansions. The cooling effect relies on a periodic variation of the pressure inside one or more thin-walled tubes – the actual "Pulse Tubes" – containing a large heat capacity regenerator and with heat exchangers at both ends [10].

The pressure cycles are provided by a rotary valve inside the PT motor-head at room temperature. This valve makes 0.7 revolutions per second and alternatively connects the PT to the high-pressure and low-pressure side of a compressor. This results in pressure waves with a frequency that depends on the PT model and which is 1.4 Hz for the CUORE PTs.

In cryogenic systems such as the ones used for rare event searches, PT cooling is becoming more popular compared to LHe bath – even with the support of systems to reduce boil-off or for in situ reliquefaction – for several reasons, which include cost, reliability, stability, duty cycle, and safety.

The downside of mechanical cryocoolers is normally the production of mechanical vibration inside the experimental apparatus. With PTs the absence of moving parts at low temperature increases the reliability and strongly reduces the magnetic interference and the intensity of vibrations generated during operation with respect to other cryocoolers, such as piston-based Gifford-McMahon heads. Small residual mechanical vibrations still occur in a PT due to the elastic deformation caused by pressure oscillations in the He gas inside them.

All these features make the PTs suitable for cooling sensitive devices like the low temperature detectors used for CUORE, but care must be taken to minimize the impact of their residual mechanical vibrations.

The large number of PTs installed in CUORE cryogenic system is determined by the significant heat load in this large system which derives from thermal radiation, conduction along mechanical supports, nearly 3000 electrical wires, and ^{3}He circulation for the dilution unit.

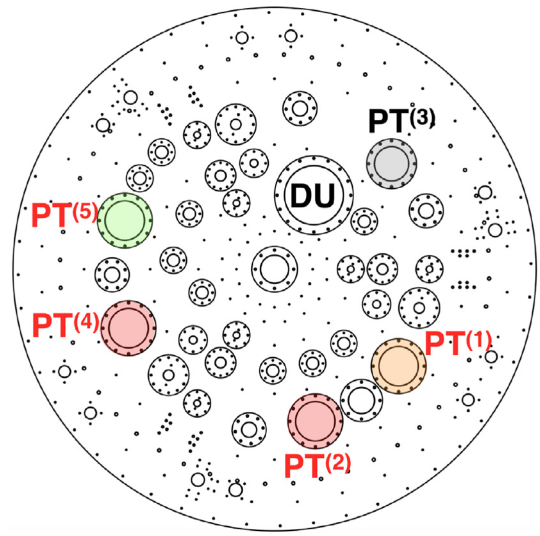

Fig. 1. Top view of the 300 K plate of the CUORE cryostat. The positions of the five PTs and of the Dilution Unit (DU) are highlighted. $PT^{(3)}$ is not powered during data taking. Colors refer to optimal phase configuration commented in Section 6: $PT^{(4)}$ and $PT^{(2)}$ are in phase opposition (red) with respect to the reference $PT^{(5)}$ (green), while $PT^{(1)}$ is in quadrature (orange) with respect to $PT^{(2)}$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

To provide the needed cooling power in all foreseeable running conditions – with a safe margin – CUORE mounts five PT415-RM by Cryomech [11]. For CUORE, the Remote Motor option flexline is longer than the standard RM product offered by Cryomech (2 ft long instead of 1 ft). This solution offers a more efficient mechanical decoupling at the cost of a ~10% reduction in the cooling power with respect to the standard PT415-RM model. With this feature, the nominal cooling power of each PT is 1.2 W at 4.2 K and 32 W at 45 K each, while the lowest temperature achievable is close to 3 K with no thermal load [12]. With these performances, the cooling power provided by no more than 4 PTs is sufficient to operate the CUORE dilution unit with the maximum cooling power. The fifth PT is therefore kept as a spare. The CUORE PTs are arranged (see Fig. 1) on a circumference with a radius of ~2/3 of the top cryostat plate (300 K plate) in a non symmetric way. $PT^{(1)}$ and $PT^{(5)}$ are the most critical as the DU condensing lines (which carries the ^{3}He/^{4}He gas from room temperature to the DU) are thermalized on them. When running the cryostat with only four PTs, any other of the three PTs can be switched off. We keep $PT^{(4)}$ and $PT^{(2)}$ active for this analysis.

3.1. Vibration noise

The effect of mechanical vibration on the CUORE detectors is twofold: electrical and thermal. The coupling of vibrations to the signal wires, which run from the detectors to the room temperature connectors, causes noise due to parasitic capacitance (~500 pF/m) combined with the high impedance of the detector thermal sensors (order 200 MΩ). Despite a differential read-out scheme [13], these cause an electrical microphonic noise pickup which can diminish the S/N of the detectors.

Mechanical vibration transmitted by the PT head to the 300 K flange and from the two cold stages of the PT to the 40 K and 4 K flanges, can propagate to the coldest parts of the system generating an excess heat load. The most affected parts are the DU stage with the lowest cooling power, i.e. the Mixing Chamber, and the weakly thermally coupled TeO_2 crystals.