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Concept of metallic magnetic calorimeters for rare event search in the LUMINEU project

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Abstract The project LUMINEU is mainly aiming at the search for neutrinoless double-beta decay of the candidate nuclide ^{100}Mo using cryogenic ZnMoO_4 detectors with simultaneous heat and scintillation light detection for radioactive background rejection. It also includes some development for dark matter search using cryogenic Ge detectors with simultaneous heat and ionization detection for background rejection. For both cases, metallic magnetic calorimeters (MMCs) are studied among several thermometer types. In double-beta decay search, the intrinsically fast response of MMCs reading out the light detector may allow for a very fast signal rise time and help to reduce the potential background due to pile-up of two-neutrino double beta decay events. In dark matter search, MMCs reading out the heat channel may improve the energy resolution with respect to the standard NTD Ge thermistor readout and hence the sensitivity of the detectors for low-mass WIMPs.

Keywords Metallic magnetic calorimeters, Double beta decay, Dark matter

1 Introduction

The main objective of the LUMINEU project is the development of cryogenic detectors for the search of neutrinoless double-beta decay ($0\nu 2\beta$) presenting almost no radioactive background. This may be achieved by the choice of the $0\nu 2\beta$ candidate nuclide as well as by background rejection techniques. The Q value of

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the double-beta decay of ^{100}Mo , $E_0\nu\beta\beta = 3034$ keV, lies beyond the energies of almost all naturally occurring γ -rays, in particular of the 2.615 MeV line of ^{208}Tl . Therefore, at the double-beta decay energy the γ -ray background is virtually zero. The remaining background is essentially due to energy-degraded α particles and can be very efficiently rejected in cryogenic heat-and-light detectors: the heat produced in a scintillating ZnMoO_4 crystal containing the $0\nu 2\beta$ nuclide is read out by a sensitive thermometer, and the small fraction ($\sim 10^{-3}$) of energy converted to scintillation light is detected with a separate calorimetric light detector. The light output for α particles is sensibly different from that for β/γ rays, and the heat-to-light ratio permits efficient rejection of the α background. This background rejection technique has already successfully been tested¹ and applied².

The LUMINEU project also comprises developments for the direct search for dark matter in the form of WIMPs (Weakly Interacting Massive Particles). Cryogenic germanium heat-and-ionization detectors offer the possibility to discriminate between nuclear recoils, induced by WIMP or neutron interactions, and electron recoils, representative of most radioactive background. The sensitivity of this class of detectors to low mass WIMPs is closely linked to the energy threshold and energy resolution.

For both double-beta decay and dark matter search different types of thermometers are being developed and tested, expecting that the detector performance can be improved with respect to the standard NTD Ge thermistor readout.

2 MMCs for the light channel in neutrinoless double-beta decay search

The detector modules developed in the frame of the LUMINEU project will consist of ~ 400 g ZnMoO_4 crystals enriched in ^{100}Mo , coupled to one or two cryogenic calorimetric light detectors, the whole enclosed in a reflective cavity. The readout of the scintillating main calorimeter will be done using NTD Ge thermistors. This is a robust, well established technique for the readout of large mass calorimeters and the energy resolution can be excellent^{3,4}.

The light detectors will be made of 50 mm diameter germanium wafers as light absorbers. In a baseline version of these detectors, the temperature rise upon light absorption will be measured by an NTD Ge thermistor. The energy resolution and threshold demonstrated with such devices (40 eV respectively 100 eV for 40 mm diameter) are largely sufficient to detect the light produced in 3 MeV double-beta decay or alpha events.

In this scenario, zero alpha and gamma background in a ton scale experiment for a several years exposure is possible. However, a non-zero background may arise from the pile-up of two-neutrino double-beta decay ($2\nu 2\beta$) events. In this regard, the relatively short $2\nu 2\beta$ half-life of ^{100}Mo ($T_{1/2}^{2\nu} = 7.1 \times 10^{18}$ y) is rather a disadvantage. The rate of unresolved pile-up events can be estimated to $\sim 2.7 \times 10^{-4} [T_R / 1 \text{ ms}] \text{ counts} / (\text{keV} \cdot \text{kg} \cdot \text{y})^5$. This means that the pulse pair resolving time T_R , or the detector signal rise time τ_r , must be minimized in order not to be limited by this background contribution.

Metallic magnetic calorimeters (MMCs) appear to be an excellent solution to achieve this since their intrinsic response is very fast: the response time is given by the electron-spin coupling, which is, for the widely used Au:Er as MMC material,

faster than a microsecond even at low mK temperatures⁶. If the response of the thermometer is fast, the signal rise time of the complete light detector is governed by several energy transport and transfer mechanisms.

The scintillation light absorbed by the Ge wafer produces a roughly homogeneously distributed population of non-thermal phonons (except close to the threshold, where only few photons may be absorbed). These phonons will down-convert in energy and quickly acquire a mean free path larger than the wafer thickness. In the following they will scatter off the wafer surfaces and propagate via quasi-two dimensional diffusion with a mean free path close to $\sqrt{3}$ times the wafer thickness. Eventually the phonons will thermalize, unless they are trapped into some structures on the wafer surface. Coupling of the phonons to the MMC can be accomplished in different ways.

(1) A chip with an MMC and planar magnetization/readout coil is glued to the wafer surface. This will result in thermalization of most of the non-thermal phonons in the wafer (mainly inelastic scattering at the wafer surface) or in the glue. The time constant will be comparable with a wafer read out by an NTD of comparable contact area. The advantage of the fast MMC response cannot be exploited.

(2) A thin metal film on the wafer surface absorbs non-thermal phonons by electron-phonon coupling, which is very efficient for longitudinal non-thermal phonons (and much less efficient for transverse phonons most of which are transmitted back to the wafer)⁷. The phonon energy is very quickly thermalized in the conduction electron system. This film is coupled to an MMC via gold bonding wires. The phonon collection time and the closely related fraction of phonons that can be collected before they thermalize in the wafer depend on the film surface. A compromise must be made between a large area film providing fast collection time and signal rise, and a small area film having a small heat capacity and enhancing the signal size. An additional contribution to the rise time will be induced by the thermal impedance of the bonding wires.

(3) The thin film MMC and planar magnetization/readout coil are patterned directly on the wafer surface. The remarks concerning the collecting area in (2) apply also in this configuration. Since the specific heat of Au:Er is one to two orders of magnitude higher than the specific heat of gold or similar metals, a small area MMC should be connected to a larger area phonon collector film made e. g. of gold. The rise time contribution of the gold bonding wires in (2) is not present in this configuration, but an additional time constant arises from the electron-electron diffusion in the collection film.

Configuration (3) seems to have some advantages (see below) over (2) and will be studied in the LUMINEU project. A disadvantage is that each light detector wafer has to undergo the full 8-layer process of the actual MMC fabrication at KIP.

Rough estimates of two major contributions to the signal rise time give the following figures:

(a) Non-thermal phonon diffusion in the wafer: The diffusion time over a length L is given by $t_{diff} \approx L^2/D$, with the diffusion constant $D = l_{ph}v_s/3$ depending on the phonon mean free path l_{ph} and the speed of sound v_s . Minimizing t_{diff} implies a rather thick wafer and hence large phonon mean free path. With a wafer thickness of 0.5 mm, $l_{ph} \approx 0.9$ mm, and $v_s = 5400$ m/s in germanium,

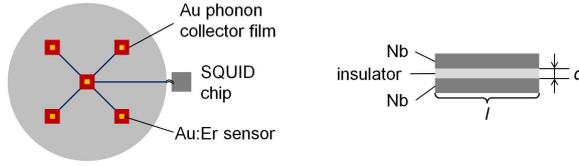


Fig. 1 (Color online) Left: Basic design of a LUMINEU light detector with several small area MMCs and planar readout coils connected in series and additional phonon collector films. Right: Low inductance niobium-insulator-niobium strip line.

$t_{diff,ph} \approx 80 \mu\text{s}$ for $L = 1 \text{ cm}$ and $t_{diff,ph} \approx 500 \mu\text{s}$ for $L = 2.5 \text{ cm}$ (corresponding to a small collecting area in the center of a 5 cm diameter wafer).

(b) Electron-electron diffusion in the collector film: the parameters determining the diffusion constant are the electron mean free path l_e and the Fermi velocity $v_F \approx 1.4 \times 10^6 \text{ m/s}$. For a gold collector film of reasonable quality ($l_e \approx 100 \text{ nm}$), one can expect $t_{diff,e} \approx 80 \mu\text{s}$ for $L = 2 \text{ mm}$ and $t_{diff,e} \approx 500 \mu\text{s}$ for $L = 5 \text{ mm}$.

From these numbers, one can estimate a rise time $\tau_r \approx 1 \text{ ms}$ for a 1 cm diameter gold collector film in the center of a 5 cm diameter wafer. This is not much faster than achievable with an NTD Ge thermistor in the center of the wafer (1 - 2 ms). A great advantage of configuration (3) is however that the MMC with its collector film can be split up to several smaller sensors, each with a collector film, and distributed over the wafer surface at roughly equidistant locations, like in the sketch in fig. 1 (left panel). For this configuration both phonon and electron diffusion lengths are divided by roughly a factor two and $\tau_r \approx 0.2 \text{ ms}$. This would reduce the $2\nu 2\beta$ pile-up rate from several $10^{-4} \text{ counts / (keV}\cdot\text{kg}\cdot\text{y)}$ to $\sim 0.5 \times 10^{-4} \text{ counts / (keV}\cdot\text{kg}\cdot\text{y)}$.

In reality, within these estimated rise times, only a fraction of the non-thermal phonons will be collected, depending on the collector film area. But the non-thermal phonon collection should at least result in a leading edge at the pulse onset that should be sufficient for pulse pair separation. For sizing the MMC and collector films relative to each other, equality of their heat capacities should be respected in order to maximize the signal-to-noise ratio⁶. For absolute sizing two extremes may be considered.

In the lower limit, their combined heat capacity would match the wafer heat capacity; in the upper limit, favouring fast phonon collection, the heat capacity corresponds to a threshold just low enough for the searched-for events being safely detected. The lower limit, with a wafer heat capacity (diameter 50 mm, thickness 0.5 mm) of 22 pJ/K at 20 mK, corresponds roughly to a Au:Er MMC size $\sim (0.5 \text{ mm})^2$, 2 μm thick, plus a gold collector film size $\sim (1.5 \text{ mm})^2$, 250 nm thick. This covers a very small fraction of the wafer and correspondingly only a small fraction of non-thermal phonons will be collected before their thermalization. The energy resolution and threshold in this configuration should be at least as good as with NTD Ge thermistor readout (few tens of eV energy resolution, threshold of order 100 eV).

For the upper limit, we will assume that $\sim 10^{-3}$ of the double beta decay energy, i. e. 3 keV, can be collected in the light detector. For a safe alpha background suppression also the light energy released in 3 MeV α particle interactions must be sufficiently above the threshold. For ZnMoO_4 the quenching factor for α par-

icles is ~ 0.3 , i. e. ~ 1 keV can be collected in the light detector. A threshold not much higher than 300 eV should be envisaged. This would correspond roughly to a Au:Er MMC size $\sim (2.5 \text{ mm})^2$, $3.5 \mu\text{m}$ thick, plus a gold collector film size $\sim (20 \text{ mm})^2$, 250 nm thick. Split into e. g. five subsensors as shown in fig. 1, each sub-MMC is $\sim (1.1 \text{ mm})^2$ in area and each sub-collector film $\sim (9 \text{ mm})^2$. With such a large collector film area a large fraction of non-thermal phonons will be collected before their thermalization. The energy resolution of such a device would still be below 100 eV.

Between these two extremes, experiments must show how close these values are to reality. The pulse pair resolving time depends on the shape of the pulse rise, which in turn depends on the efficiency of the non-thermal phonon collection. The phonon collection efficiency is determined by the Kapitza resistance between the wafer and the gold film and by the electron-phonon coupling strength for longitudinal and transverse phonons, respectively, which can be estimated only coarsely. We also did not take into account the loss of signal in the strip lines and bonding wires connecting the planar readout coil to the SQUID. In particular in the split sensor design, a total of ~ 8 cm strip lines must be considered. If the strip lines are configured as a Nb-insulator-Nb sandwich, as sketched in fig. 1 (right panel), the inductance per unit length can be estimated as $L/l = \mu_0 d/w$. For a line width of $w = 10 \mu\text{m}$ and an insulator thickness of $d = 0.2 \text{ nm}$ this corresponds to an inductance of $\sim 1.6 \text{ nH}$. In the lower limit of the MMC size, this would lead to a loss of nearly half of the signal, in the upper limit to less than 10 %.

It is worthwhile noting that MMCs may have another advantage over NTD Ge thermistors as thermometers of light detectors. MMCs combined with SQUID readout are much less sensitive to microphonics than NTD Ge thermistors with JFET based amplifiers. In particular the light detectors whose energy sensitivity is pushed to the maximum are very sensitive to microphonic noise.

3 MMCs for the heat channel of dark matter detectors

Cryogenic germanium heat-and-ionization detectors are presently among the most sensitive devices for the potential detection of dark matter WIMPs. Such detectors are being operated in the CDMS experiment, using a sophisticated arrangement of thin film structures serving at the same time as TES (Transition Edge Sensor) phonon sensors and as charge collection electrodes, and in the Edelweiss experiment, combining NTD Ge thermistors for the heat channel readout and interleaved charge collection electrodes. The respective heat channel energy resolutions at low energy are about 400 eV for 600 g CDMS detectors and 900 eV for 800 g Edelweiss detectors. The energy resolution (in both channels) determines the threshold for efficient background rejection and hence the sensitivity of the experiment for low-mass WIMPs.

Exploring the potential of MMCs for the readout of the heat channel of germanium heat-and-ionization detectors is an attempt to improve the energy resolution with respect to NTD Ge thermistor readout. The intrinsic quality of MMCs in combination with dielectric absorbers in this regard is difficult to predict quantitatively and must be found out experimentally. A clear advantage of MMCs is, like in the case of light detectors, their much smaller sensitivity to microphonics; the

energy resolution of large mass cryogenic detectors with NTD Ge thermistors can be strongly degraded by microphonic noise.

The requirements in terms of detector performance in dark matter search are not the same as in double beta decay search. The importance of the energy resolution for dark matter search has been explained above; but there is no need for a very fast signal rise time in the heat channel. If a precise timing of particle interactions is required, e. g. for the identification of coincident events in several detectors, this can be achieved via the ionization channel which has anyway a much faster rise time than the heat channel, irrespective of the thermometer type.

So there is no need, in terms of signal rise time, to process the MMC and readout coil thin films directly on the crystal surface. Anyway it is preferable to avoid repeated heating of the germanium crystals, which would be required in the corresponding photolithography processes. This leaves two ways to measure the temperature rise upon a particle interaction by an MMC, corresponding to the first two configurations described in section 2.

(1) A chip with an MMC and planar magnetization/readout coil is glued to the crystal surface. The actual Edelweiss detectors are read out by two NTD Ge thermistors glued in the centers of the two flat crystal faces. In their place, two MMC chips could be glued.

(2) A thin metal film on the crystal surface absorbs non-thermal phonons by electron-phonon coupling. This film is coupled to an MMC via gold bonding wires.

Both configurations will be tested in preliminary experiments with small germanium crystals. Since there is no stringent constraint on rise time, the best MMC size is probably given by an MMC heat capacity equalling the germanium crystal heat capacity. To take as an example the Edelweiss detectors, 800 g Ge at 20 mK correspond to 3.3×10^{-9} J/K. If two MMCs are to be used, each of them should have a heat capacity of 1.7×10^{-9} J/K at 20 mK.

In detectors with instantaneous energy thermalization in the absorber and perfect absorber-sensor coupling an energy resolution of ~ 70 eV for an individual MMC of this heat capacity and ~ 100 eV for the two MMCs could be expected. This situation may be approached in detectors with small metallic absorbers having a strong thermal contact with the MMC, but certainly not with large dielectric absorbers. The real energy resolution depends on many parameters that must be assessed experimentally.

4 Conclusions

Metallic magnetic calorimeters may improve the performance of cryogenic detectors for both neutrinoless double beta decay search and dark matter search with respect to NTD Ge thermistor readout. In double beta decay search their use for the readout of light detectors in heat-and-light detector modules may reduce the potential background due to pile-up of two-neutrino double beta decay events. The best option in this regard is the fabrication of the MMC and readout coil thin films directly on the light absorbing Ge wafer. In dark matter search the energy resolution of the heat channel of Ge heat-and-ionization detectors may be improved. Gluing of an MMC chip on the Ge crystal as well as the use of a gold phonon collector film coupled to a remote MMC chip will be tested in small test devices

and the better option will be adopted for further development. If the energy resolution can indeed be improved, MMCs may be considered as well for the readout of the heat channel of the heat-and-light detectors. Such detectors are also being employed for dark matter search, and they might benefit from this option as well.

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