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CRYOGENIC DETECTORS: STATUS AND PROSPECTS

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Abstract: The present status of cryogenic detector developments for particle physics is discussed, with emphasis on applications at the cross-disciplinary frontier between particle physics and astrophysics, where low temperature devices appear to be particularly well suited. The critical overview of to-date results is completed by a sketch of new ideas and possible ways for further improvements.

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1. INTRODUCTION

Small cryogenic detectors have already been used in astrophysics, a well-known application being the study of possible anisotropies of microwave background radiation [1]. Particle physics applications [2, 3] require: a) sensitivity to individual particles; b) comparatively large devices. Recent developments are essentially motivated by low energy neutrino physics and dark matter detection. The search for magnetic monopoles with induction loops is by now a running program [4], and a beautiful search for cosmic axions using low temperature copper cavities is being performed at BNL [5, 6]. We present here current work, focusing mainly on applications to: neutrino mass measurements (based on high precision study of weak decay endpoints), low energy solar neutrino detection (based on nucleus recoil [7] or ^{115}In inverse β reaction [8]), next-generation reactor experiments, the study of rare decays such as neutrinoless double β, and the search for galactic WIMP (weakly interacting massive particles, that may provide the Universe missing mass [6]).

The use of low temperature devices is expected to bring higher sensitivity and energy resolution, due to: a) the lower energy of elementary excitations (phonons, charge carriers, spin excitations...); b) the fast decrease of specific heats for dielectric crystals and superconductors; c) lower thermal noise for both detector and electronics. In addition, some low temperature effects provide specific signals (e.g. change in magnetization) or amplification effects (e.g. metastable phase transition in superconductors, latent heat release or quasi-particle multiplication). The wide variety of superconducting materials and crystal heat absorbers makes low temperature techniques attractive when active targets are needed.

Low temperature detectors are still at the stage of feasibility studies, but have already provided encouraging results. Further development effort is needed to promote these techniques to the level of real detectors.

2. CRYSTAL CALORIMETERS (BOLOMETERS)

The specific heat of an insulating crystal at low temperature is dominated by lattice vibrations. An energy deposition E converted into heat will lead to an increase in temperature that can be detected with a resistive thermometer (thermistor). In the ideal no read-out noise case, energy resolution is given by phonon thermal fluctuations [9]:

$$\Delta E_{rms} \simeq \zeta\,(C/k)^{1/2}\,kT \propto T^{5/2}M^{1/2} \qquad \{1\}$$

where C is the heat capacity, k the Boltzmann constant and M the mass of the crystal. The heat capacity of the thermistor has been neglected, which may not be correct for small bolometers. The coefficient ζ depends on the details of detector architecture, but is often estimated to be in the range 1.5-2. In such a scenario, a sizeable increase in detector mass can be compensated by a moderate decrease in temperature.

The measurement of the ν_e mass from the ^3H Kurie plot can be made with detectors smaller than 1 mm^3. Energy resolution of 10 eV FWHM or less on 18.6 keV electrons is needed for such purposes. A diamond bolometer (0.25 mm^3) at 1.3 K reached FWHM energy resolution of 36 keV on 5.5 MeV α particles [11], and at 100 mK a composite Si micro-calorimeter brought 17 eV FWHM resolution on 6 keV γ's [12]. Such results are obviously encouraging.

More recently, the study of large bolometers has also been undertaken. Using a 0.7 g germanium absorber at 44 mK, the Milano group [13] obtained 1% energy resolution on α particles from a ^{228}Ra source in radioactive equilibrium with its daughters. Furthermore, a previous high flux irradiation allowed to implant daughter nuclei in the crystal producing satellite peaks shifted upwards by 100 keV (Fig. 1a). As the implanted nuclei decayed, the satellite peaks disappeared and only single peaks from external α's remained (Fig. 1b). The authors conclude that the bolometer was sensitive to nucleus recoil, as expected from the 50 keV energy resolution. Similar evidence had been previously reported from work with small bolometers [14].

A new idea is the so-called "magnetic bolometer" [10]. Half of the deposited heat is converted into very low energy spin excitations (~ 10^{-6} eV) and a small change in the magnetization of the crystal can be detected by a SQUID read-out. The authors report 30 keV energy resolution at 400 mK with 5.5 MeV α's on a 7.35 g sapphire absorber with a 135 mg YAG:Eb^{3+} magnetic bolometer implanted on the sapphire.

In some applications, time resolution may be important for event identification and background rejection. Large bolometers are not fast detectors. The Milano bolometer gives rise times of the order of 200 μs and the one from [10] exhibits a 200 ms rise time. Perhaps bolometry should in some cases be combined with other detection techniques (luminescence?) in order to produce a primary fast signal as timing strobe. If light is used as a complementary signature, particle identification can be achieved through the heat-light ratio, where nucleus recoil is expected to be less luminescent than ionizing particles. The success of such a development would open the way to unprecedented achievements in background rejection for rare event experiments.

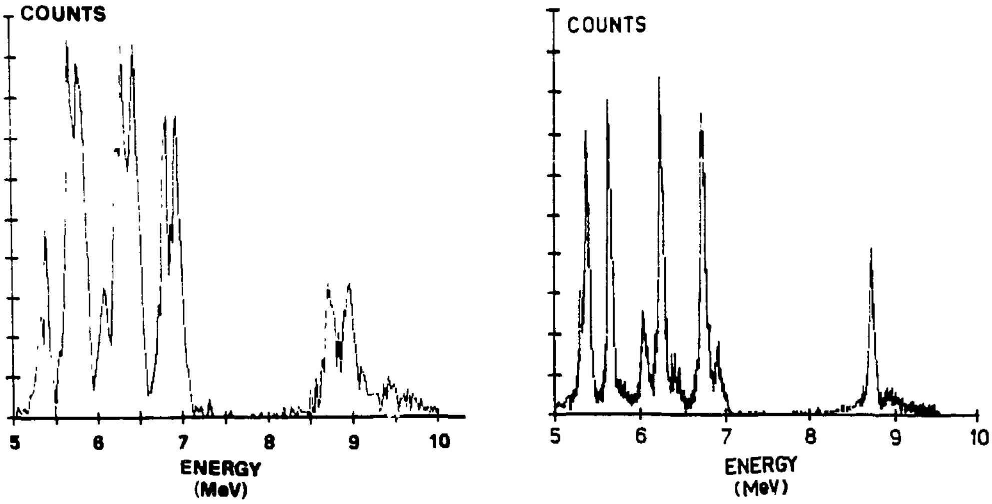

Fig.1: Energy spectra of the Milano bolometer [13] irradiated with a ^{228} Ra source. a) left: with daughter nuclei implanted in the crystal; b) right: two weeks later, after the implanted nuclei decayed.

To date, the main motivation for the development of large bolometers (100 g-1 Kg) lies in neutrinoless double β decays [15], where energy resolution is crucial for background rejection, and dark matter searches through nucleus recoil [16], where sensitivity to energy deposition below 1 keV is required. More difficult, because of background, would be a solar neutrino experiment based on ν-e^- scattering using several tons of bolometric detector [17]. Applications at reactors face similar problems.

3. SUPERCONDUCTING TUNNELING JUNCTIONS (STJ)

Superconductors provide the unique possibility of producing diodes with about 10^{-3} eV current carrier excitation energy. Then, a statistical $N^{1/2}$ law (Poisson distribution) for energy resolution leads again to exceptional performances for the detection of low energy particles. In a STJ with a small bias voltage, quasiparticles and holes tunnel across a thin insulating layer separating two superconducting samples, and the current can be read with conventional low noise pre-amplifiers. Usually, STJ are made of two metallic films separated by the insulating layer, and are not expected to be massive detectors. However, new ideas have recently emerged (e.g. quasiparticle trapping, which also provides multiplication [18]) to incorporate bulk superconducting specimens.

The bias voltage creates a thermal current $I_{th} \propto \exp(-\Delta/kT)$ that can be lowered by working at low reduced temperature ($t = T/T_c$). In order to prevent Cooper pair tunneling (DC-Josephson current), a magnetic field parallel to the oxide barrier is applied. An incoming particle will excite mainly electrons of energy much larger than the gap Δ, but these electrons will later relax emitting phonons. At $t \ll 1$, phonons mainly excite quasiparticles, which can then tunnel across the junction or recombine.

The expected energy resolution in a STJ is:

$$\Delta E_{rms} \simeq (f\ E\ \epsilon)^{1/2} \qquad \{2\}$$

where f is the Fano anti-correlation factor ($0.1 < f < 1$) and ε the effective quasiparticle excitation energy ($\varepsilon > \Delta$). Potentially, a Sn-SnO-Sn detector with $f \simeq 1$ and $\varepsilon \simeq \Delta \simeq 0.6$ meV, should reach 0.1% energy resolution on 6 keV γ's. Experimental results are not that good, but the SIN group claims [19] 48 eV FWHM resolution on the 5.89 keV ^{55}Mn K_α peak, whereas the Garching (TMU) group [20] reports 88 eV resolution, determined from the energy difference between the K_β (6.49 keV) and K_α peaks. A typical signal rise time from existing STJ is of the order of 15 μs.

Apart from the detection of low energy γ rays, a possible use of small STJ would be neutrino mass measurements [21], but if larger devices can be made, they could be used [18] to detect low energy solar neutrinos through the ^{115}In Raghavan's reaction [8]. A ^{115}In detector may also be used for $\bar{\nu} \rightarrow \nu$ oscillation experiments at reactors.

STJ provide an interesting read-out for crystal phonon detectors, where ballistic phonons would be converted into quasiparticles. Since ballistic phonons propagate along the main crystallographic axis, it should be possible to extract information on the position of the event inside the crystal [17, 22]. This possibility has been recently demonstrated by the Garching (TMU) group [22] using three aluminum STJ implanted on one of the faces of a Si wafer, and deplacing the external α source on the other side of the crystal. Position information is seen to emerge from correlations between the signals observed at two different junctions. A parallel effort along similar lines is being pursued by the Stanford group [17].

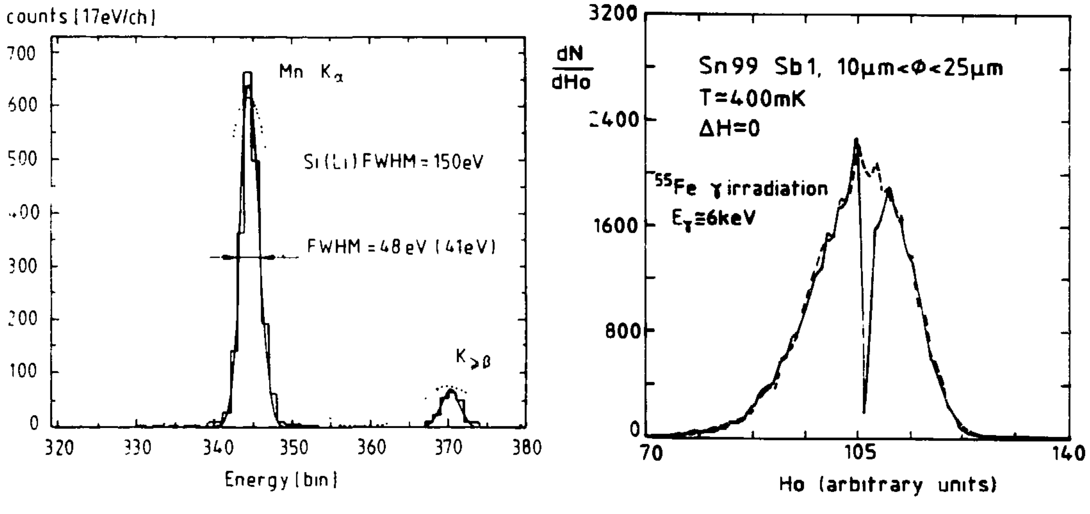

Fig.2: Recent results from superconducting detectors. a) left: energy spectra (full line) of $E \simeq 6$ keV X rays obtained at SIN [19] with a Sn STJ at 400 mK, as compared to the best performance of Si:Li detectors at LN_2 temperatures (dotted line); b) right: sensitivity test of a Sn SSG sample at 400 mK. The granules missing in the irradiated differential superheating curve (full line), as compared to the non-irradiated one (dashed line),are those having changed state during the irradiation period [23].

4. SUPERHEATED SUPERCONDUCTING GRANULES (SSG)

A type 1 superconductor with low enough κ (the Ginzburg-Landau parameter) can exhibit metastable states, due to the positive normal-superconducting interface energy. In particular, a superconducting sample may remain in this state for values of the external magnetic field larger than the critical field H_c (superheating). The superheated state and has been obtained for pure metal microspheres of 1-400 μm diameter. It was proposed long ago [24] to use SSG as a particle detector in the form of a suspension of small microspheres into some dielectric material, with a read-out of current loops oriented in the plane normal to the applied magnetic field $\vec{H}_0$. The energy released by an incident particle would originate a fast transition of one or several granules, detectable through the disappearance of the Meissner effect. Recently, progress has been made in the SSG real time read-out [25] and granules of sizes 10-400 μm have been shown to be sensitive to low energy sources down to 6 keV γ's [26]. The observed sensitivity can be theoretically understood and, when extrapolated to very small grains, gives encouraging figures: 1 μm diameter In grains at T = 200 mK would be sensitive to about 300 eV with 80% efficiency, whereas Ga grains cooled to 100 mK would achieve a similar performance for 4 eV energy deposition. Unfortunately, for realistic detection purposes, the above result is not by itself sufficient. Two examples:

1) It has been proposed [27] to use indium SSG as a detector for low energy solar neutrinos, exploiting the SSG potentiality in segmentation (crucial for background rejection). A X-Y current loop read-out would allow to segment a 4 ton indium detector into 10^7 elementary cells, with only 10^5 electronic channels. However, such an instrumentation would require 5 mm × 1 m current loops, which makes extremely difficult to detect the signal produced by 116 keV secondaries.

2) Dark matter searches through nucleus recoil encounter an even more severe difficulty, since only single grain flips are usually expected. We therefore have only a threshold detector, without any energy resolution.

To cure both diseases, we have proposed a new operating principle, based on the concept of "amplification by thermal micro-avalanche" [28]. Metastability allows for a positive latent heat in the superconducting to normal phase transition. Then, the flip of a single granule can release heat which, together with the deposited energy, will be dispersed in the detector. If heat exchanges through the dielectric material are efficient enough (low Kapitza resistances), new flips will be produced which in turn will release more latent heat. In such a scenario, with sufficiently small grains (1 μm in diameter), a signal in magnetic flux $\Delta\Phi \propto E$ is expected even for a nucleus recoil. The appearance of extra flips will lead to an amplification effect (one or two orders of magnitude), which may solve the basic problems for a ^{115}In experiment. Time resolution is expected to be in the range 10-100 ns. Other uses would then be possible: double beta decays [29], X-ray imaging [30], dark matter searches through inelastic scattering with a ^{119}Sn target [28]. Furthermore, the dielectric material can provide an active target (hydrogen for dark matter searches [28])... However, if experimental evidence for global avalanches already exists [31], further work is required to evaluate the real performance of the micro-avalanche effect. Another crucial problem is large scale production of very small grains. ϕ_{mean} (average size) $\simeq$ 25 μm tin granules are produced [32] at a rate of 5Kg/hour using a 40 KHz ultrasonic atomizer. A new development is underway in order to adapt the existing procedure to higher ultrasonic frequencies, up to 5 MHz according to the law [33]: $\phi_{mean} \propto f^{-2/3}$ (f = frequency).

An independent application, using large grains, would be the detection of magnetic monopoles [34], where the flux tube injected by the monopole would destroy the superconductivity of many granules. The advantage of SSG would be a comfortable signal (several orders of magnitude larger than in induction experiments), a good background rejection due to the large grain size, and a measurement of speed and direction.

5. OTHER DETECTORS

Energy deposited in superfluid ^{4}He at low temperature (100 mK) would create rotons (Δ/k = 8.65 K). A 200 keV electron from neutrino scattering is expected to originate $\approx 10^8$ elementary excitations, which will propagate ballistically in all directions. Some will hit the surface of the liquid and evaporate a sizeable number of helium atoms, that may be detected by bolometric techniques [35]. No experimental result exists yet on this technique, but a development is being carried on at Brown University. Even more ambitious is a proposal from the Lancaster group [36], where superfluid ^{3}He (cooled below 1 mK) would produce $\approx 10^7$ quasiparticles per deposited eV. Unfortunately, such quasiparticles are neutral and their detection far from obvious.

Several ideas on the possible use of devices operating below 1 mK have been put forward by T.O. Niinikoski [37], who was able to obtain bounds on dark matter from measured heat leaks in Cu adiabatic nuclear demagnetization refrigerators. On the other hand, high T_c superconductors already provide interesting devices, such as DC SQUIDs made of YBaCuO ceramics [38]. More classical techniques, such as semiconductors (InSb, doped Ge,...) operating at 4 K [39], or low temperature scintillators [40], may also play a significant role in the next generation of particle detectors.

If cryogenics can be successfully incorporated in the vertex of a high energy experiment, superconductive devices present potentially the advantage of an excellent radiation hardness, due to the stability of superconducting parameters with respect to defects that can lower the mean free path of conduction electrons. CERMET devices [41] made of NbN films operating as flux flow detectors at 6 K, or superconducting β-Ga granules (T_c = 5.9 K) may be interesting possibilities.

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