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LOW TEMPERATURE DETECTORS: SUMMARY AND PERSPECTIVES

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LOW TEMPERATURE DETECTORS : SUMMARY AND PERSPECTIVES

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INTRODUCTION

In this summary of the Sixth International Workshop on Low Temperature Detectors, I will briefly review the most significant developments presented at this conference. Rather than presenting an extensive summary, impossible for editorial reasons, I will focus on a few developments on superconducting superheated granule detectors (SSGs), superconducting tunnel junctions (STJs) and bolometric devices. In particular, the shift of technique from the SIS (superconductor-insulator-superconductor) to the NIS (normal-insulator-superconductor) junction detectors and the growing interplay between the fields of STJs and fast bolometric detectors are emphasized. I will also consider some physics applications where cryogenic detectors appear to be needed or competitive. Finally, I will briefly review some future physics applications and some of the major lines of developments.

SUPERCONDUCTING SUPERHEATED GRANULES

Superconducting superheated granules (SSGs) have been used as particle detectors for several years in the digital mode [1]. An analog operation mode for SSGs, the “flip-flop” mechanism, has been proposed by several authors. In this mode, a granule “flips” into the normal state under a particle interaction above the energy threshold. If the base temperature is below the supercooling transition, the granule will “flop” back to the superconducting state after a time related, if not proportional, to the absorbed energy. Using a single granule detector, Abplanalp [2] has, for the first time, demonstrated convincingly that SSGs could be used in the “flip-flop” mode. The applicability of this “linear” mode to large-scale detectors is, however, still problematic due to the diamagnetic interactions between the granules, and inhomogeneities from granule to granule.

Flux penetration nucleated by local energy deposition in a geometrically metastable superconductor has been used by Jeudy to measure a source spectrum [3]. The energy resolution, $\approx 19\%$ at 62 keV, is comparable to that of NaI crystals although the dynamic range of the energy measurement appears limited, at least in the present version of this detector.

Based on the experience of the first long-time experiment with a 13 gram SSG detector [4] and on the demonstration by the Bern group that SSGs could be used to detect nuclear recoils down to a few keV [5], two dark matter experiments using SSGs are now in preparation : the ORPHEUS experiment [6], using ≈ 1 kg of granules, and the SALOPARD experiment [7], using ≈ 100 g of SSGs. The competitiveness of SSGs relative to bolometers for Dark Matter search or neutrino physics objectives must be questioned, however, due to their limited energy resolution and to the small amount of

information available when operated in the digital mode. SSG detectors have obviously background discrimination capabilities through the counting of the number of granules flipped. However, the range of a 20 keV photoelectron is less than 1 μm in tin, so that a large fraction of the events below 20 keV will lead to the same detector response. Internal radioactivity is another concern : in such a dispersed medium, the surface is enormous, typically tens of m^2 for a 1 kg detector, with $\approx 10^{10}$ granules/kg, and the dielectric medium surrounding the granules is another source of radioactivity. Finally, the PASS planar array, presented at LTD5, has probably the best defined energy threshold of SSG detectors. A boron-loaded PASS array has been used by the UBC group [8] as a neutron detector with a high rejection factor for gammas.

SUPERCONDUCTING TUNNEL JUNCTIONS

An extensive study of the properties of the superconducting tunnel junctions (STJs) can be found in the review by Barone [9]. Here, I will focus on a few contributions which I found illustrative of the issues discussed at this conference. Following the original idea proposed by Booth [10] of quasiparticle trapping, most groups now use Nb/Al/AlO_x/Al/Nb junctions, with a few notable exceptions which we will discuss in the following.

A number of groups have presented results pertaining to the comprehension of the limiting factors of SIS junctions. If limited only by the statistical fluctuations in the number of quasiparticles, the energy resolution of a STJ detector is expected to be ≈ 5 eV for a 6 keV x-ray. On the other hand, the best resolution for a SIS junction, presented at this conference by Frank et al. [11], is 29 eV at 6 keV. The origin of this discrepancy has been studied by several groups who have investigated the influence of spatial non-uniformities and of the loss of quasiparticles into the connecting leads, at the edges of the junctions, or in the junction itself. Verhoeve et al. [12] have studied junctions of different sizes from $10\ \mu \times 10\ \mu$ to $200\ \mu \times 200\ \mu$, and with different widths of the connecting leads. The scaling properties of these devices indicate that most of the losses in the base electrode occur at the perimeter of the devices and through the leads. This interpretation appears to be confirmed by the beautiful LTSEM (Low Temperature Scanning Electron Microscope) measurements presented by Martin et al. [13], where direct measurements of quasiparticles densities have been achieved. In addition, this study showed an almost regular structure of "dots" which cannot be ascribed to surface defects as the dots structure appears to move slowly with time and could represent another source, possibly associated with trapped magnetic field (see also [3]), of inhomogeneity.

The problem of separating the events interacting in the bottom or in the top layers has been addressed particularly elegantly by Mears [14]. Since the bottom layer of the junction is usually epitaxial, and the top layer

polycrystalline, the energy resolution appears to be better for events interacting in the bottom than in the top layer. Mears et al. [14] have shown that it is possible to differentiate events from the two layers by measuring the risetime of the current pulses. This results in an improvement in the energy resolution over the previous best performance for these junctions [15] which is now 29 eV FWHM at 5.89 keV [11, 14]. Although impressive, and a factor ≈ 5 better than the best semiconductor devices, the performances of these junctions are a factor ≈ 6 above the fundamental limit for SIS junctions quoted above. It should be noted that the electronic contribution to the energy resolution, ≈ 10 eV, now gives a negligible contribution when added in quadrature to the intrinsic resolution. This is due to the use of a low-noise 200-SQUID array developed by Welty and Martinis [16] and manufactured by HYPRES. This relatively inexpensive device should generalize the use of low noise SQUIDS and can be read using conventional electronics.

One of the highlights of this conference has been the first single photon detection in the UV and visible range using Nb/Al junctions presented by Rando and Verhoeve [17, 18]. By using 120 nm thick Al trapping layers, electronic signals as high as $2.3 \cdot 10^8$ electrons at 6 keV have been observed, allowing the detection of single photons down to $\lambda \approx 500$ nm, and potentially in the near-infrared. This very high charge output per eV of deposited energy can be explained by the very high quality of small ($20 \mu \times 20 \mu$ and $50 \mu \times 50 \mu$) junctions where the average number of tunnel processes per quasiparticle is, respectively, ≈ 20 and ≈ 50 . In turn, this allows to go down to photon energies of ≈ 1 eV with a measured charge ≈ 4500 electrons/eV, surprisingly a factor ≈ 3 less than at keV energies, where recombination is expected to be more important. The typical energy resolution at 300 nm is ≈ 100 nm, and mostly due to an electronic noise contribution ≈ 80 nm.

As a reference, it is interesting to remember the performances of the SPPM (Solid State PhotoMultiplier) presented by Petroff and Stapelbroek [19] in 1988. This device, using arsenic-doped silicon, and since then classified, could be operated at temperatures between 6 and 10 K, had a ≈ 60 % quantum efficiency from 0.4μ to 20μ , and could be operated at count rates up to 10^{10} photons/s/cm² ! On the negative side, the SPPM, operated in the gated avalanche mode, has no spectroscopic capabilities and its dark pulse rate was limiting its use at fluxes $> 10^6$ photons/s/cm². Therefore, the potential of the device fabricated by Rando et al. [17, 18] resides not so much in its single photon detection capability, or in its high quantum efficiency (≈ 50 % from the visible to the X-ray range), as in its intrinsic spectroscopic capabilities which may be applied to very weak UV, visible and IR sources.

Several groups have used high purity Ta crystals or foils as absorbers in order to reach absorption efficiencies close to unity for x-rays, and a reasonable containment for γ -ray interactions [20, 21], or to use the large absorber coupled to two or more junctions as an imaging device with a few

μm spatial resolution [22]. In particular, Friedrich et al. [22], following Kraus et al. [23], used a Ta absorber $100\ \mu\text{m} \times 200\ \mu\text{m}$ and $8000\ \text{\AA}$ thick in a double junction arrangement, and showed that this device could be operated in a charge division mode with a $\approx 4\ \mu\text{m}$ spatial resolution.

Finally, probably the most significant evolution appearing at this conference may be the transition from SIS to NIS technology. Proposed at the LTD5 conference [24, 25], NIS based detectors represent now a mature technique with a high potential of development. In particular, Martinis reports a 22 eV resolution at 6 keV for a $0.5\ \text{mm} \times 0.5\ \text{mm}$ detector with acquisition rates in the $10^4\ \text{Hz}$ range, meeting the requirements for material science applications [26]. This is the best result yet for the energy resolution of an x-ray junction detector. Direct measurement of quasi-particle trapping efficiency in NIS junctions [27] is a powerful tool to further improve the performances of these junctions.

Comparing the two technologies, both SIS and NIS detectors have excellent energy resolutions, but the perspectives of improvement for NIS appear much brighter than for SIS. Short risetimes make NIS detectors adapted to material science applications. In addition, NIS do not require an external B field to suppress the Josephson current. On the negative side, to reduce noise and residual current, NIS must be operated below $\approx 100\ \text{mK}$, still a major obstacle for space applications, and the temperature dependence of their characteristics requires stabilisation.

At the interface between STJs and microcalorimeters, an even more extreme solution has been chosen by Irwin et al. [28] in the hot-electron calorimeter where a normal metal film absorber is coupled to a transition-edge Al/Ag bilayer, a variation on the proximity-effect bilayers developed by the Munich group [29], and self regulating in the transition region under voltage biasing. This important development will be reviewed in the following. Theoretical energy resolutions of $\approx 1\ \text{eV}$ are expected at $T \approx 80\ \text{mK}$ and, already at this conference, Irwin has presented an impressive energy resolution of 26 eV at 6 keV using a $0.25\ \text{mm} \times 0.25\ \text{mm}$ absorber [28], at the same level of performance as the NIS result [26].

MOSTLY BOLOMETERS

The intimate connections developing between the STJ and bolometer fields is also one of the major developments seen at this conference. Three generations of bolometers are now apparent [30] : firstly, the thermal mode with the outstanding resolutions (8 eV at 1.5 keV) reached by the microcalorimeters developed by Stahle and McCammon [31, 32] with $1\ \text{mm}^2$ pixels arranged in a 36-channel array ; secondly, bolometers sensitive to athermal phonons through the use of transition-edge sensors [29, 33] or $\text{Nb}_x\text{Si}_{1-x}$ thin film technology [34, 35], and finally the QET or SLAPS concept developed by the Stanford and Berkeley groups [36-39], (see also [33]).

For massive detectors, when due account is taken of the matching between the collection time of phonons compared to the sensor characteristic times, the performances of these three sensing schemes are expected to lead to similar energy resolutions [30]. In order to obtain submicrosecond time resolutions, on the other hand, collection times must be of the order of the time of flight of phonons over the crystal size, so that a large fraction of the crystal surface must be instrumented. For large mass bolometers, the heat capacity of a TES or metallic film over the whole crystal surface becomes prohibitive, therefore suggesting the use of superconducting high purity quasiparticle traps coupled to small TES or NIS sensors.

The W-Al Quasiparticle trapping assisted Electrothermal feedback Transition edge sensor (QET) developed at Stanford [37, 38] is a perfect illustration of this overlap between the STJ and bolometer fields. When biased well into the transition, a TES sensor coupled to a superconducting film behaves very similarly to a NIS junction. In addition, following Booth [10], athermal phonons are trapped in low heat capacity aluminum quasiparticle traps and transferred to small tungsten lines in the normal/superconducting transition region. Finally, the measurement also uses a low noise high-bandwidth HYPRES SQUID arrays [16] to optimize the readout.

In the past, transition edge sensors have exhibited limitations due to film nonuniformities. To a lesser extent, energy resolution is also degraded by the transition nonlinearity. Inspired by an analogy with electrical circuits, Irwin [40] has used feedback techniques to fight these limitations. Assuming a heat loss to the substrate proportional to $K(T^n - T_s^n)$ where T_s is the substrate temperature and n is a constant ≈ 5 when electron-phonon decoupling dominates, the return to equilibrium after an event has raised the sensor temperature, in the linear regime, is

$$C \, d\Delta T/dt = -P_o \alpha / T \, \Delta T - g \, \Delta T$$

where $g = dP/dT = nKT^{n-1}$ is the thermal conductance, α is the usual dimensionless quality factor $\alpha = (T/R) (dR/dT)$, and P_o is the Joule power dissipated in the sensor at equilibrium. When the sensor is much hotter than the substrate, $P_o \approx KT^n = gT/n$, so that the effective recovery time of the film can be readily calculated to be

$$\tau_{\text{eff}} = \tau_o / (1 + \alpha/n)$$

where τ_o is the time constant of the film in the absence of Joule heating. Since α factors of several hundreds have been achieved, the pulse duration can be reduced by two orders of magnitude. As an additional bonus, the linearity is greatly improved by the negative feedback and the energy deposited in the sensor can be directly measured, without any free parameter, as the integral of the change in the Joule power, thereby allowing

the direct measurement of the phonon collection efficiency and, potentially, of the various loss factors [38].

The energy resolution in this regime is therefore

$$\Delta E_{\text{FWHM}} = 2.36 \sqrt{4kT^2C (1/\alpha)\sqrt{n/2}}$$

and is below the naive “thermodynamic limit” ($\Delta E = \sqrt{kT^2C}$) by the factor $\approx 2.5/\sqrt{\alpha}$, typically a factor 13 for the films studied by Irwin et al. [28].

The first step towards the development of realistic detectors for Dark Matter detection, which requires massive detectors in the 100 gram range, is the 1 cm x 1 cm x 1 mm silicon detector (0.23 g) instrumented by 4 QET sensors, each one photolithographically patterned into four sets of 196 parallel cells of tungsten lines with 8 aluminum traps for each cell. The sub-microsecond response of this hierarchical structure has allowed a 0.3 mm position resolution of particle interactions by measuring the pulse height observed in each of the four sensors [37, 38].

Several other developments have been presented with Dark Matter or neutrino detection in mind. In order to take advantage of the exponential energy spectrum expected for WIMPs interactions, particularly for WIMP masses below 20 GeV, the Munich group [33] has improved its energy resolution performances (99 eV FWHM at 1.5 keV for a 32 g sapphire detector) and correspondingly lowered its energy threshold. Low events rate means fighting against radioactive contaminants and energy resolution is an important factor in the identification of background γ -ray lines [41]. In addition, if the 2-d position resolution of the Stanford group [37] can be extended to a 3-d position resolution for thick detectors, rejection of radioactive background events from surface or external contaminants, usually the two main contributions to background events, will become possible.

In addition, WIMPs particles, if they exist, are slow ($\beta \approx 10^{-3}$) and their interactions are expected to involve nuclear recoils preferentially to electron recoils. For small recoil energies, and in semiconducting devices, nuclear recoils have a smaller charge yield than the usual electron-gamma interactions, leading to discrimination by double measurement, e.g. charge and phonon signals [37, 38, 42, 43]. Understanding the charge build-up and losses in Ge and Si devices at low temperatures has been studied by several groups [42-47] and stable operation of Ge detectors over several hours without flushing the diode have been achieved with some of these detectors. The n/γ rejection factor quoted by the Berkeley group for a 62 g Ge detector is already $\approx 95\%$ on an event by event basis [43]. To further improve this figure of merit, the position resolution of a QET detector, where charge collection was implemented using a gold electrode to collect the charges [37], has been used to reject edge events with incomplete charge or phonon collection. A 500:1 rejection factor (at $E_{\text{recoil}} > 10$ keV) has been

achieved in the identification of neutron recoils vs. gamma interactions [37, 38]. As this discrimination is possible on an event by event basis, the nuclear recoil events can be selected to search for the annual modulation of the interaction rate with a much higher probability of success than with the statistical (as opposed to event by event) separation between low energy nuclear and gamma interactions in conventional scintillation or ionization detectors [48]. It should be noted that the n/γ rejection factor is calculated for all events above 10 keV. For Dark Matter search, where low energy events are the most numerous, this quantity would be more easily interpreted as a function of energy

Phonon spectroscopy has also been proposed and studied as a way to discriminate between nuclear and electron recoils [38, 49, 50] but until now, there exists no decisive evidence of a significant difference between nuclear and electron recoils in this respect.

A very strong signature of WIMPs interaction or solar neutrino interactions would be obtained by the recoil direction of the scattered particle. At low recoil energies, the recoil direction has been effectively measured in conventional low pressure gaseous detectors [51] but a 1 kg detector would require instrumenting a $\approx 1000 \text{ m}^3$ TPC. Bandler et al. [52, 53], by measuring a strongly anisotropic roton generation and scintillation by α -particles in superfluid helium, propose a second method based on the "hot cylinder", opaque to the rotons, along the particle's track. Potential limitations of this effect come from the probably smaller opacity for electron tracks than for α -particle tracks, where the energy density deposited along the track is much higher. In addition, the opacity and roton anisotropy is probably very limited at the small nuclear recoil energies induced by WIMPs interactions. Still, this important result is a reference for recoil direction.

APPLICATIONS

We have seen presented at this conference applications where low temperature detectors provide significant contributions. In particular, in a $\beta\beta$ -decay search, the Milano group has presented the first results of its 4-crystal array of TeO_2 , by far the best result on tellurium [54]. At the time of LTD7, with another 5-fold increase in mass, we may expect that this experiment will provide the best result on neutrino mass. EDELWEISS, the first dark matter experiment using bolometers [55] has already excluded a previously unexplored region of WIMPs candidates at low mass, and the CDMS [56] and CRESST [33] experiments are expected to test in a near future a wide region of phase space where SUSY particles may be expected. In nuclear physics also, spectroscopy of energetic heavy ions at the 1 % level has been studied [57] at a level of unprecedented precision.

Finally, Bradley et al. [58, 59] have presented a beautiful test experiment with a 0.008 g sample of superfluid ^3He at 100 μK . At these temperatures, an order of magnitude below the superfluid transition, superfluid ^3He behaves like an excellent vacuum in the absence of “external” excitations. The detecting medium is superbly clean due to its superfluid character. Even ^4He is almost completely immiscible with the ^3He sample. Using a vibrating wire thermometer [60], Bradley et al. convincingly demonstrate the operation of this device down to recoil energies of a few keV and the perspectives of its operation with a threshold less than 100 eV with samples in the gram range makes it an interesting principle detector for Dark Matter detection. Obviously, the cost of a very large mass ^3He detector would be prohibitive, but a 1000-channel detector of a total mass ≈ 1 kg, an excellent investment in the long term, is probably realistic.

PERSPECTIVES AND CONCLUSIONS

This conference has evidenced the rapid progress in several directions of low temperature detectors. SIS junctions of surface ≈ 1 mm² with imaging capabilities at a few μm resolution may be realized within the next few years and single photon detection with decent energy resolution in the infrared will be probably achieved at LTD7. On the technical side, sensitive diagnostics such as LTSEM may allow the design fabrication of junctions with energy resolutions close to the theoretical limit. On the other hand, with their high sustainable rates, their excellent energy resolution and areas in the 1 mm² range, NIS junctions and TES sensors appear as the future detectors for material science. However, due to their inherent lower functioning temperature, space applications using NIS will have to await cryogenic developments achieving < 100 mK temperatures in zero gravity at a reasonable cost [61] before their use can be generalized.

Whereas the possibility of neutrino spectroscopy based on a multi-ton bromine cryogenic detector has been considered by the Milano group [62], the progress on QET sensors and their timing resolution makes it possible to reconsider the possibility of a cryogenic indium solar neutrino experiment, despite the fantastic intrinsic radioactive background of the indium target (≈ 0.22 disintegration/g/s). The measurement of coherent scattering of neutrinos on a nucleus by a reactor is now mostly a background problem : a 100 eV energy threshold on a 50 gram detector appears feasible in a near future, making the experiment realistic if the background issues in the shallow environment of a nuclear reactor can be addressed. The Microwave enhanced bolometer [63], with its potentially very low energy threshold, appears as an excellent candidate for such a measurement.

Despite a large overlap in the techniques used, mesoscopic devices are remarkably absent from this conference. As an example of their potential use for future physics objectives, developments on the Single Electron

Transistor (SET) [64] makes it possible to reach a sensitivity at the level of 10^{-6} electron/ $\sqrt{\text{Hz}}$ in a near future. Measuring the weight of a *single* antiproton by comparing its trajectory to that of a H^- ion (the same electric charge as the antiproton with about the same mass) at a typical temperature of 10 mK and passing at a distance of ≈ 0.1 mm from a series of SETs, then appears feasible. Incidentally, this device makes it possible to measure the local variations of surface fields, probably the most serious challenge to this measurement [65, 66] with a three orders of magnitude improvement over conventional techniques using Kelvin probes.

Finally, the Fairbank type of physicist will attack the problem of measuring the temperature of the relic neutrinos, expected to be $\approx 2\text{K}$, with techniques probably yet to be discovered...

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