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NEW RESULTS ON DETECTOR DEVELOPMENTS FOR LOW ENERGY NEUTRINOS AND DARK MATTER

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Abstract

The motivation and present status of detector developments for low energy neutrinos and dark matter are discussed. In particular, recently proposed cryogenic techniques are expected to reach unprecedented sensitivity and energy resolution. They may provide the next generation of low background, high sensitivity detectors. The critical overview of to-date results is completed by a sketch of new ideas and possible ways for further improvements. The possibility to develop hybrid detectors, measuring simultaneously ionization and heat, is given special attention.

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1 INTRODUCTION

Astro-particle physics has provided in the last decade significant motivation for the development of a new generation of low backgound, highly sensitive detectors dedicated to: a) solar neutrino detection; b) neutrino mass measurements; c) double β experiments; d) dark matter searches, especially cosmions, axions or WIMP (weakly interacting massive particles). The basic technologies foreseen for most of the proposed experiments are closely linked among them, and are leading to the birth of a new cross-disciplinary field at the frontier between particle and nuclear physics, astronomy and material science.

The interpenetration between low energy neutrino physics and dark matter searches is twofold: first, a massive light neutrino may well be a candidate to hot, warm or cold dark matter; secondly, the detectors foreseen for cosmions, WIMP or even solar axions are very close to those proposed for the next generation of low energy neutrino experiments.

A nonvanishing electron neutrino mass may be observed by direct measurement of a β decay spectrum near the end point of maximum electron energy [1] , or indirectly through a double β decay event produced by one of the diagrams shown in Fig. 1 , where the electron neutrino is assumed to be a Majorana particle, with a small mass related to lepton number violation (neutrino-antineutrino oscillation) [2]. Similarly, the observed anomaly in the solar neutrino flux [3], if confirmed by the GALLEX experiment [4], may be an evidence for a flavour-changing neutrino mass matrix [5]. But, in the case of solar neutrinos, other explanations are possible: a) a new weakly interacting neutral particle conveying energy from the central core of the sun to colder regions (cosmion model [6]); b) an anomalous magnetic moment, leading to helicity flip of the produced neutrinos by the solar magnetic field (the neutrino should then have a small Dirac mass); c) finally, new data from Davis et al. [7] may indicate a systematic error in previous measurements, leading to a flux compatible with the standard solar model, but may also be due to time evolution in the solar activity having an influence on effect b) [8]. A plot of the solar neutrino spectrum predicted by the standard solar model [9] is given in Fig. 2 .

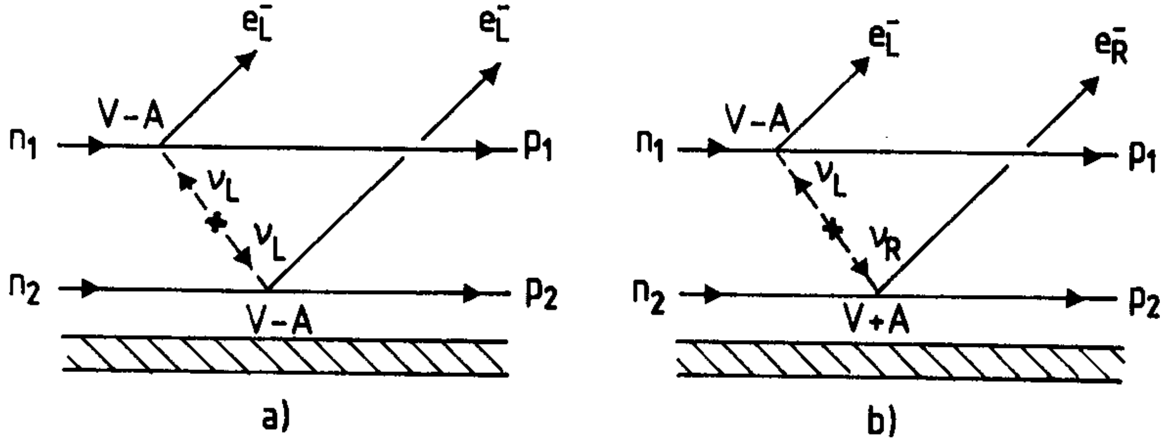


Fig. 1 - Diagrams contributing to neutrinoless double beta decay.

Dark matter candidates (see [10]) , such as cosmions or the magnino [11] , play a significant role in possible explanations of the solar neutrino puzzle. In turn, light neutrinos may themselves be dark matter candidates if they have masses in the range $5\ eV < m_{\nu_e} < 100\ eV$ or $1\ keV < m_{\nu_{\mu,\tau}} < 35\ MeV$ [12].

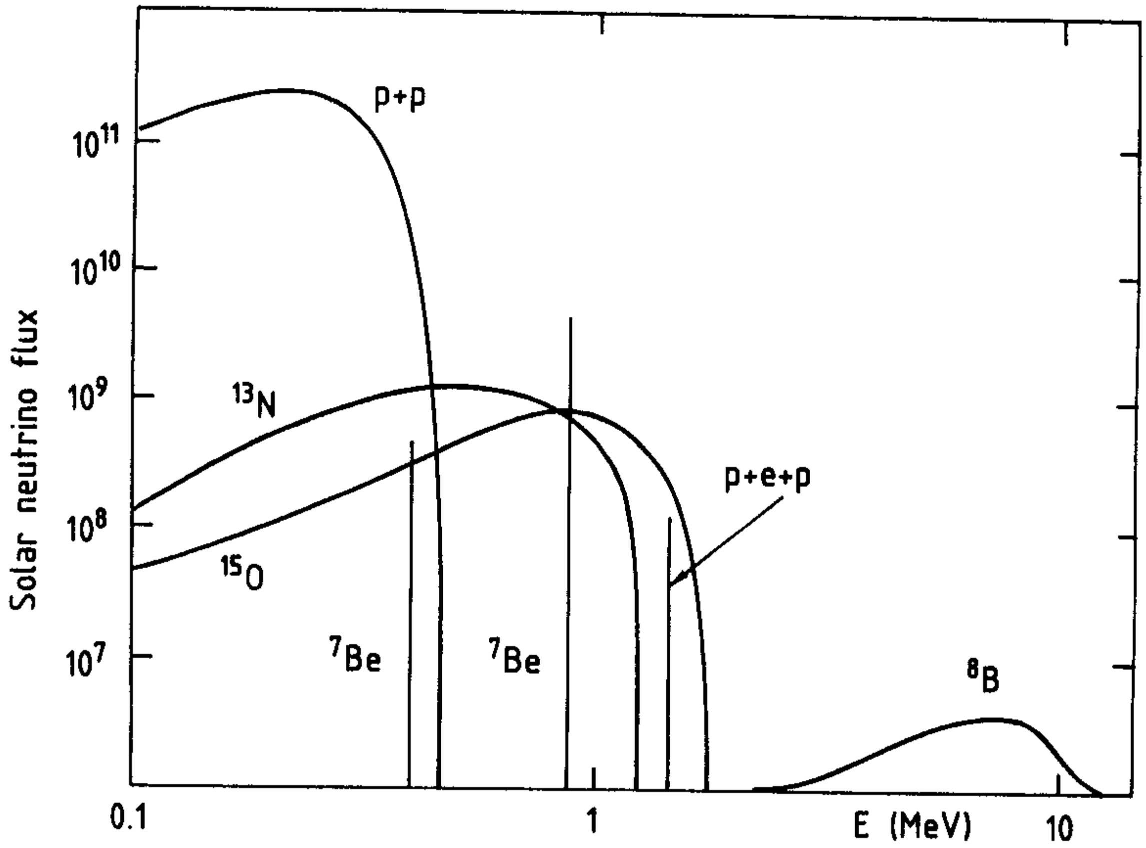


Fig. 2 - Solar neutrino spectrum (in $cm^{-2}\ sec^{-1}\ MeV^{-1}$), as predicted by the standard solar model. Narrow lines stand for integrated fluxes (in $cm^{-2}\ sec^{-1}$). See [13] .

2 NEUTRINO EXPERIMENTS

2.1 Neutrino mass

The mass of the electron neutrino has until now been measured through the tritium Kurie plot, where a nonzero mass would manifest itself at the $E \simeq E_0$ end point of the distribution:

$$dn/dE = F(E)\, p\, E\, (E_0 - E)\, [(E_0 - E)^2 - m_{\nu_e}^2]^{1/2} \tag{1}$$

p being the electron momentum, E its energy and $F(E)$ a smooth calculable Coulomb correction. E_0 is the maximum value of E if $m_{\nu_e} = 0$, $E_0 = 18.6\ keV$ for tritium.

There is at present consensus that the best result in this line of research has been provided by the Zurich axial spectrometer [14] , with 27 eV energy resolution on the electron energy, leading to the bound $m_{\nu_e} < 18\ eV$.

Although progress in axial spectrometry is still possible, new techniques are being proposed based on low temperature phenomena: thermal detection with bolometers, or excitation of quasiparticles in superconductors detectable with superconducting tunnel junctions (STJ). Both techniques will be dealt with later on.

2.2 Double beta experiments

Double beta decay with two neutrinos has been observed in a ^{82}Se experiment [15], leading to a lifetime $\approx 10^{20}$ $years$. $\beta\beta$ decay with Majoron emission was claimed with a half life $\simeq (6 \pm 1)\ 10^{20}$ $years$ in a ^{76}Ge experiment [16], but has not been confirmed by other germanium experiments [17], which give bounds better than $\tau\ >\ 10^{21}$ $years$. Other double beta isotopes used in present experiments are: ^{48}Ca , ^{100}Mo , ^{130}Te , and ^{128}Te.

Germanium detectors have until now dominated the search for $\beta\beta_{0\nu}$ events, due to the excellent energy resolution of intrinsic semiconductor germanium ($\approx 0.1\%$ in the $\approx 2-3\ MeV$ region), but various techniques are used in experiments with other targets. In the Irvine experiment [15] , a 7 $mg\ /\ cm^2$ thick enriched foil of ^{82}Se is used as the central electrode of a 80 $cm\ \times\ 80\ cm\ \times\ 20\ cm$ Time Proportional Chamber (TPC) in a 700 G magnetic field. The LBL/Mt. Holyoke/New Haven experiment [18] uses 17 g of enriched ^{100}Mo foils between layers of $Si : Li$ detectors searching for coincidence events. ^{136}Xe is incorporated in a multiwire proportional counter by the Milan group [19] , and in a TPC by the Caltech/PSI/Neuchatel collaboration [20] .

Again, cryogenic devices may well provide a next generation of double beta experiments, continuing the line started by semiconductor germanium detectors where energy resolution was the main tool to reject background. Thermal bolometers are in this respect the best suited technique, and can incorporate almost any specifc material in an active target detector. Finally, the use of enriched isotopes (already started with $^{82}Se,^{100}Mo,^{76}Ge$,...) is likely to become a general practice.

2.3 Solar neutrinos: ^8B sector

Since the (unique, and radiochemical) Homestake experiment [21] brought data in contradiction with the Standard Solar Model, a considerable effort has been devoted to the preparation of new solar neutrino experiments. KAMIOKANDE II , originally designed for proton decay, has been able to observe low energy events induced by ^8B solar neutrinos through $\nu_e\ e^-$ elastic scattering in a 3000 ton water Cherenkov detector [22]. A $^8B\ \nu$ flux of $2.6\ 10^6\ cm^{-2}\ s^{-1}$ within 30% 1 σ error may be inferred, possibly confirming a deficit with respect to the prediction of the Standard Solar Model, but obviously further experiments are needed. Another Cherenkov detector, using 1000 $tons$ of heavy water, is being proposed to be installed near Sudbury (Canada) [23] .

ICARUS [24] is a project to build a large liquid argon imaging chamber, expected to be sensitive to ^8B solar neutrinos through $\nu\ e^-$ elastic scattering, or through the reaction $^{40}Ar(\nu_e\ ,\ e^-)^{40}K^*$, where the excited nucleus $^{40}K^*$ decays to the ^{40}K ground state by emitting a γ of 4.38 MeV . Finally, ^8B solar neutrinos may also be detectable by a boron-loaded liquid scintillator (BOREX experiment [25]) where boron can be incorporated in some compounds up to 20% in weight. The relevant reactions are: $^{11}B(\nu_e\ ,\ e^-)^{11}C$

and $^{11}B(\nu_X\ ,\ \nu_X)^{11}B^*$, where X stands for any arbitrary flavour. Feasibility studies of ICARUS and BOREX are presently in progress.

2.4 Solar neutrinos: low energy sector

Two experiments sensitive to low energy solar neutrinos will be radiochemical and based on the isotope ^{71}Ga instead of ^{37}Cl : one at GRAN SASSO (GALLEX) [4], and the second one at BAKSAN[26]. The reaction $^{71}Ga(\nu_e\ ,\ e^-)^{71}Ge$ has a threshold of 235 keV in incoming neutrino energy, and therefore will be sensitive to a part of the pp solar neutrino spectrum.

Gallex uses 30 *tons* of gallium in the form of $GaCl_3$, in acqueous solution of HCl . An event rate of $\approx 1\ ^{71}Ge\ atom/day$ is expected. $GeCl_4$ will be extracted by a nitrogen purge with a small amount of Ge carrier, transformed into GeH_4 after extraction, and finally the decay of ^{71}Ge into ^{71}Ga by electronic capture ($\tau_{1/2}\ \simeq\ 11.4\ days$) will be detected with a proportional counter.

The BAKSAN experiment uses 60 *tons* of gallium in metallic form, where an extraction method from melted metal has been developed.

The ultimate goal would, however, be a real time experiment sensitive to both the pp spectrum and the ^7Be ray, allowing for a clean event identification and with background rejection good enough to accurately measure the differential solar neutrino flux. This is possibly one of the most difficult challenges ever met by particle physics instrumentation. Until now, the main effort has been devoted to devices based on the reaction proposed by Raghavan [27]: $^{115}In(\nu_e\ ,\ e^-)^{115}Sn^{**}$, with a threshold of 128 keV in the incoming neutrino energy. The excited state Sn^{**} de-excites 3.2 μs later, giving two γ rays of 116 and 490 keV , which are emitted simultaneously but can be detected in different cells of a segmented detector. In spite of its clean signature, the use of Raghavan's reaction presents the major drawback of ^{115}In radioactive background, with an event rate of $\simeq$ $1\ \beta\ decay\ cm^{-3}sec^{-1}(E\ <\ 490\ keV)$, leading to 2 β , 3 β and (β - erratic γ) coincidences that may fake solar neutrino events. Since the expected solar ν event rate is very low ($\simeq 0.3\ event\ ton^{-1}day^{-1}$), such backgrounds can be rejected only by a detector having simultaneously very fine segmentation, fast response and good energy resolution.

Aiming mainly at a measurement of the ^7Be ray, new indium loaded liquid scintillators have been developed [28], incorporating 10% In in weight, still presenting reasonable optical properties. In such detectors, the 116 keV γ would not be detected separately, but rather with the first Compton scattering from the 490 keV γ. Detection efficiency for ^7Be solar neutrinos may be of $\approx$ 30%. Along similar lines, In coated scintillating fibres are given some attention [29], although the detection of the 116 keV γ becomes more problematic and efficiency may be less than 15% [30] . In both cases, very large detectors (200 *ton* or more for 1 *event/day*) are needed and the practical possibility to reject all kinds of backgrounds remains to be demonstrated.

Potentially able to detect pp solar neutrinos may be very high quality crystal scintillators [31], semiconductor InP [32], STJ [34] or superheated superconducting granules (SSG) [36]. The last two techniques will be discussed in the next section.

Fig. 3a shows a recently grown transparent single crystal of $InBO_3 : Tb^{3+}$ [37], and Fig. 3b its emmission spectrum when excited with 292.5 nm ultraviolet laser light. Luminescence is very intense, but unfortunately Tb^{3+} fluorescence is too slow for a particle detector. The chemical feasibility of Ce^{3+} doping of several indium compounds is presently under investigation. Ce^{3+} doping is actually a nontrivial chemical challenge not only for indium borates [38], but also for well known phosphor silicates such as $Si_2In_2O_7$ [39].

InP is a very promising technique, as 1 cm^3 prototypes have already been constructed and show sensitivity to low energy electrons and photons [32]. Further material studies are required in order to optimize the response of the detector.

The main alternative to the indium program for low energy solar neutrinos would be nucleus recoil [40], where coherent scattering allows for large cross sections and a significant number of events can be reached with smaller detectors. However, energy deposition would be very small ($\approx 10\ eV$ for ^7Be neutrinos interacting with a ^{27}Al target) and the event a pure recoil without specific signature. Even if such a signal were made detectable, background problems appear at first sight practically hopeless and, in any case, have never been dealt with at such low energy deposition.

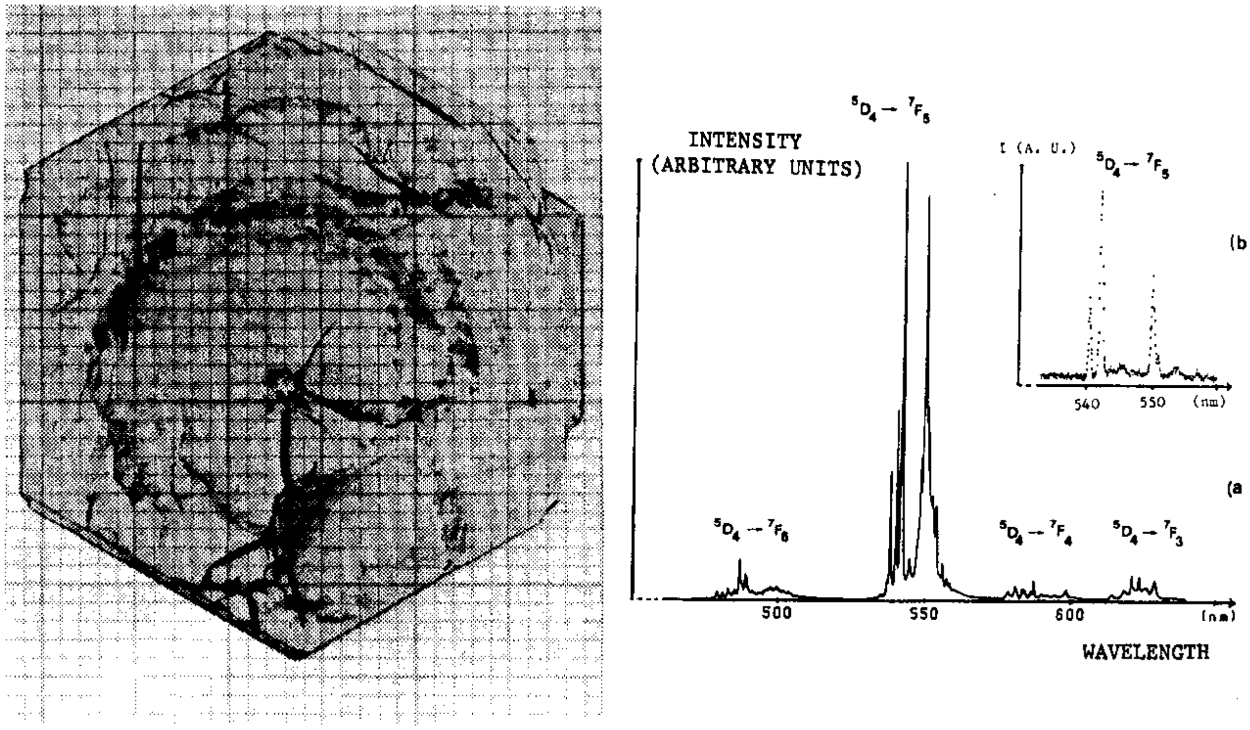


Fig. 3 - a (left): a transparent single crystal of $InBO_3 : Tb^{3+}$ grown by the flux method. b (right): its emission spectrum when excited by ultraviolet light. From [37].

3 CRYOGENIC DETECTORS

Low temperature devices are possibly the most significant noveltry in recent detector technology. Small cryogenic detectors have already been used in astrophysics, a well-known application being the study of possible anisotropies of microwave background radiation [41]. Particle physics applications [35,33] require: a) sensitivity to individual particles; b) comparatively large devices.

The use of low temperature detectors 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 quasiparticle 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. Current work concerns mainly the study of the basic properties of these new devices.

3.1 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 case of very low read-out noise, energy resolution is given by phonon thermal fluctuations [42] :

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

where C is the crystal 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 always be justified, especially 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 . From (2), a sizeable increase in detector mass can be compensated by working at lower T.

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 [43] , and at 100 mK a composite Si micro-calorimeter brought 17 eV $FWHM$ resolution on 6 keV γ's [44] . Fig. 4a shows the scheme of the Wisconsin-Goddard Si bolometer, whereas Fig. 4b exhibits spectra obtained with this device.

More recently, the study of large bolometers has also been undertaken. Using a 0.7 g germanium absorber at 44 mK , the Milano group [45] 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 a spectrum with satellite peaks shifted upwards by 100 keV (Fig. 5a). As the implanted nuclei decayed, satellite peaks disappeared and only single peaks from external α's remained (Fig. 5b). 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 [46] . More recent results on large bolometers are being presented by N. Coron at this Workshop.

A new idea is the so-called "magnetic bolometer" [47]. Half of the deposited heat is converted into very low energy spin excitations ($\approx 10^{-6}$ eV) and a small change in the magnetization of the crystal can be detected by a SQUID read-out. The authors report 30 keV noise level at 400 mK with 5.5 $MeV\alpha$'s on a 7.35 g sapphire absorber with a 135 mg $YAG : Eb^{3+}$ magnetic bolometer implanted on the sapphire.

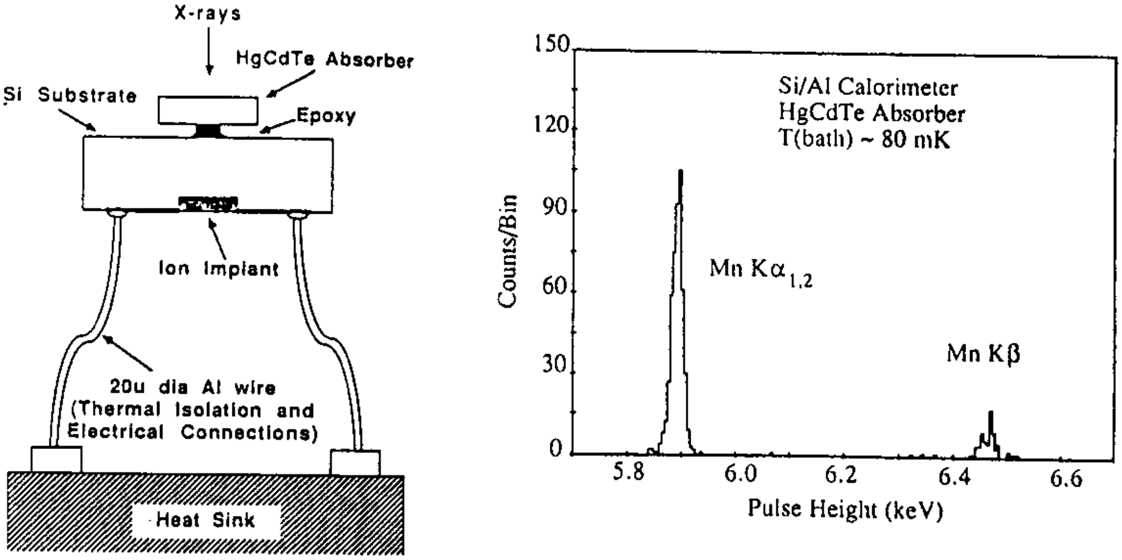


Fig. 4 - a (left): The silicon micro-calorimeter developed by the Wisconsin-Goddard group. b (right) low energy γ spectrum from [44] , obtained with a ^{55}Fe source, exhibiting $\Delta E \simeq 17$ eV for the width of the Mn K_α peak.

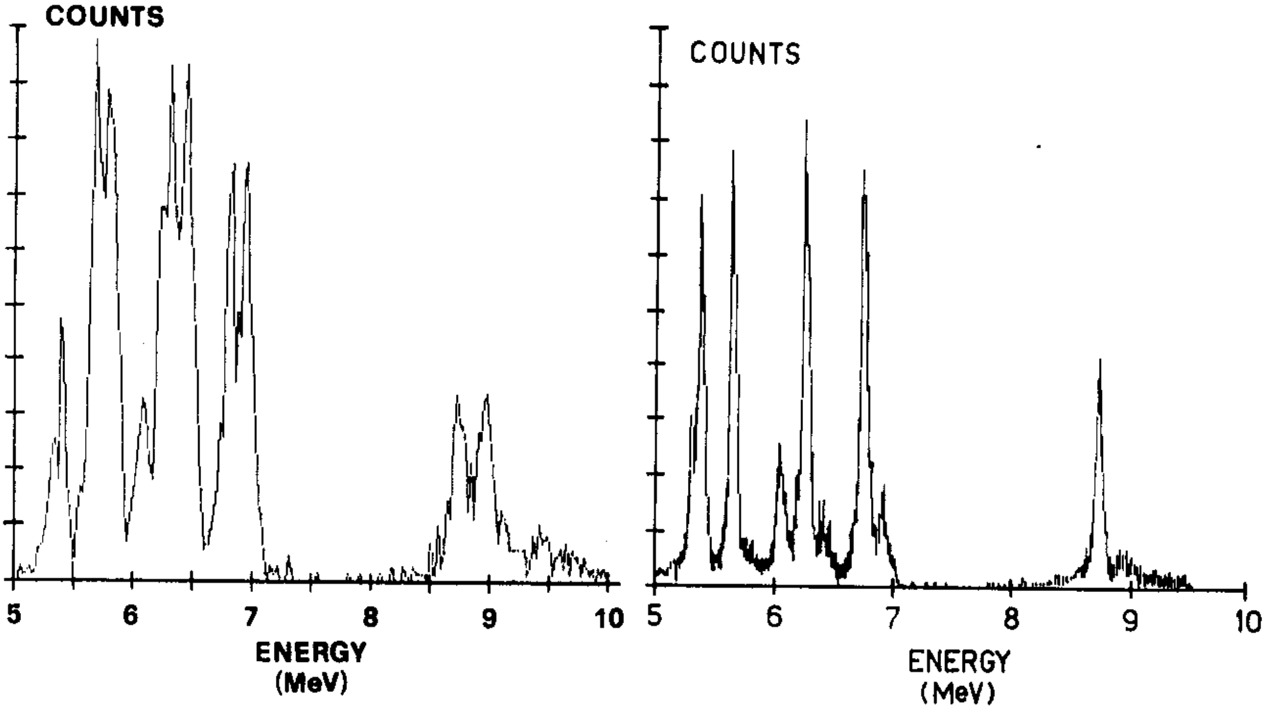


Fig. 5 : Energy spectra of the Milano bolometer [13] irradiated with a ^{228}Ra source. a) left: with daughter nuclei implanted in the crystal; b) right: two weeks later, after the implanted nuclei decayed.

Bolometer development must still undergo substantial progress before reaching theoretically expected performances. In particular, although in an ideal case one should have $\Delta E \simeq noise\ level$, in practice energy trapping by long lived electronic states, Frenkel pair formation, light emission, and other unwanted phenomena, imply substantial departures from the ideal behaviour of a purely thermal bolometer and degrade energy resolution. Furthermore, the specific heat of the sensor must also be taken into account and may limit the performance of small bolometers. To date, the main motivation for the development of large bolometers ($100\ g - 1\ Kg$) lies in neutrinoless double β decays [48] , where energy resolution is crucial for background rejection, and dark matter searches through nucleus recoil [49], where sensitivity to energy deposition below 1 keV is required. More difficult, because of background, would be a solar neutrino experiment based on $\nu - e^-$ scattering using several tons of bolometric detector [50]. Applications at reactors face similar feasibility problems.

3.2 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 (Fig. 6) , and are not expected to be massive detectors. However, new ideas have recently emerged (e.g. quasiparticle trapping, which also provides multiplication [34]) to incorporate bulk superconducting specimens.

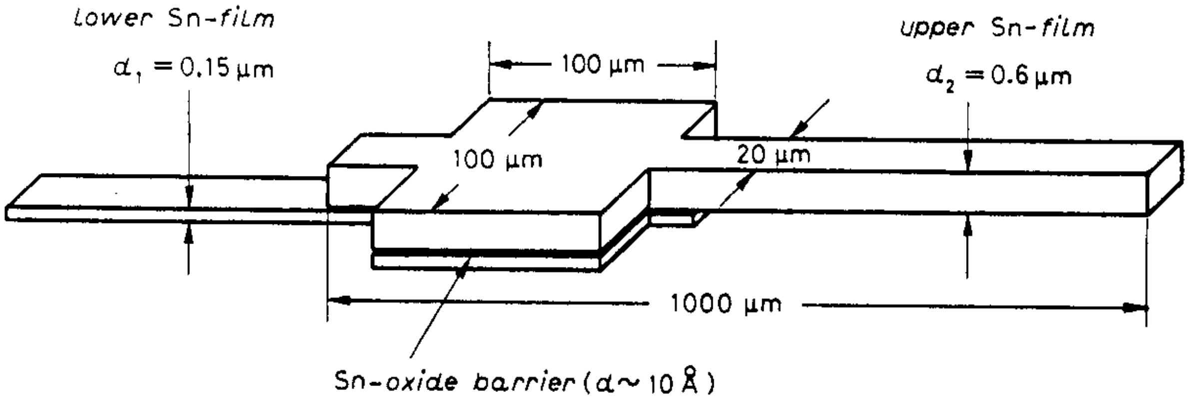


Fig. 6 - Scheme of a STJ prepared at PSI (Villigen) [51] .

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:

$$\Delta E_{rms} \simeq (fE\epsilon)^{1/2} \tag{3}$$

where f is the Fano anti-correlation factor $(0.1 < f < 1)$ and ϵ the effective quasiparticle excitation energy $(\epsilon > \Delta)$. Potentially, a $Sn - SnO - Sn$ detector with $f \simeq 1$ and $\epsilon \simeq \Delta \simeq 0.6\ meV$, should reach 0.1% energy resolution on 6 keV γ's. Experimental results are not that good, but the SIN group claims [51] 48 eV $FWHM$ resolution on the ^{55}Mn K_α peak at 5.89 keV, whereas the Garching (TMU) group [52] reports 88 eV resolution, determined from the energy difference between the K_β (6.49keV) and K_α peaks. A typical signal rise time from existing STJ is of the order of 15 μs .

Using materials with higher T_c , good performances can also be obtaiend at higher temperatures. As an example, a 10 $\mu m \times 10 \mu m$ $Nb/Al/Al_2O_3/Al/Nb$ junction [53] recently brought 250 eV energy resolution at $T = 1\ K$.

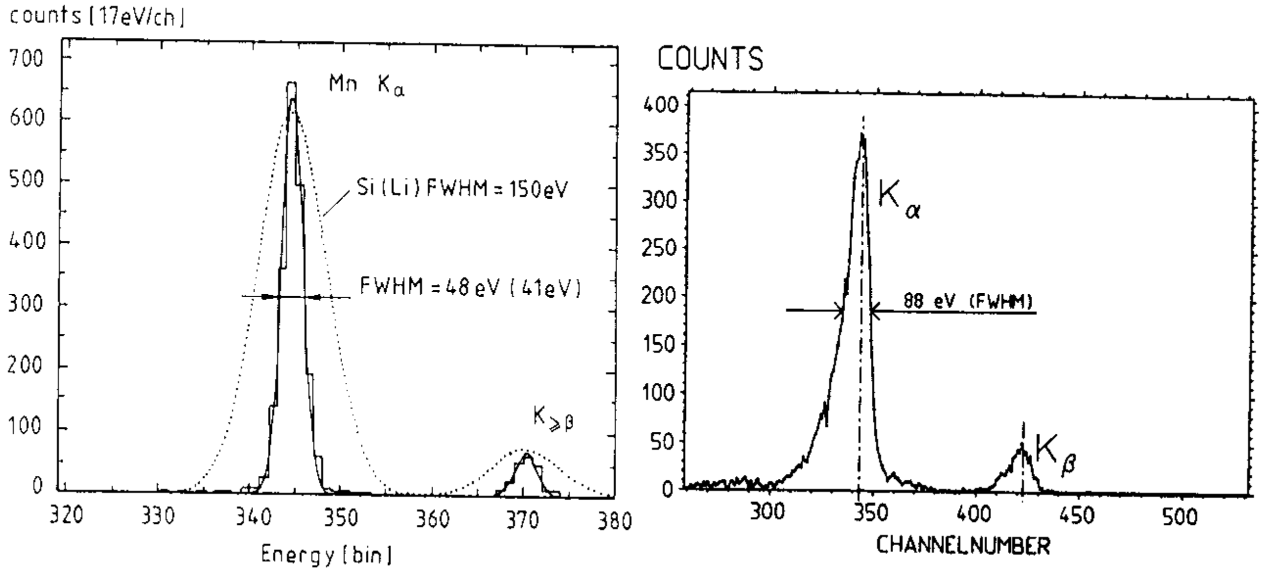


Fig. 7 : Recent results yielded by superconducting tunneling junctions. a) left: energy spectra (full line) of $E \simeq 6\ keV$ X rays obtained at PSI (Villigen) with a Sn STJ at 400 mK , as compared to the best performance of $Si : Li$ detectors at LN_2 temperatures (dotted line); b) right: similar spectra obtained by the Garching group.

Apart from the detection of low energy γ rays, a possible use of small STJ would be neutrino mass measurements [54] , but if larger devices can be made, they could be used [34] to detect low energy solar neutrinos through the ^{115}In Raghavan's reaction [27] . 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 [50,55]. This possibility has been recently demonstrated by the Garching (TMU) group [55] 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 [50] , using a superconducting strip read-out near the transition edge. Recent results from Garching are shown in Fig. 8 .

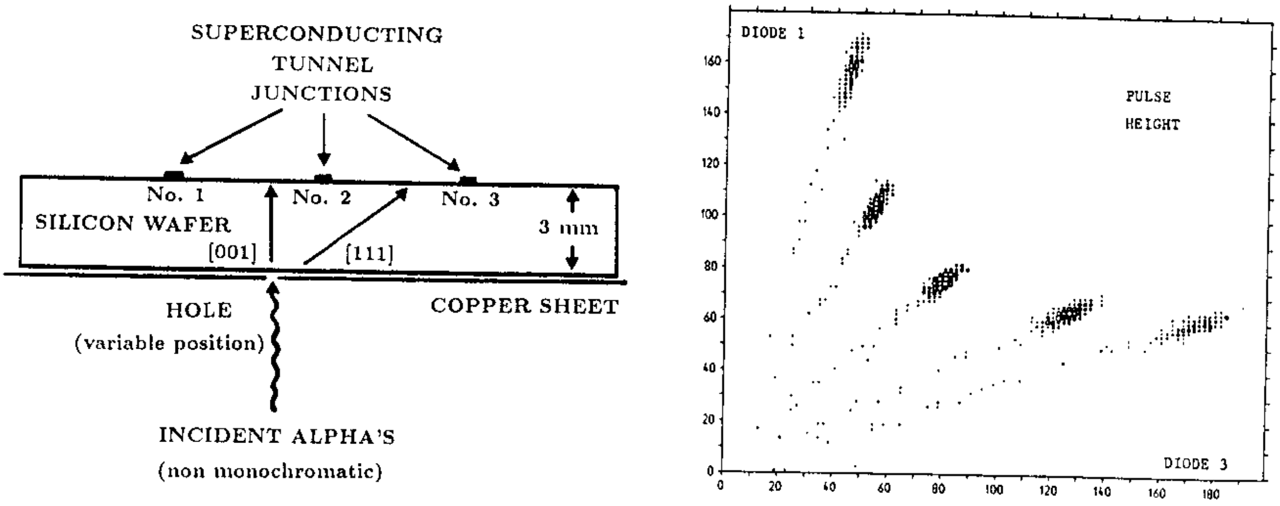


Fig. 8 - The Garching ballistic phonon experiment: a (left) schematic description of the set-up; b (right) two-junction signal scatter plot showing a clear separation between signals produced at the five different impact positions.

3.3 SUPERHEATED SUPERCONDUCTING GRANULES (SSG)

A type I 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 [56] 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.

A major drawback of SSG detector is the dispersion in effective superheated critical field observed in a realistic colloid with many granules. As the magnetic field is increased, the number of counts per unit increase in H_0 follows a rather wide distribution (the differential superheating curve). It is thus impossible to fix a value of the applied magnetic field in such a way that all the granules are set to a common small threshold in H_0 , i.e. in energy deposition for a given size. Work in progress, however, seems to suggest [57] that new fabrication techniques may possibly circunvent such a difficulty and lead to very narrow superheating curves. This, in case of success, would be a major step forward.

Recently, progress has been made in the SSG real time read-out [58] and tin granules of sizes $10-400$ μm have been shown to be sensitive to low energy sources down to 6 keV γ's [59] . 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 energy deposition with 80% efficiency, whereas good quality Al or Ga grains cooled to 100 mK would achieve a similar performance for 4 eV energy deposition. Such figures would be improved by narrower superheating.

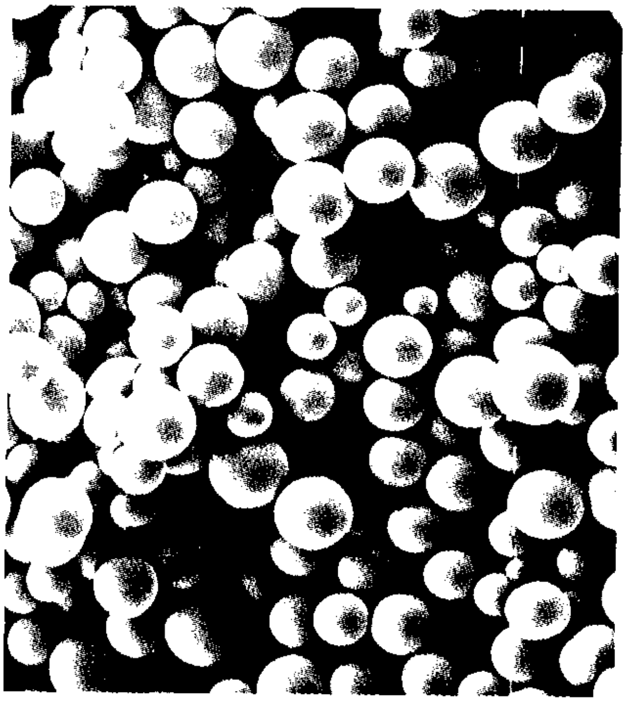
Industrial manufacturers are now able to produce at large scale rather small grains of reasonable quality (Fig. 9 - 11) by conventional techniques. In the last months, recently produced Al and Zn grains were available and have been studied for the first time for detection purposes [60] , [61] . As an example, the Al grains of Fig. 11b were irradiated in Annecy with a ^{109}Cd source (β's and γ's of $E < 88$ keV) deposited on the grains before preparing the SSG colloid. The result obtained after 5 min irradiation time is shown in Fig. 12 . In Fig. 12a is exhibited the differential superheating curve, where dN/dH_0 is the number of counts per unit increase in H_0 . Fig. 12b shows the irradiated differential superheating curve, where the applied field stays at some fixed value (the point where the gap appears on the curve) for 5 min (irradiation period) before being further increased. The missing counts in Fig. 12b correspond to grains having changed state during the irradiation period, although contrary to previous tests with tin, not all of the flips under irradiation were detectable in real time with our electronics. The test was performed at $T = 400$ mK , and already indicates excellent sensitivity, which should still be considerably improved by working at $T = 100$ mK .

Encouraging as they may look, the above results are not sufficient for realistic detection purposes. Two examples:

1) It has been proposed [62] to use indium SSG as a detector for low energy solar neutrinos. 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 $mm \times 1$ 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" [59]. 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 $\Delta\Phi \propto \Delta E$ is predicted even for a nucleus recoil. The appearance of extra flips is expected to lead an amplification effect (one or two orders of magnitude), which may solve the basic problems for a ^{115}In experiment. Calculations using the thermal conductivity of GE 7031 Varnish for heat propagation in the colloid yield time resolution in the range $10-100$ ns , and metallic spherical inclusions should not drastically change the result [63].



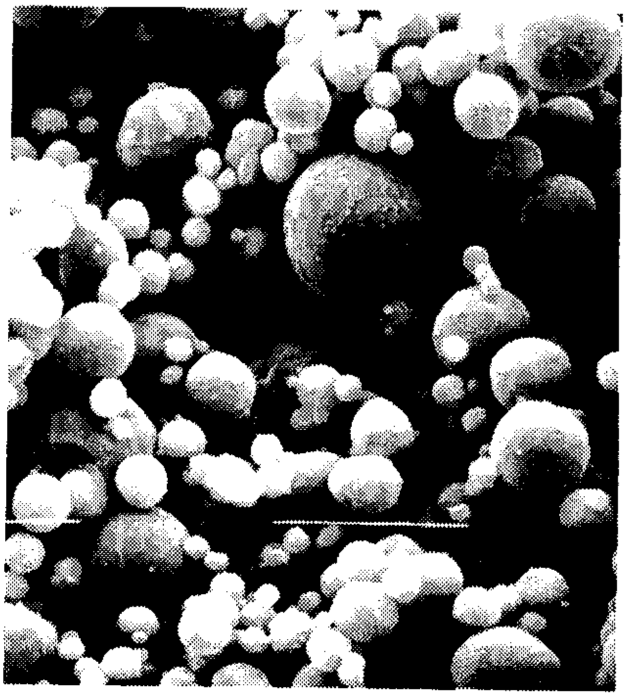


Fig. 9 (left) - ϕ (diameter) $< 25\ \mu m$ Sn granules obtained by conventional sieving from a $\phi < 40\ \mu m$ collection produced by EXTRAMET. The mark is $10\ \mu m$.

Fig. 10 (right) - $\phi_{mean} \simeq 4\ \mu m$ superfine HEUBACH Zn powder. The mark is $10\ \mu m$.

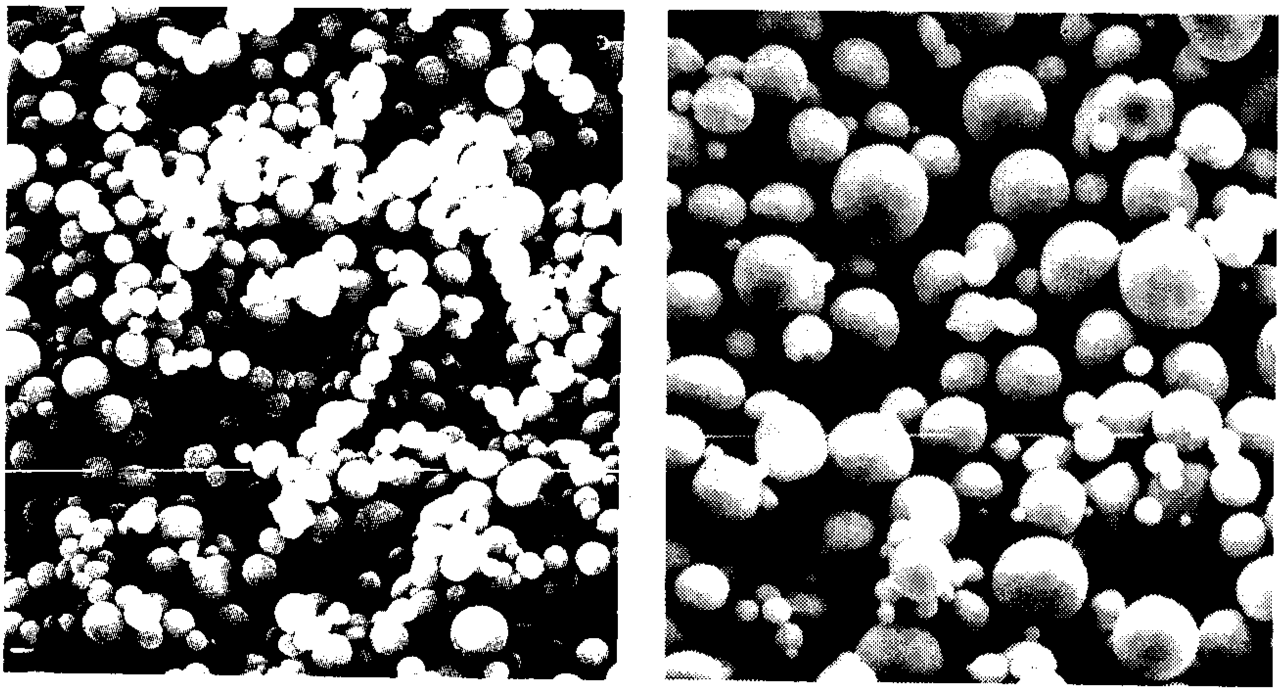


Fig. 11 - Aluminium samples obtained by centrifugation in air from a $\phi < 63$ ECKART-WERKE sample. a (left): $\phi < 5\ \mu m$, the mark is $10\ \mu m$; b (right): $12\ \mu m < \phi < 20\ \mu m$, the mark is $10\ \mu m$ (a tail of smaller grains remains).

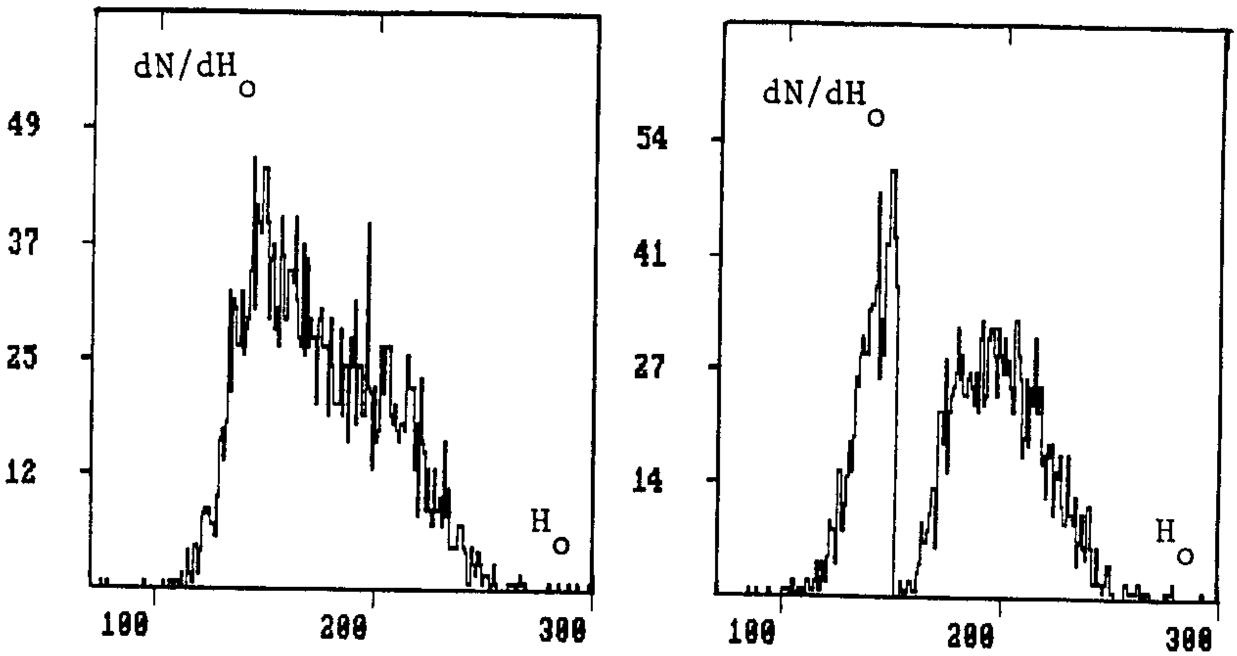


Fig. 12 - Irradiation result for the sample of Fig. 11b, with a ^{109}Cd source. a (left): differential superheating curve; b (right) irradiated superheating curve obtained staying for 5 *min* at a fixed value of H_0 before raising further the magnetic field (H_0 in a. u.).

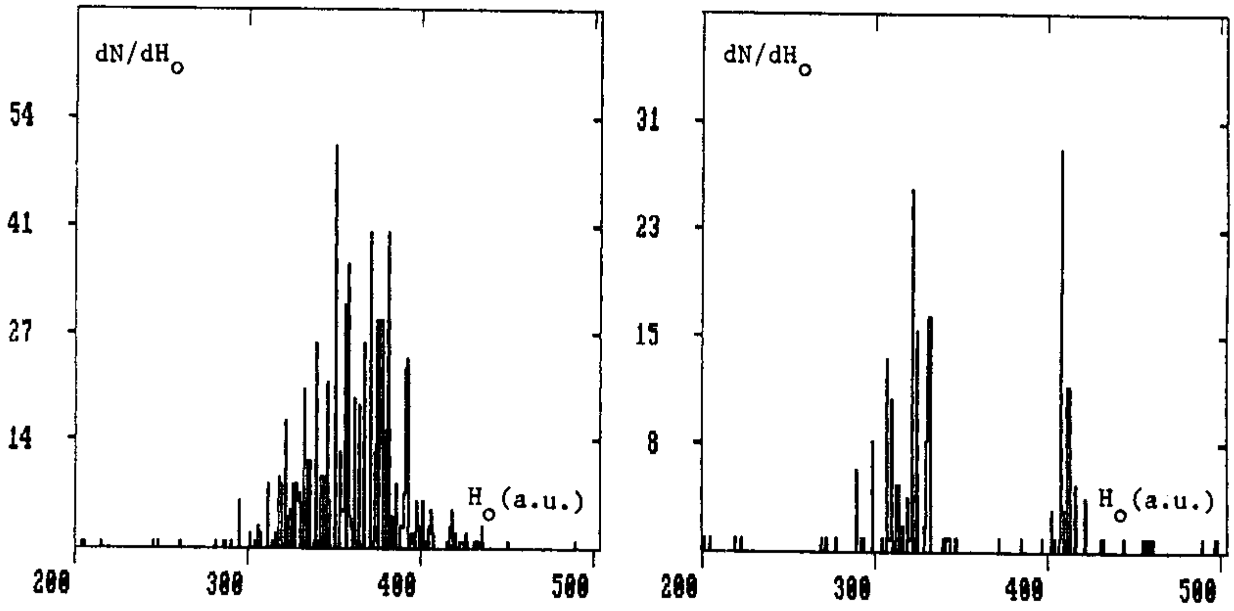


Fig. 13 - Similar test for 4 μm Zn grains. a (left) : the "avalanche" superheating curve; b (right) : irradiated "avalanche" superheating curve obtained after staying for 5 *min* at the value of H_0 where the gap starts. The source used was ^{36}Cl ($E < 714$ keV β's).

In case of success of the "micro-avalanche" scenario, other applications of SSG would become possible: double beta decays [64], X-ray imaging [65], dark matter searches through inelastic scattering with a ^{119}Sn target [59]. Furthermore, the dielectric material can provide an active target (hydrogen for dark matter searches [59]) ... However, if experimental evidence for global avalanches already exists [66] , further work is required to evaluate the real performance of the micro-avalanche effect.

We performed tests at $T = 400\ mK$ with the Zn grains shown in Fig. 10 , and possible new evidence for thermal avalanches was obtained. Very large and long pulses ($10-50\ \mu s$ risetime) were seen, whereas single grain flips could not be detected individually and previous tests with larger granules of the same origin had exhibited normal single grain pulses. Due to the superposition of a continuous slow signal and rapidly oscillating noise, each long pulse produced several counts in our read-out system leading to the distribution shown in Fig. 13a . We may call this (non reproducible) distribution the "avalanche" superheating curve. It was even possible to obtain interesting irradiation results, where practically no signal was observed during the irradiation period but in turn a large gap appeared in the irradiated superheating curve (Fig. 13b). Clearly, a careful study should be performed to really elucidate the nature of the phenomenon and further tests are in preparation down to $100\ mK$.

Development of industrial grain production should also be pursued to reach smaller sizes. ϕ_{mean} (average size) $\simeq 25\ \mu m$ tin granules are produced [67] at a rate of $5\ Kg/hour$ 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 [68] : $\phi_{mean} \propto f^{-2/3}$ (f = frequency). Other techniques seem also well suited to produce (possibly, after sieving by centrifugation) very small spheres in the $\sim 1\ \mu m$ range. For instance, direct atomization of molten metal with a nitrogen jet is currently being used for the production of Al and Zn powders [69] , [70] .

An independent application, using large grains, would be the detection of magnetic monopoles [71] , 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, as well as tracking and timing allowing for a measurement of speed and direction.

3.4 OTHER CRYOGENIC DETECTORS

Energy deposited in superfluid ^4He at low temperature ($100\ mK$) would create rotons $\Delta/k = 8.65\ K$. 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 [72] . 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 [73] , where superfluid ^3He (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 [74] , who was able to obtain bounds on dark matter from measured heat leaks in Cu adiabatic nuclear demagnetization refrigerators. On the other side, high T_c superconductors have already produced interesting devices, such as DC SQUIDs made of $YBaCuO$ ceramics [75] . More classical techniques, such as semiconductors ($InSb$, doped Ge ,...) operating at 4 K [76], or low temperature scintillators [77], may also play a significant role in the next generation of particle detectors.

4 HYBRID DEVICES

Background problems are rather difficult to handle in rare event detectors, when only one kind of signal (current, thermal pulse, scintillation...) is used. Furthermore, the way energy is degraded into elementary excitations depends crucially on the way it has been deposited (therefore, on the nature and energy of the incident particle, the type of interaction with matter, etc.). Thus, the measurement of only one component of the deposited energy may not be the best approach, as it implies a substantial loss of information (although some scintillators yield a two-component fluorescence signal). At room or LN_2 temperature, it is not possible to detect a single particle thermal pulse (large specific heat, high noise level...). At very low temperature, the extremely good performance expected from ideal thermal measurements often pushes developments in the opposite sense: only a thermal signal is aimed at, other kinds of energy losses are potentially a source of trouble spoiling energy resolution. We would like to argue, here, in favour of a simultaneous detection of ionization and heat in a composite cryogenic scintillator or semiconductor.

According to Lindhard et al. [78], a nucleus recoil at $E_R < 1\ MeV$ can be distinguished from an electron or photon by looking at the relative amount of energy converted into ionization (the nucleus ionizes 3 to 5 times less at $E_R = 10\ keV$). The smaller the recoil energy, the smaller the relative amount of ionization losses as compared to direct production of phonons. Similarly, fluorescence radiation sets a neat distinction between a slow α particle and a β or γ of the same energy, due to the dE/dx (ionization energy loss per unit length) dependence of the light yield [79]. It then follows that rare event experiments, having to face severe backgrounds, may seriously benefit from particle identification through simultaneous measurement of ionization and heat. This would in particular be the case for the search of WIMP dark matter candidates through nucleus recoil, but may also be relevant to a calorimetric double beta experiment, as far as the main background would be given by $\alpha's$. Two obvious possibilities arise when looking for ways to combine thermal and ionization measurements. One is the use of a semiconductor at very low temperature, and is discussed in the talk by B. Sadoulet. We would like here to discuss in detail the second possibility, based on suitably chosen scintillating crystals [80,37] .

Several intrinsic scintillators are known to present a high light yield when cooled down to ^4He temperatures. Undoped BGO produces 10 times more light than at room temperature [81] , whereas $CdWO_4$ improves slightly and CeF_3 fluorescence remains essentially unchanged [82] . Fluorescence decay time increases to about 200 μs for both BGO and $CdWO_4$ [81,37] but remains very fast ($\approx 40\ ns$) for CeF_3 [82], as well as for cerium-doped luminophores [83]. Although further studies, down to 50 mK, are needed, commonly used models predict a flattening of the T-dependence of the basic fluorescence parameters, which all tend to some constant as $T \to 0$. This has indeed been observed for the fluorescence decay time of $CdWO_4$ [37] , which remains unchanged between 4 K and 1.5 K . Fig. 14a shows BGO emission spectra at several temperatures, as obtained from ultraviolet excitation. The increase in light output is explicit as the crystal is cooled down. Fig. 14b presents the T-dependence of BGO fluorescence decay time below 250 K . More recent results for BGO using radioactive sources (5.5 MeV ^{241}Am α's) [84] appear to show the same trend, although further tests with sources below 200 K would be useful in order to carefully study BGO fluorescence under several kinds of irradiation.

It may even happen that materials not exhibiting significant luminescence at room temperature become good luminophores at low T . Fig. 15 shows the T-dependence of $MoPbO_4$ light yield, where the 520 nm (green) component increases by four orders of magnitude when the crystal is cooled down to LN_2 temperature. Other molybdates exhibit analogous behaviour [85]. The time evolution of $MoPbO_4$ green fluorescence splits at very low temperature in two components: one with a decay time $\tau \simeq 10$ μs ; the slower one with $\tau \approx 100$ μs , similar to tungstates.

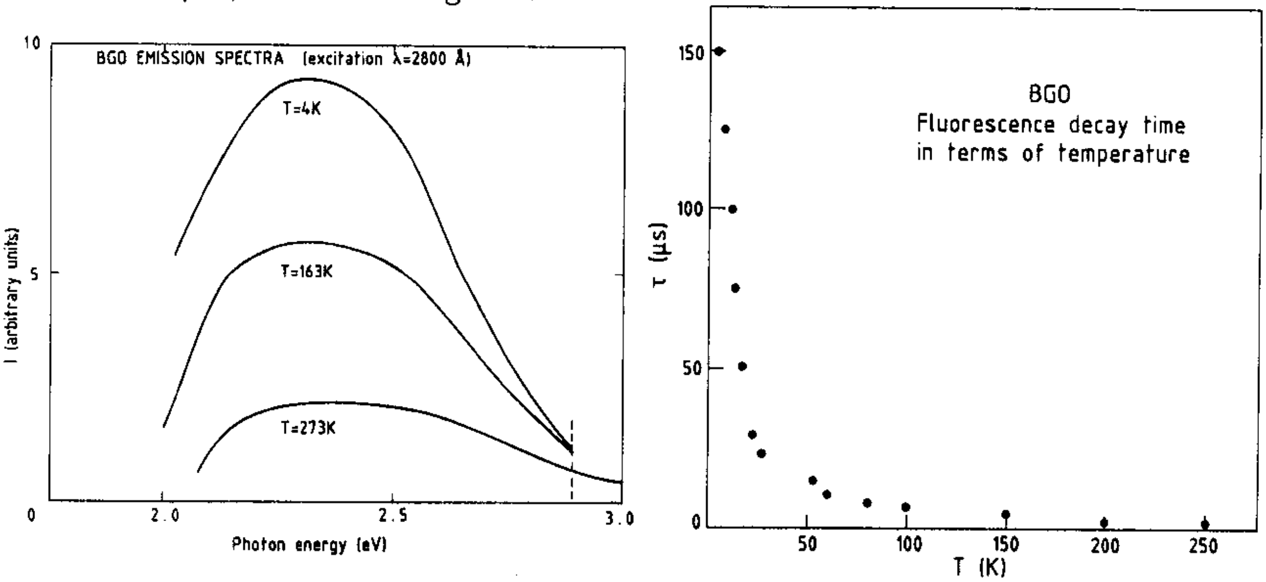
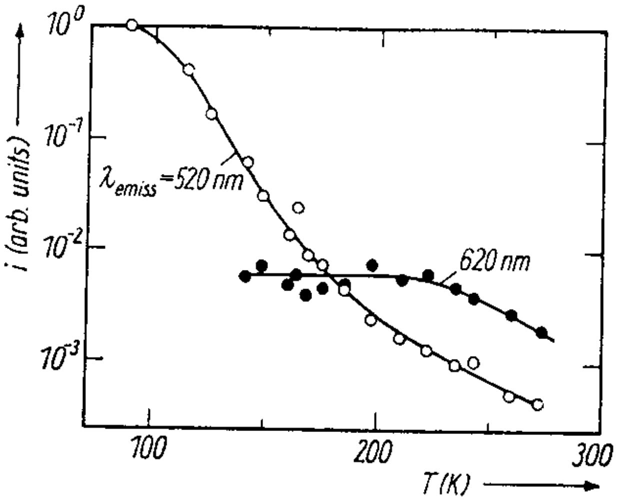


Fig. 14 - Temperature dependence of BGO fluorescence properties. a (left): emission spectrum under ultraviolet excitation ($\lambda = 280$ nm) at several temperatures; b (right): fluorescence decay time in terms of temperature. From [81].

The above conditions naturally suggest the development of a new hybrid device: the *luminescent bolometer*. A transparent scintillating crystal cooled to very low temperature would then carry a double read-out: a) a cryogenic photosensitive device; b) a thermistor. In this way, it would be possible to measure both light and heat and implement particle identification. A rough scheme (all faces painted but one, to prevent light from escaping) is shown in Fig. 16 . The main technical problem is possibly the choice or development of the best suited photosensitive device. Superconductive detectors and bolometers are possibly the best candidates, if light collection is to be made at bolometric temperature.



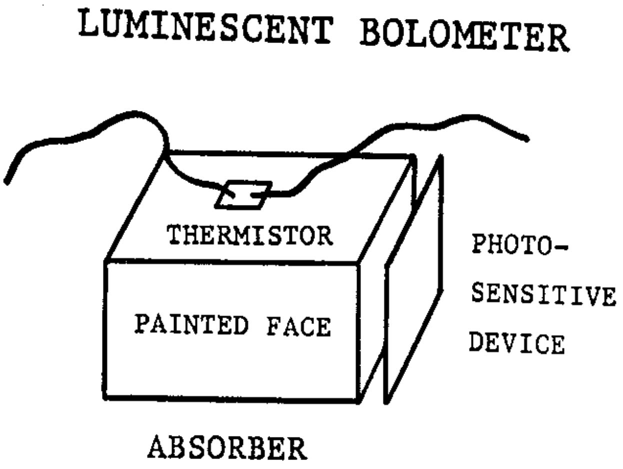


Fig. 15 (left) - Temperature dependence of the light yield of $MoPbO_4$ (lead molybdate) at two different wavelengths. The green component (520 nm) increases by four orders of magnitude between room and LN_2 temperature. From [85].

Fig. 16 (right) - Rough scheme of the proposed luminescent bolometer. From [37].

5 CONCLUSION AND COMMENTS

Detector developments for low energy neutrinos and dark matter have become a very active field in modern physics. The number of groups implied in such a program is quickly increasing, and unexpected breakthroughs in the near future should not be discounted. Cryogenic detectors are by now the most exciting subject, as unprecedented sensitivity and energy resolution may hopefully be reached.

Low temperature devices are expected to provide, not only a better calorimetric performance, but also a new approach to particle identification by looking simultaneously at thermal and ionization pulses. This kind of measurements would be impossible at room temperature, due to the comparatively high specific heats. Such a new window to event characterization would by itself justify the present effort in cryogenic detectors.

It is also worth noticing that the discovery of high T_c superconductors allows for the preparation of hybrid superconductor-semiconductor electronic devices [86], working in the range $4\ K < T < 70\ K$. In this way it may be possible to take advantage of the best qualities of both superconductive and semiconductor materials.

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