LAPP-EXP-89-16
January 1990

LARGE, REAL TIME DETECTORS FOR SOLAR NEUTRINOS AND MAGNETIC MONOPOLES

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Abstract
We discuss the present status of superheated superconducting granules (SSG) development for the real time detection of magnetic monopoles of any speed and of low energy solar neutrinos down to the pp region (indium project). Basic properties of SSG and progress made in the recent years are briefly reviewed. Possible ways for further improvement are discussed. The performances reached in ultrasonic grain production at $\approx 100\ \mu m$ size, as well as in conventional read-out electronics, look particularly promising for a large scale monopole experiment.

Alternative approaches are briefly dealt with: induction loops for magnetic monopoles; scintillators, semiconductors or superconducting tunnel junctions for a solar neutrino detector based on an indium target.

Talk given at the TAUP Workshop on Underground Physics, l'Aquila September 25-28, 1989.

1. SUPERHEATED SUPERCONDUCTING GRANULES

The feasibility study of superheated superconducting granules (SSG) devices[1] for the detection of solar neutrinos[2] and magnetic monopoles[3] has been pursued for years. SSG are small spheres of type I superconductor (a pure metal, such as Hg, Sn, In, Al, Ga, Zn..., or a well suited metallic compound) which remain superconducting in the presence of an external magnetic field H larger than the critical field H_c . The superheating quality depends on the surface state and cristallographic structure. Both properties in turn are determined by the fabrication procedure. Fig. 1 shows $Sn_{99}Sb_1$ granules produced by EXTRAMET[4] by ultrasonic atomization. Sphericity (Fig. 1a) is excellent and surface state good enough to reach the superheated state. The dendritic structure, characteristic of rapid solidification, can be seen on a closer view of the surface of the grains (Fig. 1b).

SSG are usually embedded into some dielectric material (paraffin, epoxy or varnish). The SSG colloid is known not to exhibit a narrrow superconducting to normal phase transition. A broad transition is observed, as in Fig. 2 (dashed line), where dN/dH_0 is the number of granules changing state per unit increase in applied field H_0 . Apart from lack of sphericity, surface defects and diamagnetic interactions between grains, such a phenomenon seems to be related to cristallographic anisotropies of the grains. Tests made with a single Sn grain[5] indicate a dependence on the orientation with respect to the applied magnetic field, as can be seen in Fig. 3 . All grains produced by standard atomization procedures seem to exhibit such a behaviour. An exception was found [6] for $Sn_{99}Sb_1$ grains (200 - 400 μm diameter) produced by BILLITON [7] by melting pre-forms.

The electronic read-out is based on Faraday's law, as the superconducting to normal phase transition implies the disappearence of the Meissner effect which can be detected by current loops placed arond the grains and connected to fast amplifiers. If conventional electronics is used, a SSG detector can be instrumented in foils covered by X and Y planes of loops normal to the applied magnetic field, so that position information and signal redundance are obtained by coincidence between a X and a Y loop (Fig. 4).

An irradiation experiment (e.g. in the presence of a low energy source) can be as follows. H_0 is set for a limited time (irradiation period) to a fixed value inside the superheating region and grain flips due to particles are recorded in real time. After this period, H_0 is raised further to complete the superheating curve and a gap is found (full line of Fig. 2) corresponding to the grains which have changed state during irradiation.

Magnetic monopoles. The goal is to detect superheavy monopoles in a β-independent way (β = v/c , v = monopole speed). The principle was presented previously[8]:

1. When a magnetic monopole crosses a SSG colloid, it injects a flux tube of ϕ (magnetic flux) = 2 n ϕ_0 (n = monopole magnetic charge in Dirac units, ϕ_0 = flux quantum) in each of the granules crossed. Since the superheated state is metastable, the ends of the flux tube on the surface of the grain become nucleation centers of the normal state and, if the external magnetic field exceeds a certain value, the normal zone quickly extends to the whole granule. This effect is independent of monopole speed and grain size.

2. Since large grains (30 - 100 μm diameter) can be used, well above minimum ionization in energy threshold, background rejection can be extremely good. Electronic signals would also be large ($\approx$ 10 μV amplitude and $\approx$ 100 ns risetime seem reasonable figures).

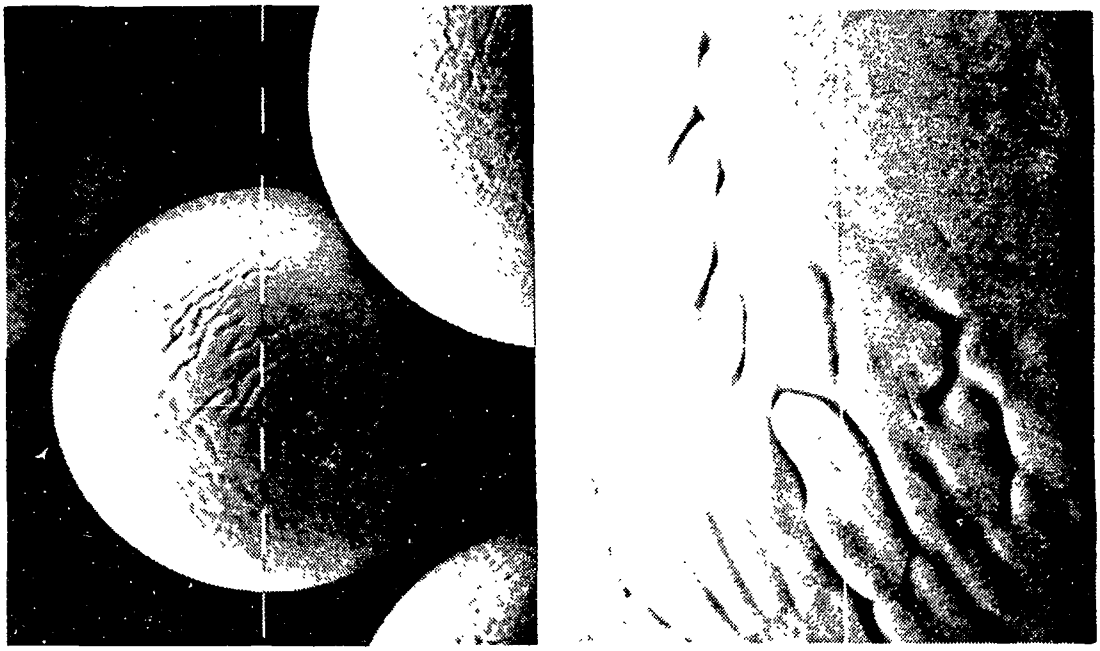
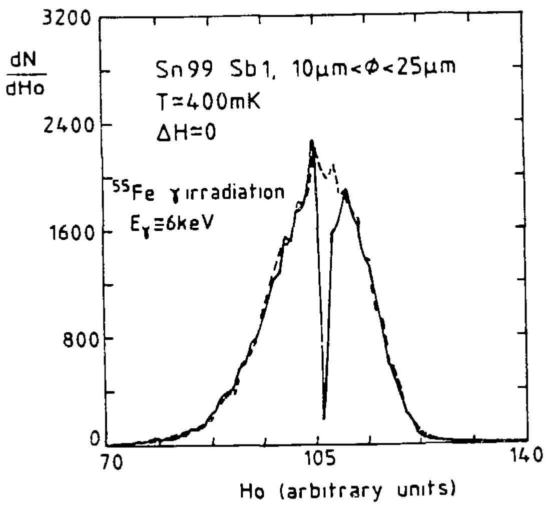


Fig. 1 - EXTRAMET grains. a (left): shape; b (right): surface state. Mark = 10 μm .



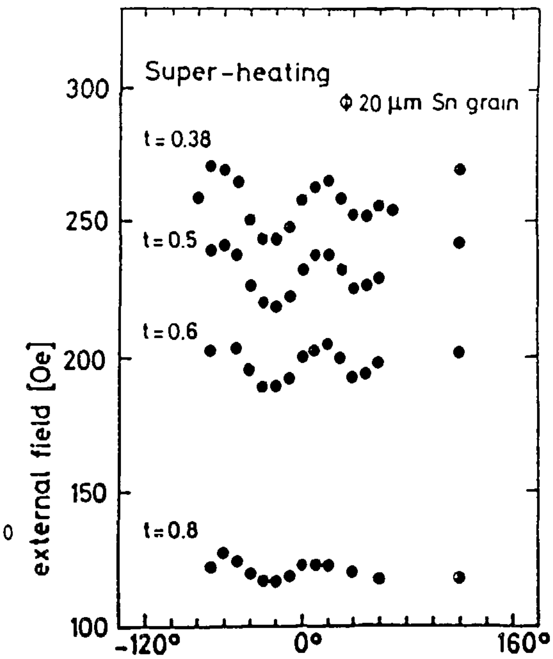


Fig. 2 (left) - Superheating curve (cut line) for 10 μm < $\varnothing$ < 25 μm $Sn_{99}Sb_1$ grains. The full line corresponds to an irradiation with 6 keV γ's. From J. Boniface et al. in 31).

Fig. 3 (right) - Angular dependence of the effective superheated critical field for a $\varnothing$ = 20 μm Sn grain, rotated with respect to an axis perpendicular to the applied field[5]).

3. The SSG monopole detector would be made of several planes of colloid, with filling factor $\approx 10\%$ in volume, and each plane instrumented with a X-Y system of current loops coupled to conventional electronics. SSG devices provide a real time, track detector able to measure the monopole speed and direction. The signal would be provided by several points (one per plane) aligned and timing compatible with the flight of a single particle.

4. The operating temperature can be $T \simeq 2$ K (superfluid helium) if Sn granules ($T_c = 3.7$ K) are used. Type I superconductors with critical temperature larger than 4.2 K exist and would allow for a large scale experiment without pumping on liquid helium.

Solar neutrinos. There are two proposals involving SSG. One is based on nucleus recoil[9], the second one would use Raghavan's reaction[10]:

$$\nu(E > 128\ keV) + {}^{115}In \rightarrow {}^{115}Sn^{**} + \beta^-(E_\nu - 128\ keV) \qquad (1)$$

and the excited nucleus Sn^{**} decays with a lifetime of 3.2 μs , producing two gamma rays (496 keV and 116 keV).

Nucleus recoil is dealt with elsewhere [11] . The indium experiment requires 4 tons of indium for 1 event.day and has to fight a severe radioactive background coming mainly from coincidences between a beta decay of indium (faking the β^- of Raghavan's reaction) and an ambient gamma (faking the two γ's of Sn^{**} decay). The advantage of SSG, as compared to other techniques, lies in their segmentation potentialities due to the X-Y read-out (10^7 elementary cells can be obtained with 10^5 electronic channels). However, the detector response needs to be improved and work on the basic physics of SSG is required. Presently, SSG detectors give a poor performance in signal/energy ratio (very small grains are required for good sensitivity) and lack energy resolution for low energy particles which are stopped in a short path (a nucleus recoil would flip only one grain). Even so, if good quality $\oslash < 3$ μm granules become available, an indium SSG detector would not be ruled out and may provide the only way to detect pp solar neutrinos in real time.

An idea to improve the SSG detector is through heat exchanges in the colloid. In the conventional scenario, the SSG response comes only from the grains directly reached by the incoming particle or by its secondaries. However, if heat exchanges between the granules and the dielectric are fast, heat propagation inside the colloid may lead to extra flips[12]. At very low temperature, the latent heat associated to the superconducting to normal phase transition can be positive and produce an avalanche effect first found by the Garching group[13]. It has been suggested[12] that, in the limit of very small grains, a limited amount of latent heat and fast thermal exchanges in the SSG colloid may lead to a new effect, "amplification by thermal micro-avalanche", where not only the response is amplified, but linearity is restaured even for nucleus recoil[11].

Some recent results

EXTRAMET[4] has developed an industrial ultrasonic device able to produce 5 Kg/hour of high quality granules in the range 30 μm $< \oslash_{mean}$ (average diameter) $<$ 200 μm . Metals with low melting point are most commonly dealt with, but the same technique has been successfully used for magnesium. By direct atomization with a nitrogen jet, ECKART-WERKE[14] has developed the production of $\oslash$ (diameter) $<$ 63 μm aluminium spherical powder containing a tail of very small grains that can be separated by centrifugation in air[15]. Industrial devices allowing to centrifugate large amounts of dry powder down to micron size can be found on the market[16] . Very fine powder ($\oslash_{mean} \simeq 4\ \mu m$) is available from HEUBACH[17] and exhibits good superheating. A new technique for grain production is presented by A.K. Drukier, with the promising feature of leading to a sharper phase transition (better sensitivity) of the SSG colloid.

Conventional silicon electronics developed for SSG read-out[18] allows to read $\oslash < 8\ \mu m$ Sn grains in a coil of 500μm inner diameter and 20 turns. The signal of a $\oslash < 8\ \mu m$ grain flip can be seen in Fig. 5. A detailed study of the structure of the signals produced by single grain flips led to good agreement with theory for $H_0 > H_c$. Another development allowed [15] to read, with signal/noise ratio ≈ 8 and risetime $\simeq 200$ ns, 20 μm tin grains in a coil of 2.5 mm inner diameter and 30 turns. Existing electronics would be appropriate for a large scale monopole experiment, but further work (possibly involving GaAs) is required for solar neutrinos. SQUID read-out is an interesting alternative[19].

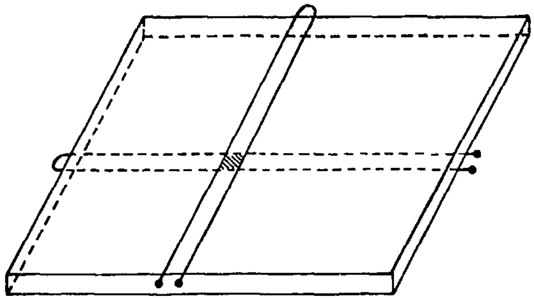
Sensitivity to low energy particles (including 6 keV γ's) has been studied[12,15,19,20], as well as to low energy electrons from a van de Graaff accelerator[18] . The results can be theoretically understood, and in the second case (a 2.5 MeV beam) it was possible to observe the coincidence between the grain flip and the signal of a photodiode placed behind the SSG detector. Local heating appears for materials with a high impurity rate, where the nucleation of the normal state on the surface of the grain is faster than thermalization. This phenomenon is important for large grains. The expected energy threshold for In grains of $\oslash = 1\ \mu m$ is ≈ 600 eV, but it can be lowered by more than an order of magnitude if pure indium is replaced by a well suited metallic compound (e.g. In_2Au[11]).

Finally, recent results[15,21,22,11] seem to provide evidence for localized thermal avalanches. This can be a step towards the implementation of the "micro-avalanche" scenario.

2. OTHER DEVELOPMENTS

Induction experiments [23] rely on first principles and can even unambiguously measure the monopole magnetic charge. However, the signal is very small and difficult to extract from both noise and background. Fig. 6 shows a 1.1 diameter concentric loop gradiometer developed by the Chicago-Fermilab-Michigan Collaboration in order to optimize two-loop coincidence, electromagnetic noise rejection and impedance matching with the SQUID read-out. A new idea is to develop a Transient Response Induced Current Detector in order to eliminate the low frequency noise and avoid expensive shielding.

Conventional techniques for solar neutrino detection with an indium target are equally being studied: crystal scintillators [24,25] can be made from Ce-doped borates with a large amount of indium. Although trivalent indium does not seem to allow for Ce^{3+} doping, it can be combined with other trivalent ions (e.g. scandium) which are known to accept Ce^{3+} as a dopant. Liquid scintillators were the original proposal by Raghavan and, due to recent technical progress, are again seriously considered. Together with scintillating fibers, they are foreseen for the detection of the neutrinos from the beryllium ray or in view of reactor experiments[26] . InP [27] semiconductor detectors have been developed at the 1 cm^3 scale and show good sensitivity to low energy particles. An ambitious approach is the use of superconducting tunnel junctions [28] . The semiconductor energy gap is thus replaced



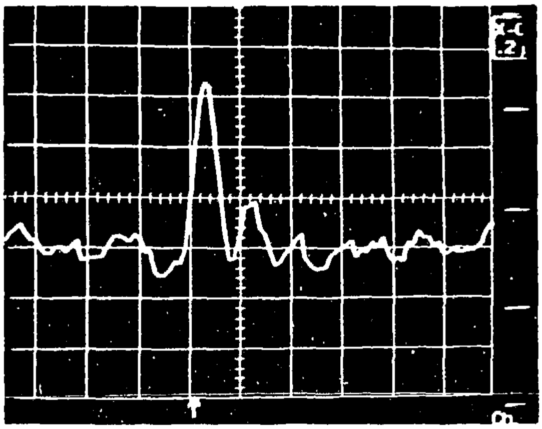
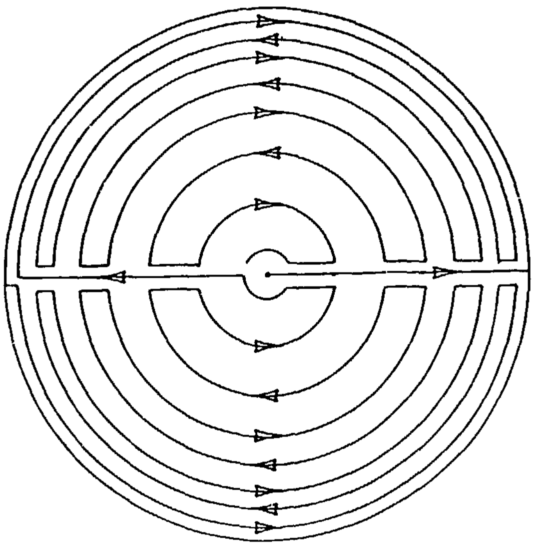


Fig. 4 (left): X-Y read-out for SSG detectors. Redundance in signal is provided by X-Y coincidence and position is given by the intersection between the X and the Y loop.

Fig. 5 (right): Signal produced by a $\oslash < 8\ \mu$m Sn grain at T $\simeq$ 1.4 K in a 20 turn, 500 μm diameter coil using the electronics developed at LPC (College de France). From A. de Bellefon et al. in 31).



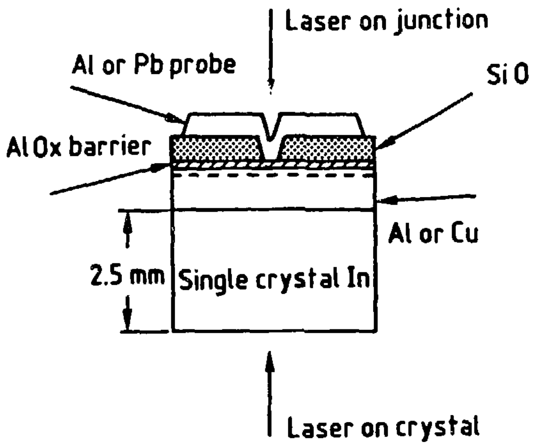


Fig. 6 (left): Gradiometric loop designed by the CFM collaboration for an inductive monopole detector[23)].

Fig. 7 (right): Design of an experiment to test the principle of quasiparticle trapping[28)] from an indium absorber.

by that (much lower) of the superconductor, but other problems arise (capacitive noise, tunneling time...). The actual signal varies like the inverse of the volume of the junction. To circunvent this difficulty, Booth proposed the idea of quasiparticle trapping, where quasiparticles from a large superconducting specimen are concentrated into a small volume of superconductor with a much lower gap. After relaxation of the incoming quasiparticles by phonon emission, the new ones can no longer quit the trap except by tunneling through the junction. Quasiparticle multiplication also occurs, due to phonon emission. Fig. 7 shows the scheme of an experiment using Al or Cu traps (not to scale in the drawing) in a junction Cu (Al) - Oxide- Al deposited directly on the crystal.

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