SUPERCONDUCTING GRANULE DETECTORS

K.P. Pretzl

Abstract

The present status of the development of superheated superconducting granules as a possible detector for neutrinos and dark matter is reviewed.

1. Introduction

The quest for solar neutrinos, the neutrino mass and the nature of dark matter has motivated the development of new unconventional detectors which would be able to measure energies in the range between 1 eV and 1000 eV. Cryogenic detectors are of specific interest since at low energies (< 1 keV) most of the energy lost by a particle traversing a detector is transformed into heat, causing a temperature change $\Delta T = \Delta E/C$ in the detector, with ΔE the energy loss of the particle and C the heat capacity of the detector. At low temperatures (where C is very small) a small energy loss can be transformed into a measurable signal with superconducting and bolometric devices. The interest in superconducting devices for particle detection is based on the very small quantum energies involved (it takes ~ 1 meV to break a Cooper pair) as compared to conventional ionization (~ 20 eV) and semiconductor detectors (~ 1 eV). Consequently, one hopes to reach very much lower energy thresholds and better energy resolutions with such devices. Fortunately, it does not represent any great difficulty to operate cryogenic detectors at millikelvin temperatures, since modern cryogenic techniques are well developed and commercially available.

Many different devices, such as superheated superconducting granules (SSG), superconducting strips, superconducting tunnel junctions, transition-edge detectors, and bolometers, are currently under study. The progress made in this field is well documented in refs [1–4].

It is the aim of this paper to describe the present status of the SSG detector development and to give an outlook for the future. This paper is organized as follows. The SSG detector principle is described in sect. 2. The superconducting properties of the granules are discussed in sect. 3. Tests of the SSG with radioactive sources and particle beams are presented in sect. 4. Section 5 deals with the grain production. Conclusions and an outlook for the future are given in sect. 6.

2. Detector principle

The idea to use superheated superconducting granules as a particle detector goes back to 1967 [5]. The detector principle is very simple. An interaction of an incoming particle within a granule (with a typical diameter of several micrometres) leads to a temperature change ΔT which can be sufficient to cause a phase transition of the granule from the superconducting to the normal state. Assuming global heating, the temperature change experienced by the granule is

$$\Delta T \sim \frac{3\Delta E}{4\pi\, c\, \rho\, R^3}\,, \qquad (1)$$

with ΔE the energy loss of the particle in the grain, c the specific heat, ρ the density, and R the radius of the grain. The phase transition of a single granule can be detected by a pick-up loop which measures the magnetic flux change due to the disappearance of the Meissner effect (fig. 1)

$$\Delta\phi \sim \frac{HR^3}{D}\,, \qquad (2)$$

with H the applied magnetic field and D the diameter of the loop. It should be noted that one loop may contain a large number of

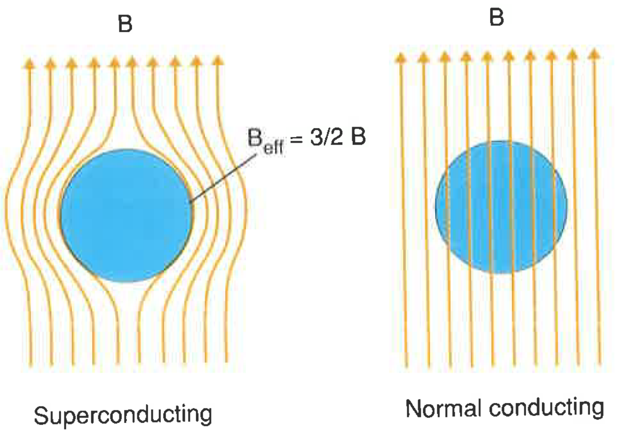

FIGURE 1

Meissner effect of a superconductor.

Particle World, Vol. 1, No. 6, p. 153–162, 1990.

granules. The average signal voltage $\Delta V \sim \Delta\phi/\tau$ is then inversely proportional to the so-called flipping time τ of the granule, i.e. the penetration time of the external magnetic flux into the granule. This penetration time is related to the decay time of the eddy currents in the diamagnetic grain

$$\tau \sim \frac{R^2}{\rho'} \tag{3}$$

and therefore inversely proportional to the normal-state resistivity ρ' of the grain material. Typical flipping times are in the nanosecond range.

Fast phase-transition signals can be obtained with grains made of type-I superconducting materials (table 1). These superconductors have a superheating (H_{sh}) and a supercooling (H_{sc}) phase transition as shown in fig. 2. The ideal superheating is determined by the Ginzburg–Landau parameter κ, which is the ratio of the penetration depth to the coherence length. For $\kappa < 1/\sqrt{2}$ the superheating and supercooling fields are given by

$$H_{sh} = H_c / \sqrt{\kappa\sqrt{2}} \text{ and } H_{sc} = 2.4\ \kappa\ H_c \tag{4}$$

with H_c the thermodynamic critical field. In the region between H_{sh} and H_{sc} the granules are in a metastable state. The effects occurring in the superheated liquid of a bubble chamber are in close analogy to those of the superheated field in a superconductor. In both cases the phase transition begins from a metastable state. In this respect, an SSG detector is similar to a bubble chamber.

Table 1

Some well-known type-I superconductors with their critical temperature T_c and critical field H_c (at $T = 0$). The H_c values are based on magnetic measurements

Metal	T_c (K)	H_c (gauss)
Pb	7.2	803
Sn	3.7	305
In	3.4	293
Re	1.7	200
Al	1.2	99
Ga	1.1	51
Mo	0.92	98
Zn	0.85	54
Zr	0.61	47
Cd	0.56	30
Ru	0.49	69
W	0.015	1

An SSG detector consists of a large number of tiny spherical granules dispersed in a dielectric medium (paraffin etc.) with a filling factor of 10% to 30% in volume. The grains serve as target and detector material at the same time. They are cooled down below the critical temperature T_c and are mounted in an applied magnetic field. The energy needed to cause a phase transition of the grain is determined by the grain size and material, by the operating temperature, and by the applied magnetic field. For a given grain size and material the detector threshold can be chosen by varying the operating temperature and (or) the applied magnetic field.

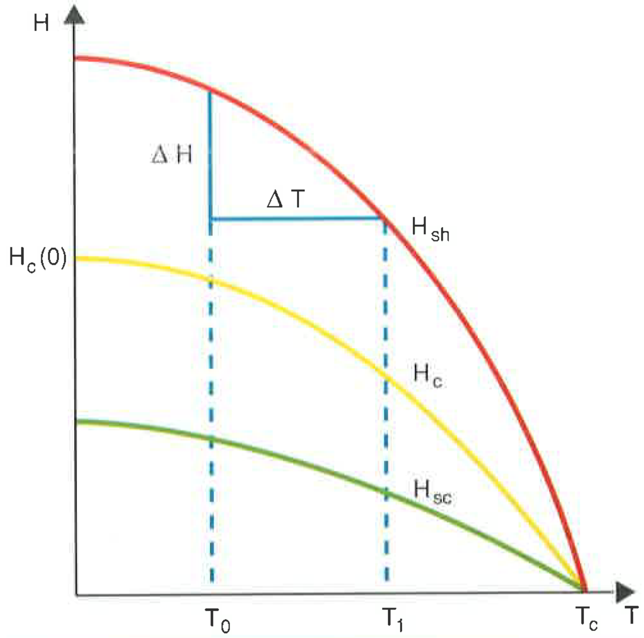

FIGURE 2

Phase diagram of a type-I superconductor, with H_{sh} = superheating field and H_{sc} = supercooling field. The critical thermodynamic field, H_c, is given approximately by $H_c(T) = H_c(0)\,[1 - (T/T_c)^2]$.

In principle, an SSG detector measures phase transitions only above a given energy threshold. However, there exists a possible mechanism by which the energy transferred to the grain can be measured directly. If a grain sits in the phase diagram at a temperature T ($< T_c$) and an applied field H ($< H_{sc}$) it can, via a sufficient energy transfer, be heated up, become metastable, and eventually flip into the normal state (fig. 2). After the phase transition it slowly loses its heat to the surrounding material. The cooling time of the grain can be adjusted to be longer than its flipping time by choosing the appropriate surrounding material, with a high enough thermal boundary resistance. After the grain has cooled down to the original operating temperature of the cryostat it will "flop" back to the superconducting state. The time which passes between the flip and the flop signal of the granule could then be a measure of the energy deposited in the grain ("flip–flop" effect, ref. [6]). In order to keep the energy threshold low, the SSG would have to be operated close to T_c and therefore at a low magnetic field. Another possibility would be to reduce the metastable region by choosing grain materials doped with a small percentage of impurities. A small admixture of impurities decreases the coherence length of the superconductor and therefore increases κ. Reduced metastability was observed in Sn grains doped with 1% Sb [7].

It has been suggested that the phase-transition instability observed by a Technical University Garching group [8] with Cd grains could be used to obtain a direct energy information from SSG. It was found that by lowering the operating temperature T below 350 mK a larger fraction of the grains in a sample undergoes a phase transition at the same external magnetic field. This so-called "avalanche effect" occurs if the latent heat associated with the flip becomes positive in the sense that it produces heat. If this excess heat is large enough to induce flips of neighbouring grains, a chain reaction is started, leading to an avalanche. The observed amplification effect could not have been due to the diamagnetic influence of neighbouring granules since the SSG sample had a very low filling factor (~ 3–4%). Avalanches have recently been observed in other SSG samples such as, for example, Al and Zn [9]. By diluting the granules in a material with an appropriate thermal boundary resistance, the amplification could be confined to microavalanches. The number of flipped granules is proportional to the energy released by the interacting particle provided that the grains are small enough. The "flip–flop" and the avalanche effect are at present under experimental investigation by various groups.

The signal read-out of a 1 kg SSG detector represents one of the major problems which need to be solved. Using conventional electronics and pick-up loops, the number of read-out channels becomes very large. This problem seems to be common to almost all cryogenic detectors.

Flips of 15 µm Sn granules have been detected with a signal-to-noise ratio of ten-to-one using multiloop pick-up coils of 2 mm in diameter and several millimetres in length [10]. Signals with grain sizes < 10 µm were obtained with voltage-sensitive amplifiers and with low-inductance pick-up loops [11]. The signal-to-noise ratio is proportional to

$$\frac{S}{N} \sim \frac{\Delta\phi}{\sqrt{L}}\,, \qquad (5)$$

with L the inductance of the pick-up loop.

Current loops can, for example, be made on printed-circuit boards with small wire distances (≤ 50 µm). A layer of granules diluted in paraffin is surrounded by a coordinate system of current loops as sketched in fig. 3. In this arrangement an event can be localized in space by the coincidence of two loops perpendicular to each other. For a full-size detector, many of these layers can be combined and sandwiched together. However, the number of read-out channels for such a device can become quite large.

A radio-frequency (RF) Superconducting QUantum Interference Device (SQUID) system has been employed to detect phase transitions of 6 µm grains [12]. This technique offers the possibility to read-out a larger SSG detector volume and consequently to reduce the number of read-out channels considerably. With commercially available d.c. SQUIDs it would perhaps be possible to measure single-grain flips within a detector volume of a few cubic centimetres. However, SQUIDs are difficult to handle since they need elaborate magnetic shielding. They also have a rather slow time response. This, however, is not a problem when low counting rates are expected. Since this seems to be a promising read-out technique it is currently under investigation by many research groups.

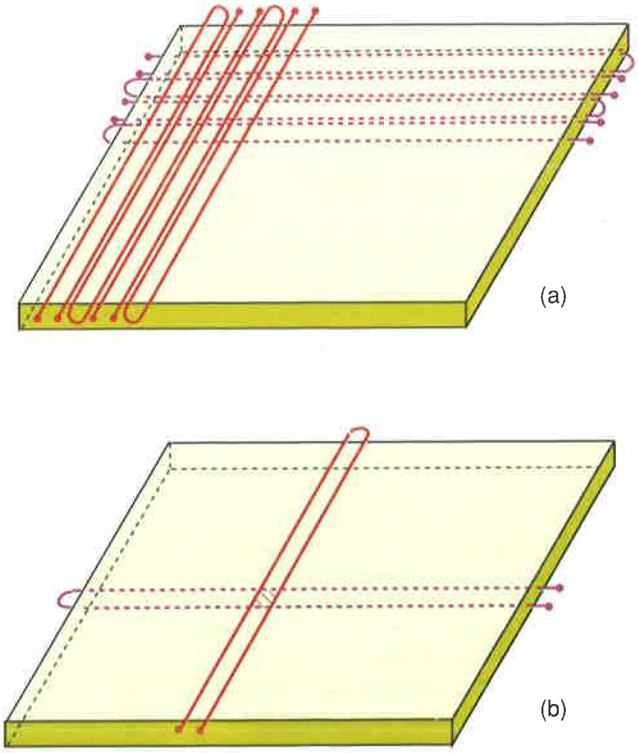

FIGURE 3

(a) A foil of grains surrounded by a (x, y)-coordinate system of pick-up loops; (b) a localized event detected by a coincidence of two loops perpendicular to each other.

The envisaged detection principle for neutrinos or dark-matter candidates (if they exist in form of weakly interacting massive particles, the so-called WIMPs) is based on neutral-current (n.c.) interactions with a nucleus in a granule (coherent neutrino–nucleus scattering) [13]. The nuclear recoil energy transformed into heat can cause a phase transition of the granule producing a signal in the pick-up coil. In this application, the neutrino as distinct from a minimum ionizing particle (m.i.p.) would only flip one single granule (in this case, the SSG detector would have to be operated at a temperature where the avalanche effect does not occur). A m.i.p. can be recognized by the fact that it causes many granules to flip. Its energy loss in the detector is proportional to the number of flipped grains. This signature can be used to reject background events due to cosmic rays, Compton scattering and surrounding material radioactivity. The cross section for coherent neutrino–nucleus scattering can be calculated from the standard electro-weak model

$$\frac{d\sigma}{d(\cos\theta)} = \frac{G_F^2}{8\pi}[Z(4\sin^2\theta_W - 1) + N]^2 E^2 (1+\cos\theta), \quad (6)$$

with Z the number of protons and N the number of neutrons in the nucleus. For $\sin^2\theta_W \cong 0.22$ (with θ_W, the weak interaction Weinberg angle) and $G_F = 1.166 \times 10^{-5}$ GeV^{-2} (the weak interaction Fermi coupling constant), the cross section

$$\sigma \cong 0.42 \times 10^{-44} N^2 E^2 [\mathrm{cm}^2] \quad (7)$$

is essentially proportional to N^2 and E^2, with E the energy of the incident neutrino measured in mega-electronvolts. The coherence condition $R_A \times \Delta \leq 1$, where R_A is the radius of the nucleus and Δ the momentum transfer of the neutrino to the nucleus, is fulfilled for SSG materials with an atomic weight up to Sn, and neutrino energies below 30 MeV.

Because of the coherence factor N^2 the cross section for neutrino scattering is larger by a factor 10^3 to 10^4 than that of the inverse beta-decay reactions used, for example, in the solar neutrino GALLEX experiment. Thus, an SSG detector with an effective mass of a few kilograms will measure the same solar neutrino event rate as a multiton detector based on inverse beta decay. By varying the energy threshold of the SSG detector, the energy spectrum of solar neutrinos can be examined. Because of the n.c. interactions, the SSG detector is sensitive to all neutrino flavours and therefore insensitive to neutrino oscillations. In this respect, an SSG detector would provide interesting complementary information about the solar neutrinos. The expected event rates per kilogram of SSG per year for solar neutrinos, reactor neutrinos, and WIMPs are given in table 2.

Table 2

Expected event rates per year for 1 kg neutral current detectors of various SSG materials.

	Al	Cd	Sn	Pb
Reactor ν ($E_\nu = 3$ MeV)	6×10^4	3×10^5	3×10^5	6×10^5
Solar ν ($E_\nu = 0.3$ MeV)	2	9	10	19
WIMPs ($m_x \cong 100$ GeV)	4×10^4	1.7×10^6	1.7×10^6	2.2×10^6

The principal difficulty of this method is, of course, the detection of the small nuclear recoil energy Q. Its average value is given by

$$\bar{Q} = 0.7E^2/A \text{ [keV]}, \quad (8)$$

with E the neutrino energy measured in mega-electronvolts, and A the atomic weight of the grain material. Typical recoil energies range from 1 eV to 1000 eV.

When choosing the detector material a compromise has to be made between a cross section increasing with N^2 and a recoil energy decreasing with A. Assuming global heating, the sensitivity of detecting very small recoil energies depends on the specific heat and the size of the grains.

For WIMPs the maximum nuclear recoil energy is

$$Q_{\max}^{\text{recoil}} = \frac{2m_x^2 M}{(m_x + M)^2} \mathrm{v}^2, \quad (9)$$

where M is the mass of the nucleus in the grain, m_x the mass of the WIMP, and v the velocity of the dark-matter particle. Assuming Sn grains and $\mathrm{v}/c \cong 10^{-3}$, for a typical velocity of objects in our galaxy, the recoil energies range from 16 eV to 50 keV for particles of mass between 1 GeV and 100 GeV. The recent Z^0 decay data, however, put a new constraint on the mass range of the WIMPs [14].

A prominent dark-matter candidate, the photino, interacts with nuclei via spin-dependent forces. Thus, grain materials with a large nuclear spin (Al or Ga) should be chosen. A list of suitable materials, with their quality factors, is given in ref. [15]. By using SSG detectors with different materials, one can distinguish between spin-dependent (photinos) and spin-independent (massive neutrino, sneutrino, etc.) interactions of dark-matter particles. The event rate due to photino interactions in a detector using Ga grains is 100 times larger than in one using Zn grains, for example. The estimated event rate for photino masses of ≅ 2 GeV is 0.1–1 ev./kg/day [13]. A recent review on the application of SSG detectors for solar neutrinos, dark matter, monopoles, and double-beta decay and their limitations is given in ref. [16].

3. Superconducting properties of the SSG

The description of the SSG-detector principle given in sect. 2 was made under the assumption that the superconducting properties of the granules are "ideal". However, early measurements with a sample of Sn or Cd granules [17] showed a substantial broadening ΔH of the so-called "hysteresis curve" as the applied field was swept through the superheating (H_{sh}) and supercooling (H_{sc}) phase transition (fig. 4). Typical values of 20–30% were obtained for $\delta H/H$.

For a better understanding of this effect, experiments with single grains were performed, rotating the grains around an axis perpendicular to the applied magnetic field [18, 19]. By sweeping the field at a fixed temperature, H_{sh} and H_{sc} were measured as a function of the rotation angle (fig. 5). Experiments with Al, Zn, In, and Sn grains at various operating temperatures exhibited a

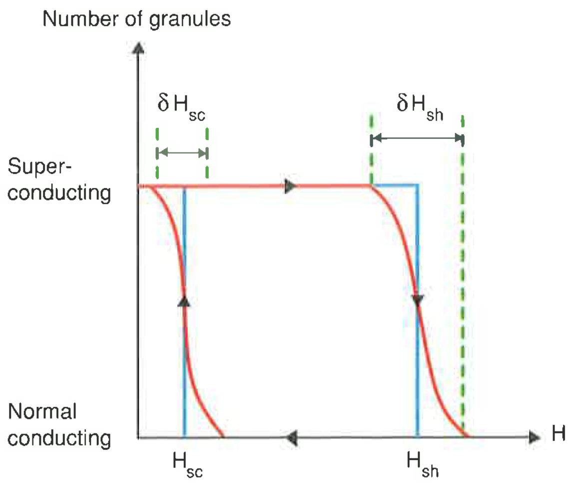

FIGURE 4

Schematic view of external field hysteresis for a group of granules at fixed temperature. The experimental observation is shown as a red line while the ideal behaviour is indicated as a blue line.

phase-transition smearing $\delta H/H$ of 10–30%. It appears that the entire broadening of the phase transitions observed with groups of grains in a sample can be explained by the behaviour of individual granules. This phase-transition broadening is of significance for an SSG detector since it smears the energy threshold, and consequently limits the sensitivity and the energy resolution of the detector. This behaviour can be understood in terms of a simple geometrical model in which so-called nucleation centres on, or near, the surface of the grains are moving under the rotation of the grains in a region where the field lines are compressed. These nucleation centres can cause a grain to flip at less than its "ideal" superheating field. As shown in figs 6 and 7, the experimental results can be reproduced by this simple geometrical consideration. Nucleation centres can arise from surface imperfections, impurities, dislocations, etc., or from the crystalline structure of the grains. The crystalline structure is probably the dominant effect since the supercooling phase transition, which is insensitive to surface defects, exhibits a similar variation as the superheating phase transition. Measurements on single superconducting Sn crystals have shown a considerable anisotropy of the field penetration depth with respect to the orientation of the

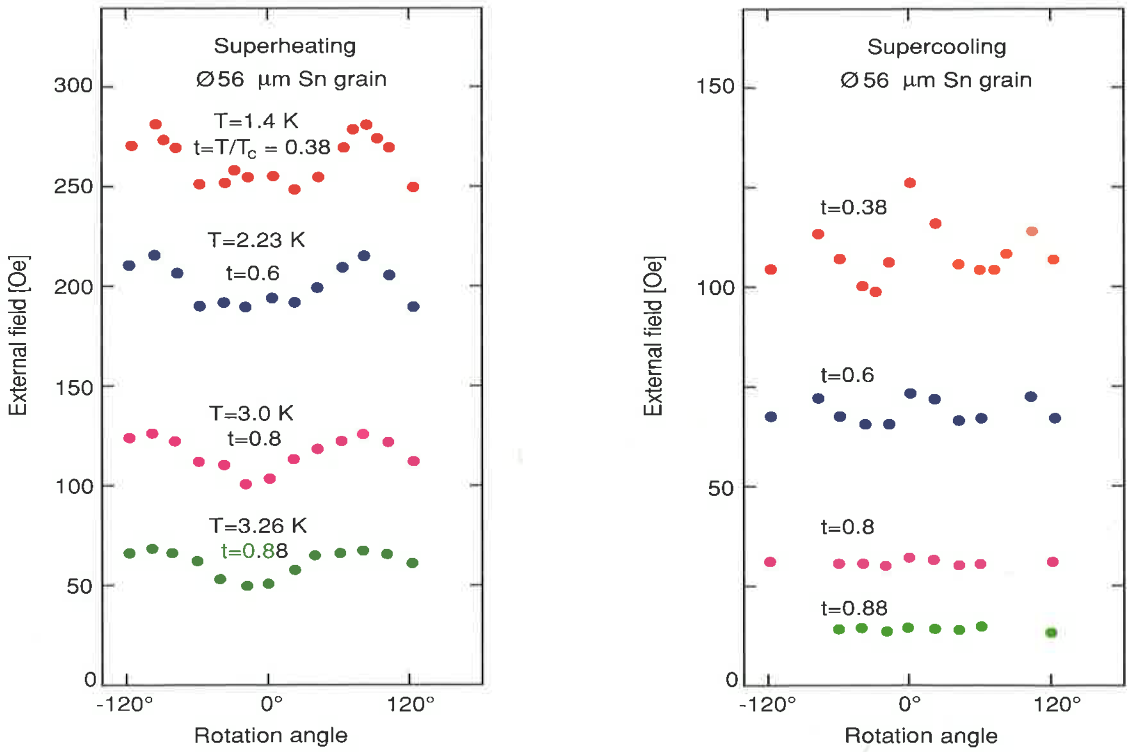

FIGURE 5

Superheating and supercooling field for a Sn grain of 56 µm diameter at various temperatures (from ref. [25]).

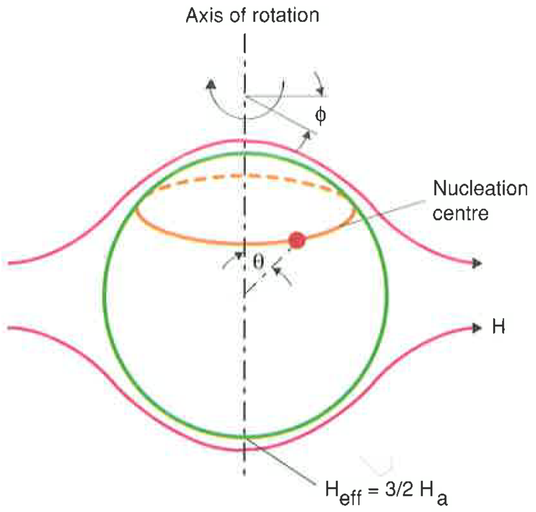

FIGURE 6

Grain in an applied field H_a with a nucleation centre at the polar angle θ with respect to the rotation axis. The rotation angle ϕ is also shown (from ref. [19]).

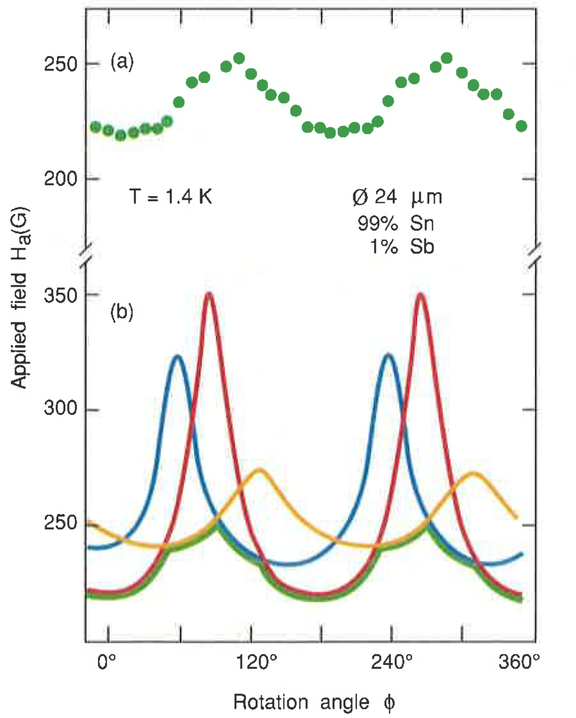

FIGURE 7

(a) Superheating field H_{sh} as a function of the rotation angle ϕ of a 24 µm Sn–Sb grain at 1.4 K; (b) as indicated by the green line, three nucleation centres are sufficient to fit the data in (a) (from ref. [19]).

crystallographic axis in the external magnetic field [20]. The reason is that electrons from different regions of a non-spherical Fermi surface become responsible for the effective shielding currents of the superconductor when changing the orientation of the crystal. A metallurgical investigation of the grains has shown that approximately half of the examined grains were monocrystals while the other half contained several monocrystals with different orientations(*). Thus, the superconducting behaviour of the grains (H_{sh} and H_{sc}) can change according to the orientation of the crystals. It was suggested that by adding some impurities the crystal formation can be influenced in such a way that the variation of the phase transition diminishes [21]. Experiments with Sn grains doped with 1% Sb showed a considerable flattening of the rotation curves for 250 µm grains [7]. However, for 25 µm doped grains, compared with undoped grains, no change was found. The metallurgical examination of the doped grains showed that the Sb was not uniformly dissolved in Sn, but rather concentrated in distinct clusters. This suggests that the observed flattening with big-size grains (250 µm) could be due to a large increase of nucleation centres, which averages out the variation in H_{sh} and H_{sc}. More experiments with impurity-doped grains are necessary for a better understanding of this effect.

Encouraging results with lithographically produced In grains were recently reported (ref. [22] and sect. 5). The obtained spread in transition temperatures was nearly an order of magnitude smaller than with granules from other productions. It would be interesting to know whether this improvement is due to a different crystalline structure of the In grains. Perhaps the lithographic production process of the grains introduces a polycrystalline structure, which reduces the phase-transition variation.

The phase-transition broadening observed with a group of granules can also be attributed to the formation of an intermediate state in which a granule is subdivided into superconducting and normal zones. When raising the magnetic field some zones stay superconducting and others flip to normal at different values of the applied field below the "ideal" H_{sh}. The observed flip signals were very much smaller than expected for phase transitions of an entire grain (refs [11] and [18]). This intermediate-state behaviour was frequently observed with granules of large diameters (≥ 50 µm) and much less frequently with smaller granules. Since the probability of the intermediate-state formation is expected to decrease with decreasing grain diameter, this effect may no longer be of importance for small grains.

The phase-transition smearing is one of the main difficulties to be overcome for the development of SSG detectors with high sensitivity. Impurity-doping or polycrystalline grain structures may offer a promising solution to this problem. This has to be considered in the grain production.

(*) The crystalline structure analysis of the grains was made by H.E. Exner, J. Paul and S. Mc Kay from the Max-Planck Institut für Metallforschung, Stuttgart, Deutschland.

4. Irradiation experiments

In order to investigate the sensitivity as well as the heating mechanism of the granules (global versus local heating) several experiments were done by bombarding granules with α, β, and γ particles from radioactive sources and with e, π, and μ from accelerator beams (refs [8, 18, 19 and 23–27]).

In a global heating model, it is assumed that the entire grain is uniformly heated before it eventually undergoes a phase transition. For a superconductor in thermal equilibrium the amount of heat per volume V needed to raise the temperature from T_0 to T_1 is given by

$$\frac{Q}{V} = \int_{T_0}^{T_1} c\, dT \qquad (10)$$

with the specific heat

$$c = \alpha T^3 + 8.5\gamma\, T_c \exp(-1.44\, T_c/T) \qquad (11)$$

and the specific constants of the material α and γ. The α term represents the specific heat due to phonons and the γ term due to electrons.

A systematic study of the heating mechanism was recently performed by the MPI-Munich group by bombarding single Al, Zn, Sn, and In granules with 4 MeV and 2 MeV α particles (ref. [19]). It was assumed in these measurements that the α particles lose all their energy in the granules. The deposited energy may then suffice to flip the grains into the normal state when the external field is raised close to H_{sh}. This happens at a certain field value ΔH below H_{sh}, corresponding to a temperature change ΔT of the grains (fig. 2). In a global heating model a measurement of ΔH can be considered as a measurement of a temperature change ΔT of the grains. Thus, the quantity $\Delta H/H_{sh}$ is related to the sensitivity of the grains. Figure 8 shows the measured $\Delta H/H_{sh}$ values as a function of temperature, for 4 MeV and 2 MeV α particles incident on a 60 µm and a 40 µm diameter Al grain. The solid curves in fig. 8 were calculated from eqs (10) and (11). They represent constant values of a given deposited α energy per grain volume. The agreement of the measured and the calculated thermal behaviour of the Al grains is very good. Similar results were obtained with Zn grains. Thus, the thermal behaviour of Al and Zn granules can be predicted quite accurately. The results show only a small increase in sensitivity when the SSG detector is operated at very low temperatures $T << T_c$. The largest sensitivity $\Delta H/H_{sh}$ can be reached close to T_c. However, this situation involves very small external magnetic fields which enter directly into the detector signal. In general, large sensitivities can be obtained with granule materials with low T_c. For the detection of solar neutrinos and reactor neutrinos, very small granules have to be employed in order to reach the necessary sensitivity. As an example, the corresponding Q/V values are listed in table 3 for Al granules.

On the other hand, Sn and In granules behave quite differently. Early measurements showed that Sn grains are more sensitive

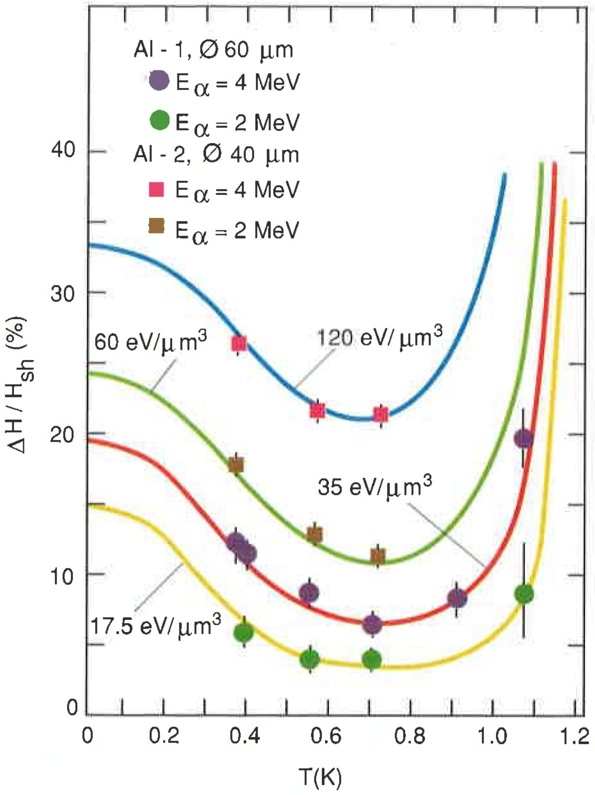

FIGURE 8

The measured $\Delta H/H_{sh}$ values as a function of temperature, for 4 MeV and 2 MeV α particles incident on 60 µm and 40 µm diameter Al granules. The points with error bars are the measured values and the solid curves were calculated from eqs (10) and (11) assuming global heating (from ref. [19]).

Table 3

The corresponding Q/V [eV/µm^3] and $\Delta H/H_{sh}$ values are shown for reactor neutrino, solar neutrino and dark-matter candidate interactions in Al grains of various diameters. The temperature of the grains is assumed to be 100 mK.

	Average recoil energy [eV]	Grain diameter [µm]	$\frac{Q}{V}\left[\frac{\text{eV}}{\mu\text{m}^3}\right]$	$\frac{\Delta H}{H_{sh}}$
Reactor ν				
(E_ν = 3 MeV)	222	2	53	0.22
Solar ν				
(E_ν = 0.4 MeV)	4	2	1	0.05
(E_ν = 1 MeV)	25	2	6	0.10
WIMPs				
(m_x = 100 GeV)	33 000	10	63	0.25

when α particles strike near their equator, where the effective magnetic field is higher, than at their pole [25].

It was also found that large-size granules flipped under the bombardment of α particles even when the total energy transfer of the α particles did not suffice to heat the entire grain above the phase-transition threshold [25, 26]. These observations suggested that a local heating process takes place. In this case, only a small fraction of the grain needs to be heated to cause a breakdown of the superconduction and consequently a grain flipping. This is in contrast to a global heating process, where the entire grain needs to be heated before it can flip. It turns out that flips due to local heating occur at smaller applied fields than flips due to global heating. This results in an increased sensitivity of a grain.

The local heating effect finds a possible explanation when considering the heat diffusion process in the grain [28]. A highly-ionizing α particle produces electrons when stopping in the grains. These electrons lose energy via electron–electron interactions whereby Cooper pairs are broken and quasi-particles created (the loose partner of a former Cooper pair is called a quasi-particle). But also electron–phonon interactions with phonon emission take place. Phonons can break Cooper pairs and produce quasi-particles as long as their energy is larger than the binding energy of the Cooper pairs. These subsequent relaxation processes continue until quasi-particles and phonons reach thermal equilibrium. In Sn and In grains the quasi-particles apparently lose their energy within a short distance, and a warm spot is created along the track of the α particle before the heat can spread over the whole grain. Therefore, a nucleation centre near the warm spot can experience a temperature change before the entire grain is heated, and cause it to flip. This heat diffusion process is in contrast to the one observed in Al and Zn granules. In the global heating process the quasi-particles spread fast across the entire grain before thermal relaxation occurs. Therefore, the nucleation centres cannot be heated more than the rest of the grains, no matter where the α particle hits the grain. This fits well with the fact that quasi-particle lifetimes are unusually large for Al and Zn [29].

The local heating effects observed with Sn and In grains indeed lead to a substantial increase in sensitivity (factors of up to 25 were observed) but they imply a poor definition of the phase-transition threshold. Therefore, materials with local heating effects seem not to qualify for use in SSG detectors, which aim for a sharp threshold behaviour.

However, in coherent neutrino scattering the recoil energies can be well below the ionization energy, in which case most of the energy is transformed into phonons and the global-heating model may apply. What fraction of this energy is used up, for example, by the recoil atom in producing permanent lattice dislocations, is still unexplored. However, radiation damage studies indicate that it is small. Furthermore, it can be assumed that at low enough energies ($E \sim 20$ eV for Al) recoil atoms do not leave their lattice positions and all their recoil energy is transformed into phonons.

Experiments with low-energy neutrons (9–70 MeV) are planned to study the sensitivity of SSG to recoil nuclei in elastic neutron–nucleus scattering [30]. The mono-energetic neutrons will be obtained from the proton accelerator at the Paul Scherrer Institute (Villigen, Switzerland). The SSG serve as target and detector at the same time. The recoil energy of the nucleus will be determined by the measurement of the neutron scattering angle. The sensitivity of SSG to recoil energies down to a few kilo-electronvolts or lower can be studied this way. These measurements present an important step for the better understanding of SSG as a recoil detector.

It should be mentioned that small samples of SSG were recently exposed to an electron beam of 3 MeV at the University of Paris [24] and to e, π, and μ beams of 220 MeV/c at the Paul Scherrer Institute [27]. This is the first time that SSG were operated as a beam particle detector. Coincident signals between the beam counters and the SSG signals were observed. The efficiency of the SSG detector for detecting minimum-ionizing particles was found to be 100%.

5. Production of the granules

Large quantities of granules can be industrially fabricated(*). Frequently used production techniques involve pulverization or ultrasonic atomization of molten metals. The latter technique, which is similar to the one used in commercial humidifiers, produced the best-quality granules. A thin film of liquefied grain material is brought onto the surface of an ultrasonic transducer head. The granules evaporate from the head with an average diameter of

$$\bar{d} \sim f^{-2/3} \tag{12}$$

with f, the operating frequency of the ultrasonic transducer. They obtain their spherical shape from the surface tension which they experience during their flight and cool-down time in an inert gas before being collected in a funnel. The sphericity and surface quality of the grains can be seen in fig. 9. However, the grain diameter distribution is very large ($\Delta d/\bar{d} \sim 50\%$ full width) and requires further grain-size selection after the fabrication of the grains. Several possibilities are conceivable, such as molecular sieves, centrifugation, and sedimentation. The selection of small-size grains in large quantities, with a diameter variation of a few per cent, is one of the most urgent problems to be solved for the SSG detector development. Up to now, small grains with diameters down to 5 μm have been fabricated industrially. One big problem connected with this production technique is the above-discussed crystalline structure of the grains.

(*) Extramet, F-74380 Bonne-sur-Menoge (Haute-Savoie) France.
Valimet Inc., P.O. Box 6186, Stockton CA 95206, USA.
Heubach, Heubachstr. 7, D-3394 Langelshein, Germany.

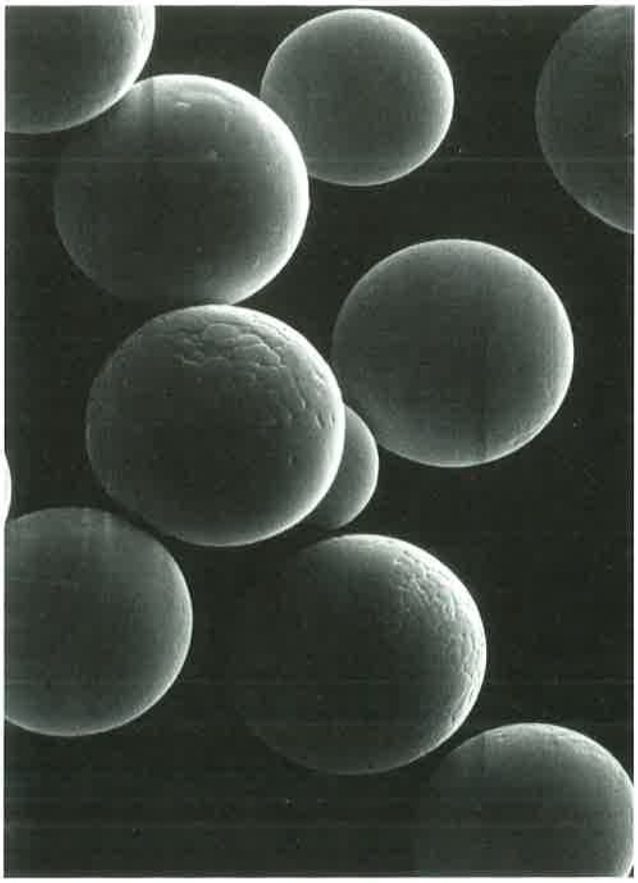

FIGURE 9

Tin granules, as shown by an electron microscope.

The above-mentioned results (sect. 3), obtained by a group at the University of Vancouver (British Columbia, USA) with a new type of SSG detector consisting of a planar array of granules, looks promising [21]. They named their detector "PASS" for Planar Array of Superheated Superconductors. They managed to produce spherical In granules from a planar array of squares, using photolithographic techniques on a suitable substrate. By slowly melting the squares on the substrate, spherical granules could be formed with diameters that were equal within 10%. The great advantage of this method is the resulting reduction on the phase-transition spread and the good size selection of the granules. It remains to be seen whether this method can also be applied to other superconducting materials. In any case, this rather complicated production process puts limits on the mass production of the granules.

With techniques commonly used for the fabrication of integrated circuits, it is possible to bring a large quantity of equal-size granules with a well-defined geometry (cubes or cylinders) together with the read-out loops on a suitable substrate. This arrangement has the advantage that the read-out loops can be brought very close to the grains. A prototype SSG detector consisting of Al grains with typical dimensions of $5 \times 5 \times 4\ \mu m^3$ and read-out loops made of gold on a 1 cm^2 sapphire substrate is at present in preparation(*). It is hoped that such a device can be read-out with conventional electronics. Of course, the number of read-out channels needed is still quite large for a full-size detector.

Lithographic techniques may help in the future to solve the problem of the production of equal-size granules as well as the problem of the phase-transition smearing.

6. Conclusions

The development of SSG detectors is still in an initial phase. It is not clear at this moment whether the goals to detect low-energy neutrinos or dark matter can be reached in the near future. However, an enormous step forward has been made in the better understanding of the superconducting properties of the granules and their behaviour under irradiation.

Compared with other cryogenic detectors, SSG offer some unique features. The large list of suitable type-I superconductor materials allows an optimization for various applications whith, for example, the dark matter (spin-dependent and spin-independent interactions), the solar neutrino, and the double-beta decay detection. Possible background due to cosmic rays, Compton scatterings, and radioactive materials can be reduced by the ability to distinguish m.i.p.'s, which cause many grains to flip, from neutrino interactions, which cause only one grain to flip. If required, a fast timing information can be obtained from the SSG since the flip time of small-size granules is in the nanosecond range.

A successful use of SSG as a particle detector will strongly depend on future developments with respect to granule production, size selection, and signal read-out. Promising steps in this direction are the lithographic planar array production of the granules and the read-out using SQUID techniques. The detection of nuclear recoil energies in elastic neutron interactions will be an important bench-mark test for SSG in the near future.

The technical realization of a 1 kg detector, however, seems to be still an unsolved problem for most of the cryogenic detectors under development.

Acknowledgements

I would like to thank P. Freund, D. Perret-Gallix, L. Stodolsky, and my colleagues from the Laboratory for High-Energy Physics in Berne (Switzerland) for their critical reading of the manuscript and very useful discussions.

(*) Laboratory for High-Energy Physics at the University of Berne in collaboration with the Institute for Micro-technology at the University of Neuchâtel, Switzerland.

References

[1] K.P. Pretzl, N. Schmitz and L. Stodolsky (eds), Low-temperature detectors for neutrinos and dark matter, Springer Verlag, Berlin (1987).

[2] L. Gonzalez–Mestres and D. Perret–Gallixeds (eds), Low-temperature detectors for neutrinos and dark matter II, Editions Frontières, Gif-sur-Yvette, France (1989).

[3] L. Brogiato, D.V. Camin and E. Fiorini (eds), Low-temperature detectors for neutrinos and dark matter III, Editions Frontières (1990).

[4] A. Barone (ed.), Superconducting particle detectors, World Scientific, Singapore (1988).

[5] H. Bernas et al., Phys. Lett. A24 (1967) 721;
C. Valette, Thesis, Orsay (1971);
D. Huebner, C. Vallette and G. Waysand, Cryogenics, (July 1981) 387.

[6] A.K. Drukier and L. Stodolsky, Phys. Rev. D30 (1984) 2295.

[7] P. Freund et al., in ref. [4] p. 305;
A. Singsaas et al., Ann. Phys. (Paris) 13 (1988) 151.

[8] W. Seidel et al., Rev. Sci. Instr. 58(8) (1987) 1471.

[9] P. Freund et al., in ref. [3] p. 55.

[10] Berne University (paper in preparation).

[11] A. de Bellefon et al., in ref. [2] p. 425.

[12] A. da Silva et al., in ref. [2] p. 417.

[13] A. Drukier and L. Stodolsky, Phys. Rev. D30 (1984) 2295;
M.W. Goodman and E. Witten, Phys. Rev. D31/12 (1985) 3059–3063.

[14] L.M. Krauss, Phys. Rev. Lett. 64/9 (1990) 999–1002;
J. Ellis et al., Phys. Lett. B245/2 (1990) 251–257.

[15] R.A. Flores, in ref. [2] p. 103.

[16] K.P. Pretzl, in ref. [4] p. 213;
L. Stodolsky, First Intern. School in Astroparticle Phys., eds A. de Rújula, D.V. Nanopoulos and P.A Shaver, World Scientific, Singapore (1987) 629.

[17] F. v.Feilitsch et al., Nuovo Cimento 9C/2 (1986) 598.

[18] K.P. Pretzl, in New and Exotic Phenomena, Proc. 7th Moriond Workshop, Les Arcs, France, eds O.C. Fackler and J. Tran Thanh Van, Editions Frontières, Gif-sur-Yvette (1987) 243.

[19] M. Frank et al., Nucl. Instr. and Meth. A287 (1990) 583–594;
M Frank et al., Phys. Lett. B230 (1989) 159.

[20] P.C.L. Tai et al., Phys. Rev. B11/l (1975) 411.

[21] B.S. Chandresekhar (private communication).

[22] M. Le Gros et al., in ref. [3] p. 91.

[23] A. Kotlicki et al., in ref. [1] p. 32.

[24] A. de Bellefon et al., in ref. [3] p. 109.

[25] K.P. Pretzl et al., in ref. [1] p. 30.

[26] L. Gonzalez Mestres and D. Perret-Gallix, in ref. [1] p. 9.

[27] Berne University, LAPP Annecy and Max-Planck Institute Munich (report in preparation).

References (Cont'd)

[28] M. Frank et al., Max-Planck Institute, MPI–PAE/Exp. EL. (1990) 225.

[29] S.B. Kaplan et al. Phys. Rev. B14 (1976) 4854.

[30] Berne University and LAPP Annecy Collaboration, PSI Proposal R–89–07.1 and Add. Z–90–12.1 (1989–1990).

Address:

University of Berne
Laboratory for High-Energy Physics
Sidlerstr. 5
CH–3012 Berne, Switzerland

Received on 10 July 1990.