INVESTIGATION OF SUPERCONDUCTING TIN GRANULES FOR A LOW ENERGY NEUTRINO OR DARK MATTER DETECTOR

presented by
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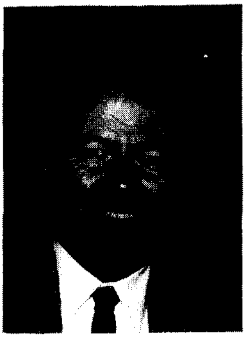

ABSTRACT

The properties of single superconducting tin granules with a diameter between 20 and 112 μm were studied between 3.26 and 1.4 Kelvin in a magnetic field. The granules were rotated around an axis perpendicular to the magnetic field axis and the superheating and supercooling fields were determined. We observed that each granule exhibits its own characteristic superheating and supercooling field which strongly depends on the rotational angle. For granules with effective superheating fields just above the critical thermodynamical field a phase transition was observed which took place over only a part of the granule (intermediate state). Single tin granules were also irradiated with α-particles of 5.5 MeV energy. Phase transitions were clearly observed. The results are consistent with local heating.

1. Introduction

Superheated superconducting granules (SSG) have been suggested as possible detectors for solar neutrinos and dark matter particles [1,2]. The method uses the neutral current process of neutrino-nucleus elastic scattering (also for dark matter particles, if weakly interacting). The main advantages are:

a) The coherent scattering cross section is 3 orders of magnitude greater than the cross sections of other processes like, for example, inverse beta-decay. Thus a SSG detector with a weight of a few kilograms would measure the same event rate as a multiton detector based on other processes.

b) The SSG detector responds to all kinds of neutrinos equally.

The principal difficulty with this method is, of course, the detection of a very low nuclear recoil energy E_A. Its average value is given by $\overline{E}_A = 2\,E_\nu^2/3A$ [keV] (with the neutrino energy, E_ν, measured in MeV) and comes out to be 0.9 eV (assuming Sn grains) for solar neutrinos with $E_\nu = 0.4$ MeV.

In a uniform heating model most of this energy will be transformed into heat, leading to a temperature change ΔT of the grain. This temperature jump can flip a grain from the superconducting to the normal state. This is illustrated in Fig. 1 for a tin (Sn) grain which has a superheating transition field H_{SH} and a supercooling field H_{SC}. For a grain with a radius r, a density ρ and a specific heat c, the temperature change is $\Delta T = 3E_A/4\pi c\rho r^3$. To measure 0.4 MeV solar neutrinos, for example, a SSG detector would have to be made of tiny Sn grains with a diameter of 1.7 μm which are cooled down to T = 50 mK, if the minimum energy threshold would be set to 0.9 eV, corresponding to ΔT = 10 mK. The grain flip can be detected with a pick-up coil which measures the flux change due to the disappearance of the Meissner effect (Fig. 2). The expected event rates per year per kilogram SSG are 30 for solar neutrinos and 6.10^4 for weakly interacting dark matter particles with a mass of 1-2 GeV. Dark matter candidates with spin dependent interactions (e.g. photinos) can also be detected with SSG, provided the grain material has a large nuclear spin.

Backgrounds due to natural radioactivity of the detector-material and cosmic rays are a major problem to be solved, but this will not be discussed here.

The SSG technique is still under feasibility study. Several groups [3] have reported results at this meeting. We present measurements which we performed with single Sn grains of diameter 20-112 μm. In section 2 we report on granule properties when rotated around an axis perpendicular to the external magnetic field. In section 3 we show results obtained when irradiating single grains with α-particles. Section 4 gives the conclusions.

2. Properties of individual Sn grains in an external magnetic field

This investigation was motivated by the observation [3,4] that groups of Sn or Cd grains exhibited a washed-out phase transition $\Delta H_{SH}/\overline{H_{SH}} \sim \Delta H_{SC}/\overline{H_{SC}} \sim$ 20-30% [Fig. 3]. In order to study possible surface or crystaline structure effects, we rotated individual grains around an axis perpendicular to the external magnetic field. By cycling the magnetic field at fixed temperature we measured H_{SH} and H_{SC} as a function of the rotation angle (Fig. 4). The experiment was performed in a temperature range of 1.4 K < T < 3.26 K. The results for one Sn grain with a diameter of 56 μm are shown in Fig. 5 for various temperatures. We found a similar behaviour with grains of 20 μm and 112 μm diameter (see also ref. 5). The measured variations $\Delta H_{SH}/\overline{H_{SH}}$ and $\Delta H_{SC}/\overline{H_{SC}}$ of individual grains when rotated in an external field came out to be as large as 30%, thus explaining the magnitude of the phase transition smearing observed for a group of grains.

For granules with effective H_{SH} (in Fig. 1 shown as H'_{SH}) very close to the critical thermodynamical field H_c, we measured grain flip signals which were very much smaller than expected for a phase transition of an entire grain. This observation is consistent with what one would expect if the granule were subdivided into superconducting and normal zones (intermediate state). In some cases the superconductivity of the grain is only partially broken, up to the point where $H_{eff} < H_c$ (with H_{eff} being the effective field at the equator of the grain where the field lines are compressed, Fig. 2).

3. Irradiation of individual Sn grains with α-particles

We have chosen an α-source (Am^{241} source with $E_\alpha \sim 5.5$ MeV) for the irradiation experiment since α-particles, in central collisions, lose all their energy in the grain. Their penetration length in Sn is 14 μm. The α-source, with an activity of 6.35 μCi, was mounted at a distance of about 200 μm from the grain inside the pick-up coil. In order to reactivate the grain after it flipped into the normal state, the external magnetic field was cycled as shown in Fig. 4. The helium bath was kept at T = 1.4 K. Due to the energy release of the α-particle in the grain, the magnetic field at which the flip of the grain occurs is ΔH_α below H_{SH} at T = 1.4 K (Fig. 1). In the case of global heating, ΔH_α is proportional to the energy release of the α-particle and inversely proportional to r^3 for small ΔT. Fig. 6 shows the measured distribution of the magnetic field at which the phase transition occured for a Sn grain with 56 μm ϕ. As shown schematically in Fig. 6, the measurement was performed at various irradiation angles (0^o, 45^o and 80^o). For monoenergetic α's a sharp peak at $H_{SH}-\Delta H_\alpha$ would be expected. However, because of the finite energy loss of α's in the helium bath and non-central collisions with the grain, this distribution is broadened. The change of the center of gravity of the distribution at 80^o indicates that the grain is more sensitive if α-particles hit at the equator of the grain, where H_{eff} is largest, than at the pole. The same effect we observed with a 100 μm ϕ grain. Furthermore, the maximal ΔH_α came out to be 41(41)Oe at 0^o, 33(25)Oe at 45^o and 24(25) Oe at 80^o rotation angle for 56 μm(100 μm) ϕ Sn grain. For global heating, one would expect ΔH_α to be 5.7 times smaller for the 100 μm ϕ grain than for the 56 μm ϕ grain. Both observations are consistent with local heating, where the superconductivity of the grain starts to be broken locally around a region where the α-particle releases most of its energy. In contrast to the nucleus recoil in coherent neutrino scattering, the energy loss of α's is mostly concentrated on the surface of the grains and well above the ionisation energy. This leads to a fast local break up of cooper pairs, which apparently occurs before the grain is globaly heated by phonons.

3. Conclusions

In a feasibility study of a SSG detector for low energy neutrinos and dark matter, we performed measurements with individual Sn grains of 20-112 μm in diameter. It was shown that the smearing of the supercooling and superheating transition fields, previously observed with a group of grains, is largely due to the different behaviour of individual grains. When irradiating Sn grains with α-particles, local heating of the grains seems to be the dominant process.

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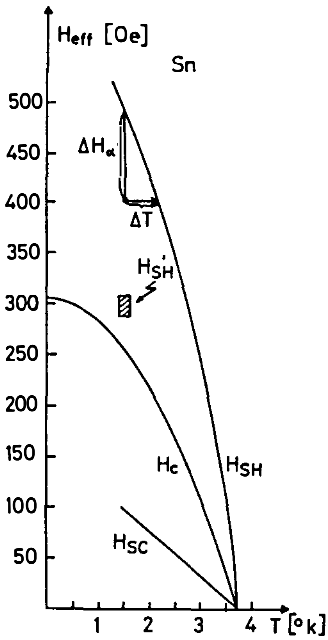

Fig. 1: Phase diagram of Sn granules with H_{SH} = superheating field, H_{SC} = supercooling field and H_c = critical thermodynamic field.

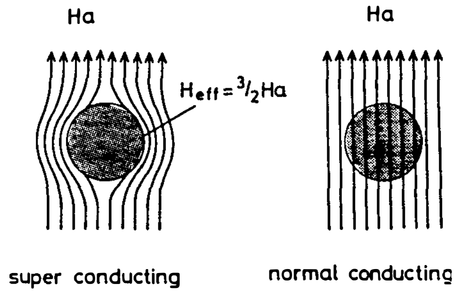

Fig. 2: Schematic view of the Meissner effect.

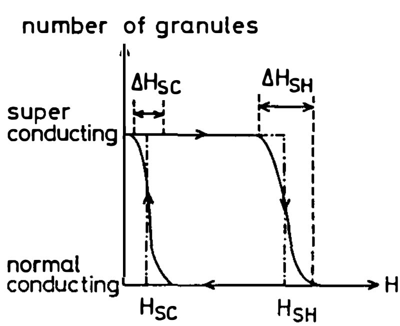

Fig. 3: Schematic view of external field hysteresis for a group of granules at fixed temperature. The experimental observation is shown as a solid line while the ideal behaviour is indicated as dash-dotted line.

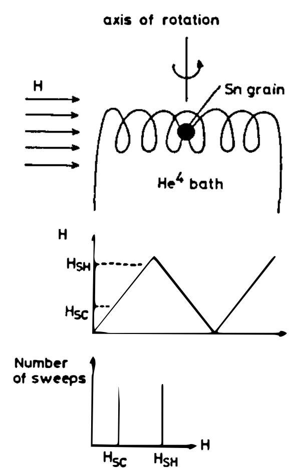

Fig. 4: Schematic view of experimental method.

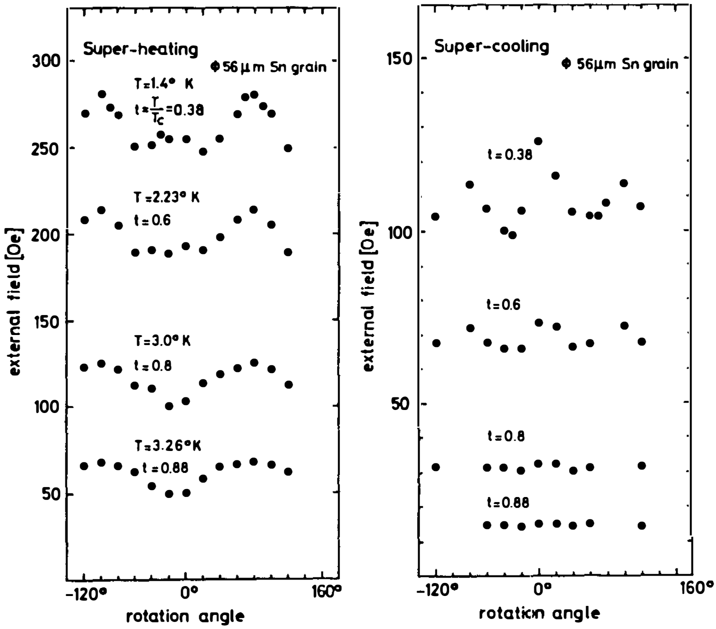

Fig. 5: Superheating and supercooling field for a Sn grain with 56 μm diameter at various temperatures.

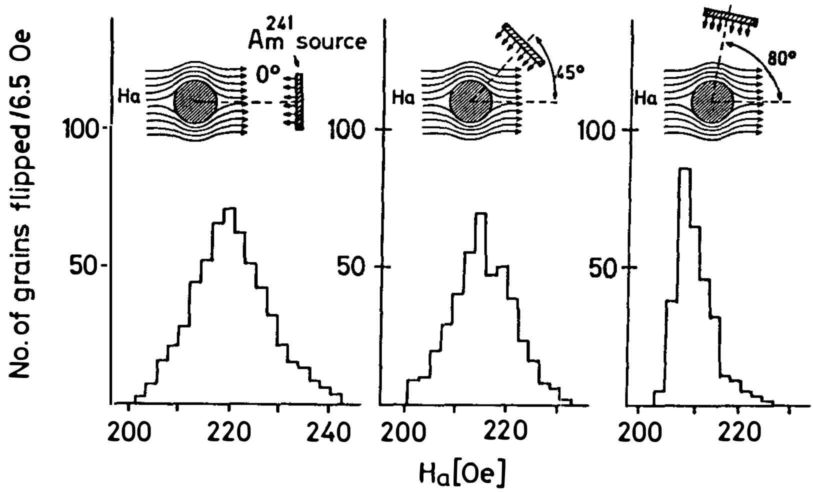

Fig. 6: The phase transition field H_a of a single Sn grain (ϕ = 56 μm) irradiated by α-particles at different angles is shown for T = 1.4 K.