BASIC PROPERTIES OF SUPERHEATED SUPERCONDUCTING GRANULES (SSG) DETECTORS : IRRADIATION RESULTS (α,γ) AND VERY LOW TEMPERATURE STUDIES

L.GONZALEZ-MESTRES and D.PERRET-GALLIX

Laboratoire d'Annecy-Le-Vieux de Physique des Particules
B.P.909, 74019 ANNECY-LE-VIEUX, France

ABSTRACT.

We present new results on the basic properties of superheated superconducting granules (SSG) detectors, concerning : a) Irradiation tests of Sn granules between 10 µm and 400 µm diameter with α,γ and β^- sources at temperatures 1.4K< T < 3.4 K. b) The behaviour of SSG at very low T (T $\geq$ 450 mK).

New α irradiations confirm and further develop our previous results presented at the München Meeting on Low Temperature Detectors in March 1986 : a) Granules in the range 45 µm $\leq$ Ø (diameter) $\leq$ 400 µm exhibit metastability and turn out to be sensitive to α particles ; b) The observed thresholds in applied magnetic field provide clear evidence for a local heating mechanism where the superconducting to normal (or intermediate state) phase transition starts before the whole granule is thermalized.

Granules of sizes 10 µm < Ø < 25 µm exhibit good sensitivity to 140 keV γ's of $^{99}T_c$ (about 8 % sensitive granules). The observed decrease of flipping rate with the source activity ($t_{1/2}$ ≈ 6 hours) provides clear evidence for flips under single photon interactions. The same granules are also sensitive to β^- (about 1,5 % for ^{36}Cl electrons) and to very low energy particles (6 keV γ's of ^{55}Fe, about 0,5 % sensitive granules).

Tests made at lower temperature (T $\geq$ 450 mK) show the absence of avalanche effect for several samples of Sn granules with about 10 % filling factor in volume. We compare this result with the previously observed avalanches for Cd granules below 350 mK. We also present estimates on the behaviour of the detector at very low T, where a thin layer of normal electrons at the surface is shown to contribute to the heat capacity of a superheated granule. We finally briefly comment on some of the proposed experiments.

1. INTRODUCTION. The list of proposed experiments [1-6] using superhead superconducting granules [7] is growing faster than the evidence for the faisability of any of them. One reason for this gap may be the lack of a systematic irradiation study. Apart from the present talk, other results on irradiation with α's [8] and with γ's [9-11] are reported in this conference or elsewhere.

Our α irradiations were made from February to July 1986, and those with γ's started in October. Tests at very low T (temperature) were performed in May 86 for a short period of time, using a He^3 cryostat. Irradiation tests were performed at $1.4K<T<3.4K$ proceeding as follows. The applied magnetic field H_o was slowly raised from 0 to a certain value H_{test}, usually close to mean value of the differential superheating curve (Fig. 1a). At this point, a small sweep in H_o is made creating a gap in magnetic field ΔH_{min}. Then, for a granule flipping at $H_o=H_{test}+\Delta H_{min}$, a (minimal) thermodynamical energy threshold ΔQ_{min} has been created :

$$\Delta Q_{min} = \int_T^{T+\Delta T} C \, dT, \quad \Delta T = \Delta T(\Delta H_{min}) \tag{1}$$

C is the heat capacity of the superconducting granule in the presence of $\vec{H}_o$ and ΔT is obtained from the equation : $H_{sh}^{eff}(T+\Delta T) = H_{test}$. H_{sh}^{eff} is the effective superheated critical field of a granule such that $H_{sh}^{eff}(T) = H_{test}+\Delta H_{min}$. Equation (1) assumes that the whole grain is thermalized before nucleation of the normal state on the surface of the granule starts irreversibly. In a naîve model, one can identify the nucleation time τ_N to the time for the external magnetic field to penetrate over a depth of a coherence lenght ξ. We can write [12] : $\tau_N \sim 2\rho^{-1}\pi\xi^2 H_o(H_o-2/3\ H_c)^{-1}$, where ρ is the normal state resistivity and H_c the thermodynamical critical field. For $\rho = 6\times10^{-8}\Omega$cm, we get $\tau_N \sim 6\times10^{-9}$ sec, allowing heat propagation over a distance $r(\tau_N) \sim 11$ µm. Then, for large granules (diameter $\emptyset >> 10$ µm) expression (1) is expected to fail and we would be in a local heating situation. The heat realeased locally near the granule surface creates a nucleation center large enough and lasting long enough to lead to the destruction of the metastable state. For $\rho = 10^{-6}$ Ωcm, we expect local heating to happen at the ~ 1 µm scale. A typical irradiation result is shown in Fig. 1b, where the integrated number N of observed individual grain flips appears as a function of time. The roughly exponential decrease dN/dt is related to the decrease of remaining sensitive granules. Finally, we are interested in the behaviour of the detector at very low T ($T << T_c$, the critical temperature), because of the fast decrease of the superconducting specific heat :

$$c_s \simeq a\,T^3 + b\,T_c \exp(-f\,t_r^{-1}) \tag{2}$$

$t_r = T/T_c$ and a,b and f are know experimentally for all relevant materials.

2. THE GRANULES. Several tin samples were used :

a) Billiton tin, whose measured low T residual normal state resistitivity [13] was : $\rho \simeq 6\times10^{-8}\Omega$cm. The granules were produced by EXTRAMET [14] in April 85. By sieving, two collections were extracted for α irradiations with diameters : 45µm $<\emptyset<$ 63µm (collection a_1) and 125µm $<\emptyset<$ 200µm (collection a_2).

b) Prolabo tin, with measured residual $\rho \simeq 1,5\times10^{-7}$ Ωcm. A collection of granules with 200µm $<\emptyset<$ 300µm was prepared by EXTRAMET in January 86. After sieving, a collection with 250 m $<\emptyset<$ 300µm was obtained and used for our α irradiation test.

c) Metallum tin, with estimated residual $\rho \sim 10^{-7}\Omega$cm. From a collection of granules prepared by EXTRAMET in December 86, several samples with 10µm $<\emptyset<$ 25µm were obtained by sieving and used for our γ irradiations.

d) With an alloy $Sn_{99}Sb_1$, estimated residual $\rho \sim 10^{-6}\Omega$cm, BILLITON [15] produced a collection of 200µm $<\emptyset<$ 400 µm granules in November 85 that were used

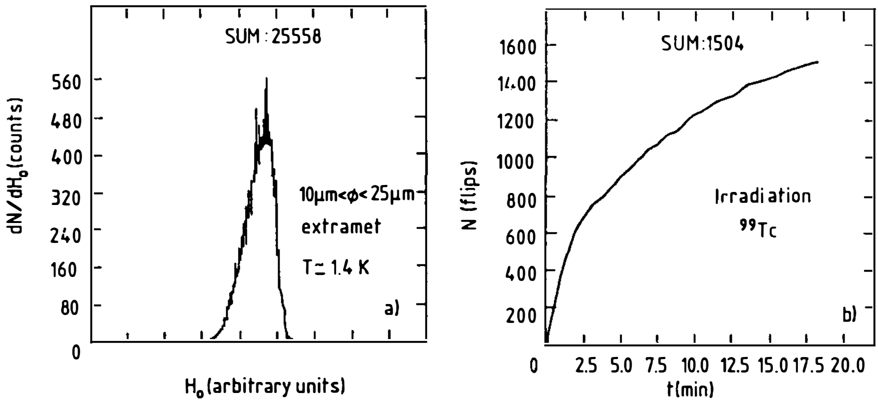

Fig.1 : a) Differential superheating curve for sample c. The applied magnetic field H_o varies from 0 to about 530 Gauss ; b) Integrated number of counts as a function of t (irradiation time) for the same sample at : T ≈ 1.4K, ΔH_{min} ≈ 0 and H_o ≈ 280 Gauss.

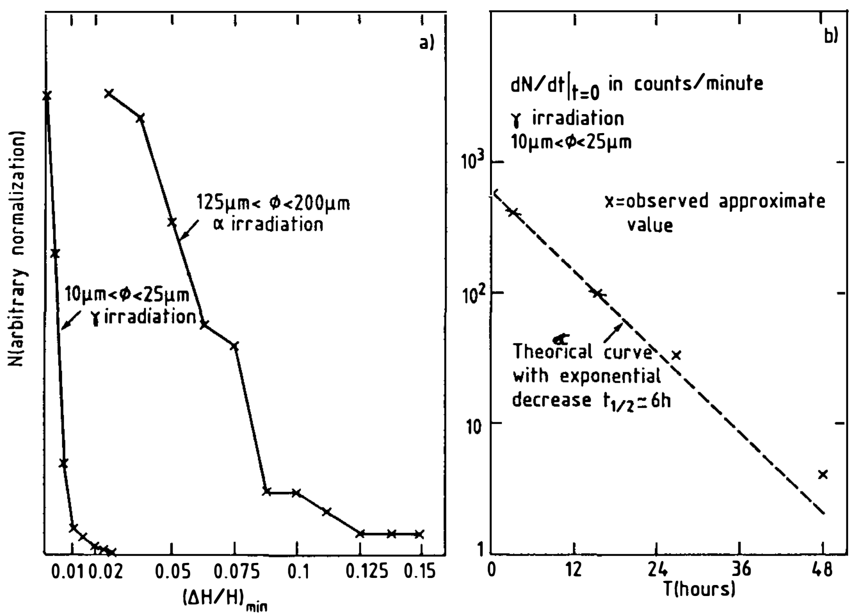

Fig.2 : a) Integrated number of counts after 10 minutes for sample a_2 irradiated with α particles at T ≈ 3.3K, as a function of $(\Delta H/H)_{min} \equiv \Delta H_{min}/(H_{test}+\Delta H_{min})$, and similar curve (after 20 minutes irradiation time) for sample c irradiated with 140 keV γ's ; b) Decrease of the slope of the integral irradiation curve at t = 0 and ΔH_{min} ≈ 0 for sample c, in terms of the time T since the source started being used.

for our α irradiation test. Such granules still exhibit metastability although the differential superheating curve is peaked lower than the supercooling curve (transitions from normal and superconducting state to the intermediate state).

3. α IRRADIATIONS. An open ^{241}Am source (5000 Bq, implanted on platinum) was put in contact with small detector prototypes (3 mm to 1 cm reading multi-turn loop diameter) where the granules were embedded into paraffin with dilution coefficient of 5 to 20 % in volume. As a consequence, a few ^{241}Am atoms drifted into the samples, that remained irradiated even after the source was removed. The number of contaminated granules turned out to be small as compared to the total number of granules in each sample. In this way, individual flips of granules under the action of single α particles were detected in real time. The irradiated samples were a_1,a_2,b and d. In all cases, flips were observed for $\Delta H_{min}/H_{test}$ as large as 0.25 (Fig.2a). For larger values of this ratio, the study was limited by the width of the superheating curve. From this value, the estimated ΔQ_{min} from (1) (global heating situation) is larger than 100 MeV for 50 μm grains, as compared to the 5.5 MeV of ^{241}Am α's. This clearly provides evidence for a local heating mechanism. For a half sphere of radius $r(\tau_N)$ = 11 μm, we get $\Delta Q \simeq 3$ MeV which looks more in agreement with the observed data.

4. γ IRRADIATIONS AND OTHER RESULTS. A medical $^{99}T_c$ source ($t_{1/2} \simeq 6$ hours) of about 200μC, emitting 140 keV γ's was deposited on an absorbing texture, isolated and put inside the cryostat close to the detector prototype. 30 turn loops of 2 to 3 mm diameter were used with granules of collection c(10μm <Ø< 25μm) at about 15 % filling factor in volume. Flips under the action of individual γ's were observed in real time. For a given ΔH_{min}, the value of dN/dt at t = 0, was found to closely follow the time decrease of the source activity (Fig.2b). Flips were observed for $\Delta H_{min}/H_{test}$ as large as ≃ 0.02 , (Fig.2a), which at T = 1.4 K corresponds to $\Delta Q \simeq 60$ keV for Ø=10 μm and $\Delta Q \simeq 1$ MeV for Ø=25 μm. The total number of sensitive granules was about 8 % (2000 granules over 25.000), which looks remarkably good as compared to other γ irradiations with Sn granules. Some local heating phenomenon might be at work due to the comparatively high normal state resistivity of the tin used.

Very recently, we started tests with β^- sources (^{36}Cl, E<714 keV) and 6 keV γ sources (^{55}Fe) using the same granules. In both cases the source was mixed with the detector itself, and flips have been observed. As a preliminary result, about 1,5 % of granules turn out to be sensitive to β^- at $(\Delta H/H)_{min} \leq 0.01$. For 6 keV γ's, we get about 0,5 % sensitive granules at $(\Delta H/H)_{min} \leq 0.005$.

5. VERY LOW T STUDIES. An avalanche effect was found by the Garching Group [10] for Cd grains (T_c=560 mK) below 350 mK, where the heat released by a granule flip produced the flip of other grains and the phenomenon spread to the whole detector. We performed tests with several samples of tin granules, at about 10% filling factor in volume and T≥450 mK. No avalanche effect was found in our case. The heat released by a single granule flip is given by :

$$2/3\ H_c < H_o < H_c \ :\ \Delta Q^L = \frac{H_c^2 V}{8\pi}\left[2 + 9/2\ h^2 - 6h - \frac{(12h-8)t_r^2}{1-t_r^2}\right] \quad (3a)$$

$$H_o > H_c \ :\ \Delta Q^L = \frac{H_c^2 V}{8\pi}\left(3/2\ h^2 - 1 - \frac{4t_r^2}{1-t_r^2}\right) \quad (3b)$$

where $h = H_o/H_c$ and V is the grain volume. Since Cd exhibits higher superheating than Sn, we expect a more important heat release for this material. The details of heat exchange, depending on whether the sample is helium or in vacuum, may also play an important role. For high filling factors (larger than 20%), the avalanche effect could be a severe problem if H_{sh} is too high. Lowering H_{sh} with impurities may be a way out in some cases.

Finally, we have estimated the heat capacity of a small granule at very low T for $H_o \neq 0$. When the radius R of the granule becomes of the same order as ξ, normal electrons due to the presence of the applied magnetic field create an extra contribution to the heat capacity of the grain, which then writes :

$$C = c_s V + c'S \qquad (4a)$$

where S is the grain surface and a rough approximation ($R \gg \xi$, $\kappa \ll 1$), to c' using the Ginsburg-Landau description is :

$$S\,c' \simeq 0.07\ T_c^{-1} H_c^2 \xi_o t_r R^2 \qquad (4b)$$

where ξ_o is the Pippard coherence length. The surface term is expected to be particularly important for low T_c materials (large ξ). As a result, with global heating, 2 to 4 μm diameter In granules (solar neutrino detection) are required to be sensitive to minimum ionization at $\Delta H/H_{test} \simeq 0.05$ ($\Delta H = H_{sh}^{eff} - H_{test}$), and $T \simeq 200$ mK. For Ga (dark matter detection), 10 μm granules would be sensitive to 1 keV deposit of energy a $T \simeq 100$ mK and a similar value of ΔH. For 50 eV deposit of energy, 3 μm diameter grains would be required. Existing samples show at best a spread in H_{sh}^{eff} of 15 to 20 %.

6. CONCLUSION. New results on irradiation of SSG detectors with 5.5 MeV α parpicles confirm our previous evidence for local heating mechanism. For the first time, Sn granules read in real time with conventional electronics and irradiated with 140 keV γ particles show reasonably large sensitivity (about 8 %). Preliminary results on β^- and very low energy γ's are also encouraging. Substantial progress has been made on the understanding of the basic properties of the detector. The existence of collections of large metastable granules with high values of ρ (fast flipping times [16]), is encouraging for monopole detection. Irradiation tests with better granulometry (Ø<10 μm and 20 μm<Ø<25 μm) and at lower temperatures ($T \gtrsim 300$ mK) are in preparation, and other sources will also be used.

REFERENCES.

[1] A.K.Drukier, C.Valette, G.Waysand, L.C.L.Yuan and F.Peters, Lett. al. Nuovo Cimento 14, 300 (1975).
[2] A.K.Drukier and L.Stodolsky, Phys. Rev. D30, 2295 (1984).
[3] G.Waysand, Proceedings of the Moriond Meeting on Massive Neutrinos, January 1984, Ed. J.Tran Thanh Van, p.319.
[4] L.Gonzalez-Mestres and D.Perret-Gallix, same Proceedings.
[5] M.W.Goodman and E.Witten, Phys. Rev. D31, 3059 (1985).
[6] A.F.Pacheco, Mod.Phys.Lett.1, 167(1986).
[7] H.Bernas, J.P.Burger, G.Deutscher, C.Valette and S.T.Williamson, Phys.Lett. 24A, 721 (1967). For an updated introduction, see L.Gonzalez-Mestres and D.Perret-Gallix, Proceedings of the "Astro-Particle School", Erice, January 1987.
[8] K.Pretzl, these Proceedings.
[9] P.Espigat, these Proceedings.
[10]F.Von Feilitzsch, W.Seidel and L.Oberauer, Proceedings of Underground Phys. 85, Ed. Il Nuovo Cimento, p.598, and W.Seidel, Thesis (Garching, 1985).
[11]B.G.Turrell, A.Kotlicki, M.A.Le Gros, A.K.Drukier, Astrophysical Observatory order n° 505-06510 Final Report (1986).
[12]T.E.Faber, Proc. Roy.Soc. Ser.A.219, 75(1953).
[13]Measurements by A.Vermandé (LTPCM, Grenoble) and M.Renard (CRTBT, Grenoble)
[14]EXTRAMET, Zone industrielle de Cranves-Sales, 74380 Bonne-sur-Ménoge.
[15]BILLITON WITMETAAL, Neuilly.
[16]L.Gonzalez-Mestres and D.Perret-Gallix, Proceedings of Underground Physics 85, p.573, and Proc. of the EPS Int.Conf.on High Energ.Phys., Bari July 85.