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NEW IDEAS ON THE DETECTION OF COLD DARK MATTER AND MAGNETIC MONOPOLES

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Abstract:

Superheated superconducting granules (SSG) provide several interesting targets for cold dark matter detection, not only through coherent scattering off nuclei, but also for Majorana fermions through spin-spin interactions. The concept of "localized micro-avalanche" should introduce crucial improvements in SSG devices and, eventually, make feasible a cold dark matter detector based on nucleus recoil. Recent results on the metastability of very large granules also suggest that a SSG large area monopole detector may be feasible, if the theoretically conjectured detection principle (destruction of the superheated state by two injected flux quanta) is checked experimentally.

We also consider the use of special crystal scintillators to detect Majorana fermions through inelastic scattering.

1. SUPERHEATED SUPERCONDUCTING GRANULES

Superheated superconducting granules [1] were proposed for particle detection [2] by a Orsay group [3,4] and further studied in Rennes [5], where irradiation tests with a low energy electron beam were first performed. Subsequent attempts to build transition radiation detectors [6] or X-ray imaging devices [7] failed. The two main problems related to the use of SSG detectors have been until now the following:

a. Very small grains are required if the detector has to be sensitive to minimum ionizing particles, which leads to small electronic signals.

b. SSG may be used for the detection of low energy particles, which deposit most of their energy on a short path. But then energy resolution is rather poor and the electronic signal remains comparatively small.

For a dark matter experiment, the main problem of SSG is the presumed absence of energy resolution. The recoil energy of a single nucleus thermalizes in a single grain and, in the conventional scenario, the detector response is a single grain flip. Therefore, it is usually believed that SSG detectors are only threshold detectors as far as nucleus recoil is concerned. Furthermore, the dispersion in grain size makes such threshold a rather ill-defined quantity. In these conditions, SSG should to our opinion be discarded as a dark matter detector.

In spite of such drawbacks, SSG have the basic advantage of being an active target detector that can be instrumented with a simple X-Y read-out system, optimizing the ratio between the number of electronic channels and the size of the detector elementary cell. Typically, 10^5 channels allow for segmentation into 10^7 elementary cells. With fast and sensitive electronics, time resolution can be rather good since the flipping time of very small granules is expected to be fast (less than 1 nsec for a 1μm diameter grain). These are crucial points for background rejection in experiments involving time delayed coincidences, and may prove relevant for the detection of galactic Majorana fermions. Furthermore, SSG are not "very low temperature" devices, that must be operated at 50 mK or so. We actually expect, in case of success, to be able to perform all proposed experiments at ^{3}He or ^{4}He temperatures (between 0.3 and 4.2 K). Then, SSG would be the best suited cryogenic detector for large volume experiments. Also, the sensitivity of existing prototypes is at least as good as predicted by naive theoretical calculations (global heating). The detection of ^{55}Fe 6 keV γ's with comparatively large grains (10 μm < ϕ, diameter, < 25 μm) has recently been demonstrated [8], even if the efficiency is rather low. In this case, a local heating mechanism is obviously at work. All irradiation experiments [9, 10] have clearly confirmed the principle of grain flipping by particle energy deposition. Such considerations justify further efforts to improve the performance of detectors based on SSG, through a better understanding of their basic properties.

Another possible application of SSG is the detection of superheavy magnetic monopoles [11, 12] through a velocity independent effect. As a magnetic monopole crosses a superheated superconducting granule, it leaves behind two flux quanta injected into the sample. The ends of the flux tube create nucleation centers of the normal state on the surface of the grain, so that in most cases the granule should flip instantaneously from superconducting to normal state. SSG may in this way provide a real time, track detector with a high background rejection due to the use of large granules (30 to 100 μm in diameter). SSG would also give a large signal that can be read with conventional electronics (several large granules would flip in each elementary cell crossed by the monopole), and seem better suited than induction loops to reach comparatively large surfaces.

2. AMPLIFICATION BY THERMAL MICRO-AVALANCHE

It was first noticed by the Garching group [13] that, at very low temperature, the latent heat released by the flip of a single granule can spread to the surrounding granules and produce new flips. This appeared in a rather spectacular way when, working with Cd granules at $T < 300$ mK, the whole detector was seen to collapse under the effect of a thermal avalanche. We performed tests with Sn granules at $T > 450$ mK and found no avalanche effect. Both data can actually be understood in a simple model [8, 9], whose results are as follows:

a. The superconducting to normal state latent heat can be positive only in the case of superheating and at $t_r = T/T_c$ (reduced temperature) less than a critical value.

b. When going down in temperature from the point where q^ℓ (latent heat per unit volume) = 0, a domain is found where thermal avalanches remain localized instead of spreading to the whole detector. One then has a local amplification effect to be discussed later on.

c. If t_r is set below this domain, q^ℓ becomes too large and the SSG detector cannot be operated because of the global thermal avalanche.

The localized micro-avalanche can be described as follows. Let H_{test} be the value of H_0 (applied magnetic field) at which the detector operates, δH a small sweep in H_0 setting a small threshold, V the volume of detector reached by heat propagation and V_{flip} the total volume of granules having changed state due to the particle interaction. For a point-like deposit of energy ΔE, we assume V to be the volume of a isothermal sphere of radius $R(t) \simeq 2\,(Dt)^{1/2}$ (t = time, D = detector heat diffusion coefficient). Taking for all granules a universal dependence of the effective superheated critical field in terms of temperature:

$$H_{sh}^{eff}(T) \simeq H_{sh}^{eff}(0)\, f(T) \qquad \{1\}$$

we can write a relation between the increase of temperature ΔT inside the isothermal hot sphere, and the equivalent threshold in magnetic field ΔH [2]:

$$\Delta H = H_{test}\,[f(T) - f(T+\Delta T)]\,[f(T+\Delta T)]^{-1} \qquad \{2\}$$

The rate of granules changing state at a distance R from the interaction point is given by:

$$dV_{flip}/dV = \int_{H_{test}+\delta H}^{H_{test}+\Delta H} d\psi/dH_0 \; dH_0 \qquad \{3\}$$

Where ψ is the filling factor in volume and $d\psi/dH_0$ the differential superheating curve in filling factor [2, 8].

Finally, ΔT is related to ΔE, V_{flip} and V through the equation:

$$\Delta E + V_{flip}\, q^{\ell} = V \int_T^{T+\Delta T} c_{det}\; dT' \qquad \{4\}$$

where c_{det} is the average specific heat of the SSG colloid. A first consequence of equations {1-4} is that ΔE simply sets an overall scale for volume, time and distance in the evolution of a localized micro-avalanche. This can be seen writing:

$$x = V\,\Delta E^{-1} \;,\; y = V_{flip}\,\Delta E^{-1} \qquad \{5\}$$

Then, expressing the above equations in terms of x and y removes all explicit dependence on ΔE. If the total flipping volume V_{flip} $(t=\infty)$ is finite, one has: $\Delta\Phi$ (signal in magnetic flux) $\propto \Delta E$, whereas the maximum of the signal in voltage is reached in a time $\tau \propto (\Delta E)^{2/3}$ and is proportional to $(\Delta E)^{1/3}$. Amplification by localized micro-avalanche preserves the proportionality of the signal in magnetic flux and can be used to improve the response to low energy particles. For a minimum ionizing particle, the relation $\Delta\Phi \propto \Delta E$ remains, but the rise time τ depends only on the detector parameters. Then, studying in detail the shape of the signal, it is possible to get an insight on the nature of the interaction.

Using very small granules (about 1μm diameter), the new concept of localized thermal micro-avalanche would allow to:

a. Increase the electronic signal by one or two orders of magnitude;

b. Obtain a better linearity for very low energy particles (e.g. the 116 keV γ produced in the ^{115}In solar neutrino experiment first proposed by Raghavan [14]) and lower the energy threshold by the use of very small granules;

c. Eliminate problems related to the lack of uniformity in grain size;

d. Produce, for the first time in a SSG detector, a linear response to the recoil energy of a nucleus (e.g., dark matter detection);

e. Use the dielectric material as an active target (e.g., hydrogen target for dark matter searches).

Fig.1 shows the solution of {1-4} in a simplified version of the SSG Ga detector (T_c = 1.09) for dark matter searches (nucleus recoil), with ψ = 0.3, at t_r = 0.5. The detector response at $\delta H/H_{test} = 0.005$ for several values of the deposit of energy is exhibited through V_{flip} in terms of V. Even at $q^\ell = 0$, the solution of {1}-{4} differs from the conventional SSG scenario in that the detector response does not stop at the granule(s) where the energy was deposited by the incident particle. Heat keeps propagating in the detector, and it can be shown analytically that V_{flip} $(t=\infty)$ diverges logarithmically in t as $\delta H \to 0$. When $q^\ell > 0$, this divergence becomes power-like but remains regularized by the cutoff δH if q^ℓ does not exceed a certain value. If q^ℓ is too large, one gets asymptotically $dV_{flip}/dV \propto V^\alpha$, with $\alpha > 0$, and a global avalanche is produced.

To a first approximation, time propagation can be described taking for the heat diffusion coefficient of the colloid that of the dielectric material. For $\psi < 0.3$, this is known to be correct within a factor of 2 [15]. Also, at the beginning of the micro-avalanche phenomenon, Kapitza resistances can play a significant role. We have checked that, using Varnish GE 7031 [9] and taking a standard value of Kapitza resistivity for this material [16], heat exchanges between granules and the dielectric would occur in about 10 nsec. In 200 nsec (the time resolution required for a In solar neutrino experiment), a point like deposit of heat would have spread to a radius of about 30 μm. For dark matter detection through elastic scattering, time resolution is less crucial and it should be possible to work with dielectric materials that conduct heat more slowly (therefore allowing for a more efficient heat transfer between the granules and the dielectric).

If inelastic scattering with ^{119}Sn is used [17], the situation becomes difficult since the lifetime of the 9.4 keV excited state is only of 18 nsec. Perhaps a shorter micro-avalanche (smaller q^ℓ and V_{flip} , in an optimized composite medium) would allow for the use of very fast voltage amplifiers [18].

Fig. 2a shows a sample of 10 $\mu m < \phi < 25$ μm Sn granules in GE Varnish 7031, at a comparatively low filling factor. We have started an experimental study of Sn grains - GE varnish composite materials at ^{3}He temperatures, in order to check the validity of the micro – avalanche scenario.

3. PRESENT STATUS OF THE MONOPOLE PROJECT

The case for monopole detection with SSG has been considerably improved by our recent experimental results on the metastability of very large granules made with low purity materials [8]. Our main conclusions are:

a) Adding impurities to the pure metal indeed shortens the flipping time of grains without spoiling metastability (althoug the superheated critical field decreases for impurity levels larger than 0.1%). We have observed normal superheating curves for tin granules with impurity levels between 0.1 and 1%. Fast enough flipping times were always observed, having in mind the requirement of large voltage signals and good time resolution (to measure velocity) for a monopole detector.

b) Samples of very large granules prepared by industrial procedures (EXTRAMET [19], BILLITON [20]) exhibit superheating at reasonable values of the applied field. This is particularly encouraging for large area experiments, where several tons of grains would be required (EXTRAMET can at present produce ≈ 5 Kg/hour of Sn grains).

As an example, superheating was still observed for 200 to 400 μm diameter granules prepared by BILLITON with an alloy $Sn_{99}Sb_1$. These granules give electronic signals with risetimes of less than 300 ns. When irradiated, they turned out to be sensitive to 6 keV γ's (local heating at the surface leading to nucleation). Such results are extremely encouraging for the feasibility study of a SSG monopole detector, since very large granules can be used without spoiling time resolution. In the expression for flipping time: $\tau \sim R^2 \rho^{-1}$ (R = radius, ρ = normal state resistivity), the increase in grain size is compensated by a higher impurity rate [12]. Furthermore, the irradiation result obtained with ^{55}Fe γ's indicates that a local surface phenomenon can indeed flip a large superheated grain. A possibility to perform the SSG monopole experiment at liquid helium temperature (4.2 K), would be to use β-Ga spheres. The feasibility of collections of metastable granules involving only this phase of gallium (T_C = 5.9 K) was demonstrated long ago by Feder and Parr [21]. As a more conventional solution (working at superfluid helium temperatures), Fig. 2b shows a collection of ≃ 200 μm 998 pure Sn grains produced by EXTRAMET in a He atmosphere. They exhibit good metastability properties, and so do smaller grains from the same producer.

The main concern for the monopole project is at present to perform an experimental test of the detection principle itself (i.e., check the incompatibility between the superheated state and the presence of two flux quanta injected into the sample). This is a highly nontrivial solid state experiment, and is likely to require a long term specific study.

4. DEDICATED SCINTILLATING CRYSTALS

Inorganic scintillating crystals, like SSG devices, fall into the group of target detectors. A large amount of target element can be found in some crystals, still remaining transparent to scintillating light. Developing new scintillating crystals, based on compounds of specific target elements is not a simple task. Some examples can be found in [22], where indium borate has been proposed for neutrino detection. Photino cross-sections may be quite dependent on the target nucleus and therefore using a large variety of target elements may help to get a better dark matter signature. We are here confronted with the problem of detecting a very low energy deposition. Scintillating crystals have been shown to be sensitive to low energy γ's down to 800 eV [23]. Cooling down crystals and photomultipliers can in some cases increase by one or two orders of magnitude the light yield, still reducing the background. An applied electric field may also for some compounds enhance the light output and even help to obtain some directionality information. Two cases deserve particular attention:

4.1 Coherent scattering for scalars and Dirac fermions

Depending on the masses of the WIMP and target elements, the event rates range from a few to several thousands per kg and per day. Adapting the mass of the target nucleus to the explored mass range for the WIMPs, a higher recoil energy can be obtained (about $10^{-6}m_{WIMP}$). Not much is known about light yield from recoiling heavy ions, however 300 keV ^{12}C ions have been detected and one observes an increase at low energy (< 1 MeV) of the relative pulse height per unit energy [24]. Clearly, specific studies and experiments should be performed to investigate the low energy scintillation light yield from recoiling nuclei.

4.2 Inelastic scattering for Majorana fermions

The natural way to reject background would be to detect, in a time delayed coincidence, the recoil of an excited nucleus followed by the γ ray associated to its decay to the ground state. However, the cross-sections here seem [17] much smaller than previously suggested [25]. ^{187}Os (E_γ = 9.8 keV) has a lifetime of 2.4 nsec and may bring an event per ton and per day. It would provide the smallest detector, but a very difficult time delayed coincidence. Rare earths (^{149}Sm, τ lifetime = 7.6 ns for E_γ = 23 keV ; ^{151}Eu, τ = 9.5 ns for E_γ = 22 keV) allow in principle to produce scintillating crystals with a high light yield but require 30 tons of detector for 1 event/day. The above mentioned ^{119}Sn leads to 10 tons for 1 event/day, but allows for more confortable delayed coincidences. Unfortunately, it is not obvious whether conventional detectors would be able to incorporate ^{57}Fe ($\tau \simeq$ 98 ns , similar event rate). In spite of such extremely low rates, detectors based on inelastic scattering may indeed be able to reject background if the recoil energy turns out to be detectable and the delayed time coincidence can be observed. A detailed study of the basic properties of detectors (scintillators, semiconductors, SSG,...) incorporating specific target elements must be performed in order to eventually find a suitable inelastic scattering detector for galactic Majorana fermions. The case for conventional techniques (as compared to cryogenic detectors) may improve in the future, if high energy experiments provide more stringent lower bounds on the masses of supersymmetric particles, for a heavier WIMP would carry a larger kinetic energy.

5. CONCLUSION AND COMMENTS

The improved version of SSG may provide a leap forward in the feasibility study of a dark matter detector based on recoil energy. A ^{119}Sn inelastic scattering detector seems much more problematic, and in any case belongs to a later generation of dark matter experiments. Monopole detection with SSG remains extremely tempting, but the crucial point is to check experimentally the validity of the proposed detection principle.

For inelastic scattering, no good solution exists by now, but dedicated scintillating crystals may be worth considering if they can see the nucleus recoil and if they are fast enough to observe the delayed time coincidence. In any case, this is the most ambitious part of dark matter searches and should not be considered as a short term goal.

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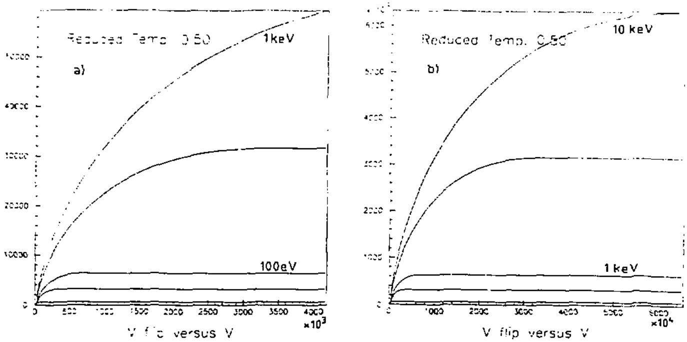

Fig.1 : V_{flip} versus V at $\delta H/H_{test} = 0.005$ for: a) $\Delta E = 10, 50, 100, 500$ and 1000 eV ; b) $\Delta E = 0.1, 0.5, 1, 5$ and 10 keV. All volumes are given in μm^3.

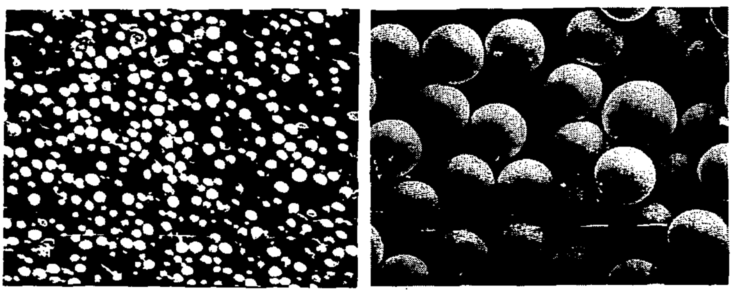

Fig.2 : Left: $Sn_{99}Sb_1$ granules (10 $\mu m < \phi <$ 25 μm) in GE Varnish 7031 ; Right: 200 μm diameter Sn 998 grains prepared in He atmosphere.