Feasibility study of a Superheated Superconducting Granule detector for cold dark matter search

M. Abplanalp, C. Berger, G. Czapek, U. Diggelmann, M. Furlan, A. Gabutti, S. Janos, U. Moser, R. Pozzi, K. Pretzl, K. Schmiemann
Laboratory for High Energy Physics, University of Bern, Sidlerstrasse 5, CH 3012 Bern, Switzerland

Abstract

The presented results are part of a feasibility study of a Superheated Superconducting Granule (SSG) device for weakly interacting massive particles (WIMPs) detection. The sensitivity of SSG to nuclear recoils has been explored irradiating SSG detectors with a 70MeV neutron beam proving that energy thresholds of $\sim 1\text{keV}$ can be reached in $30\mu\text{m Zn}$ and $17\mu\text{m Sn}$ granules. The successful irradiation experiments with neutrons encouraged us to plan a prototype SSG dark matter detector. The status of the project will be presented and the expected counting rate for spin-independent WIMP interactions in SSG detectors will be discussed.

1 INTRODUCTION

Various astronomical observations like the flatness of spiral galaxy rotation curves emphasize the suggestion that the Milky Way is embedded in a non-luminous halo which appears to make up 90% of the galactic mass. Possible candidates for dark matter are weakly interacting massive particles (WIMPs)
with couplings of the weak scale and masses between 50GeV and some TeV \(^1\). The theory of Supersymmetry naturally predicts the existence of stable WIMPs, e.g. the Lightest Supersymmetric Particles LSP \(^2\). After the proposal of Drukier and Stodolsky \(^3\) and the work of Goodman and Witten \(^4\), attention has been devoted to the possibility of detecting WIMPs via elastic neutral-current scattering with the nucleus. An overview on the dark matter detection can be found in Ref.\(^5\).

In this paper the possible use of Superheated Superconducting Granule (SSG) detectors for dark matter search will be discussed. A review of the status of the SSG detector development can be found in Ref.\(^6\) and the measured sensitivity of SSG to nuclear recoils of \(\sim 1\)keV is discussed in Ref.\(^7\).

## 2 DARK MATTER DETECTION WITH SSG

In the currently accepted model, the dark matter halo is assumed to be gravitationally trapped in the galaxy with a Maxwell-Boltzman velocity distribution in the galactic rest frame. The Earth rotates together with the luminous matter through the halo, generating a dark matter flux in the Earth’s rest frame. Due to the Earth’s motion around the Sun, a seasonal modulation in the dark matter flux with a maximum in June and a minimum in December is expected \(^8\).

Weakly interacting massive particles can be detected measuring the recoil energy released when they interact with ordinary matter via neutral current elastic scattering. The spin-independent coherent elastic scattering cross section is assumed to be isotropic and proportional to \(N^2\), with \(N\) the number of neutrons in the nucleus. When the de Broglie wavelength of the momentum transfer is small compared to the nuclear radius, the nuclear form factor has to be taken into account in the cross section. In Ref.\(^9\) an analytical formula is derived to evaluate the spin-independent detection rate and the amplitude of the seasonal modulation versus the detector energy threshold including the nuclear form factor and the dynamics of the dark matter halo. The rates are calculated for “ideal” detectors, with no smearing in the energy threshold \(E_{th}\).

Considering a WIMP mass of 50GeV/c\(^2\) and a dark matter density on Earth of 0.4GeV/cm\(^3\), counting rates of \(\sim 1000/kg/day\) are expected in ”ideal” Sn and Zn detectors with \(E_{th} < 5\)keV \(^9\). At the same energy threshold, the counting rate in Si detectors is only \(\sim 100/kg/day\). The SSG detectors made of 15-20\(\mu\)m Sn and 28-30\(\mu\)m Zn granules which we tested in neutron irradiation experiments \(^7\), have shown to be sensitive to recoil energies of \(\sim 1\)keV. In this experiment, we were not able to test the detector sensitivity to lower recoil energies due to the limited angular resolution of the neutron detector. However, recoil energies below 1keV can in principle be detected with SSG by lowering the thresholds.

From the phase diagram, the energy threshold \(E_{th}\) of a single granule can be related to the magnetic thresholds \(h = 1 - H_a/H_{sh}\) with \(H_{sh}\) the granule superheating field and \(H_a\) the applied field strength \(^7\). Using the formula pro-
posed in Ref. for the dark matter detection rate and the relation between $E_{\text{th}}$ and $h$, it is possible to estimate the rate $R(h)$ in units of $kg^{-1} \text{day}^{-1}$ of an "ideal" SSG detector with a sharp energy threshold. Since a SSG detector is a collection of granules with different superheating fields, the corresponding spread in the detector energy threshold has to be considered in the evaluation of the dark matter counting rate. The measured superheating field distributions have standard deviations $\sigma$ of the order of 10-15% . The width of the superheating field distribution is partially due to the crystallographic orientation of the granules with respect to the applied magnetic field, to surface defects and diamagnetic interactions among granules. The dependence of the superheating spread on the detector filling factor and on the crystallographic structure of the granules is under investigation by our group.

A typical dark matter search experiment with SSG detectors will be divided into cycles during which the magnetic field is raised from zero to a reference value $H_1$, then reduced to a slightly lower plateau value $H_2$, kept constant for a long period of time and reset to zero. The detector energy threshold is defined by the magnetic threshold $h_{\text{th}} = 1 - H_2/H_1$. Using a gaussian parameterization for the superheating field distribution, we evaluate the density function $S(h)$ of granules inside the detector with a threshold $h$. The dark matter counting rate of the SSG detector, in units of $kg^{-1} \text{day}^{-1}$, can be then evaluated from:

$$\text{Rate} = \int_{h_{\text{th}}}^{h_{\text{max}}} S(h) \cdot R(h) \, dh$$

where $R(h)$ is the rate of a granule with threshold $h$. The integration limits are the detector threshold $h_{\text{th}}$ and the threshold $h_{\text{max}}$ corresponding to the maximum recoil energy released by the dark matter particle.

The dependence of the expected dark matter detection rate on the superheating field spread is shown in Fig. 1 for a Zn and a Sn SSG at the temperature $T_b=50\text{mK}$ with a threshold $h = 0.005$. The values are calculated for a $50\text{GeV}/c^2$ dark matter mass assuming a WIMP density on Earth of $0.4\text{GeV}/\text{cm}^3$ and weak vector coupling. In the comparison, the reference field $H_1$ is the mean value of the gaussian distribution of the superheating field.

The counting rate of SSG detectors made of $10\mu\text{m}$ Zn granules is almost independent on the spread of the superheating field distribution because of the high sensitivity of the granules to the recoil energies produced by $50\text{GeV}/c^2$ WIMPs. The smearing in the energy threshold is more important in Sn detectors. For instance, for $\sigma > 8\%$, a SSG detector made of $10\mu\text{m}$ Sn has lower counting rate than a SSG detector with Zn granules of the same size. As a result, the expected detection rate of the presently considered Zn SSG detector with a superheating spread of about 15% does not differ significantly from the case of an "ideal" detector. In the case of Sn, narrower superheating field distributions are needed to reach dark matter counting rates of $\sim 1000/\text{kg/day}$. 


3 PROTOTYPE DARK MATTER SSG DETECTOR

The successful irradiation experiments with neutrons encouraged us to plan a prototype SSG dark matter detector to be placed in the underground laboratory of the Bern University at a depth of 70 mwe. A possible setup for the dark matter search experiment is sketched in Fig. 2a. The detector will be thermally connected to the mixing chamber of a $^3$He-4He refrigerator by a cold finger and cooled down to 50 mK. To have appreciable rates, the prototype SSG dark matter detector will consist of several elements of 40 cm$^3$ in volume, with $\sim$85 grams of Sn or Zn granules in each element and a volume filling factor of 30%. To be able to readout the large volume of each element, we are studying the possibility of using a magnetometer Helmholtz coil connected to a SQUID (Superconducting Quantum Interference Device). The choice of the granules size to be used in the SSG dark matter detector will depend on the noise level of the SQUID readout. The expected change in flux due to the transition of a single 10 $\mu$m Sn or 20 $\mu$m Zn granule inside the 40 cm$^3$ target is $\sim 10^{-3}$ in units of a magnetic flux quantum ($\phi_0$). Smaller granules could be used, for instance 5 $\mu$m Sn or 10 $\mu$m Zn, lowering the SQUID noise level below $10^{-4}$ $\phi_0$. As an alternative to the SQUID readout we are also investigating the possibility of reading large volumes with conventional pickup coils.

The onion structured shielding around the detector will consist of scintillating counters to veto cosmic ray particles, a layer of paraffin to moderate neutrons and layers of lead and electrolytic copper. An important source of background is the $\gamma$ activity from the surrounding materials and the detector itself. The response of the planned Sn or Zn SSG to the radioactivity of Rn$^{222}$ and its daughters has been explored using the GEANT code [12]. In the simulation the detector is assumed to be a regular array of granules with superheating spread $\sigma=15\%$ imbedded in a plastic matrix with 30% filling factor. A dark matter interaction produces the phase transition (flip) of a single granule while charged particles and $\gamma$ background can deposit energy in more than 1 granule. The multiplicity spectrum of the flips induced by photons from Rn$^{222}$ (with an energy range of 295 keV to 1764 keV) is shown in Fig. 2b for SSG detectors 40 cm$^3$ in volume, made of 5 $\mu$m Sn or 20 $\mu$m Zn granules. About 70% of the photons impinging in the detector will not release enough energy to induce a phase transition, 20% will produce multiple flips and only $\sim$10% will fake a dark matter event with a single flip signal. By analyzing the multiplicity spectrum of the SSG it is possible, in principle, to derive the number of photon induced single flips which can be used to estimate the background contamination. It is important to note, that in the neutron irradiation experiment, we were able to clearly distinguish single from multiple flips. The background studies in the Bern underground laboratory are under way as well as the investigation of the radioactivity of the materials. [7].
In Fig. 3a the expected spin-independent dark matter counting rates in SSG detectors made of 1kg of Sn or Zn with 15% spread in the superheating field distribution are plotted versus the dark matter mass at a detector threshold of $h = 0.005$. The values are calculated assuming a WIMPs density on Earth of 0.4GeV/cm$^3$. Counting rates of $\sim 40$ per day can be reached in each 40cm$^3$ element of the prototype SSG dark matter detector. The seasonal modulation in the dark matter signal will be beneficial to discriminate against background. The amplitude of the modulation is plotted in Fig. 3b for the proposed Sn and Zn SSG detectors. The dependence of the modulation on the dark matter mass and on the detector material is discussed in Ref.[9]. An appreciable statistical significance of the modulation can be obtained using five 40cm$^3$ SSG elements in parallel.

4 CONCLUSIONS

The successful irradiation experiments with neutrons encouraged us to plan prototype Sn and Zn SSG dark matter detectors to be operated in the underground laboratory of the University of Bern. In this paper, we have shown that Sn and Zn SSG detectors with the presently measured superheating spread of about 15% can be used as prototype detectors for dark matter. Appreciable counting rates and statistical significance of the seasonal modulation can be obtained using several SSG detector elements each of 40cm$^3$ in volume. Since the amplitude of the modulation depends on the detector material, the comparison between the counting rates of Sn and Zn SSG detectors can be used to better distinguish the WIMP signal from background. The first phase of the project will be dedicated to the study of the radioactive background and to the optimization of the detector readout.

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Figure Captions

1. Expected spin-independent detection rate of 50GeV/c² WIMPs in Zn and Sn SSG detectors \( h=0.005 \) versus the spread \( \sigma \) of the superheating field.

2. a) Sketch of the shielding setup for the SSG dark matter search experiment. b) Calculated multiplicity spectrum of the flips induced by \( \gamma \) activity of Rn²²² in the planned 40cm³ Sn (5µm) and Zn (20µm) SSG detectors at 50mK with magnetic threshold \( h=0.005 \).

3. a) Expected spin-independent dark matter counting rate in SSG detectors made of Sn or Zn granules at 50mK with \( \sigma=15\% \) and magnetic threshold \( h=0.005 \). b) Amplitude of the seasonal modulation.
This figure "fig1-1.png" is available in "png" format from:

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