Detection of nuclear recoils in prototype dark matter
detectors, made from Al, Sn and Zn Superheated
Superconducting Granules

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Abstract

This work is part of an ongoing project to develop a Superheated Superconducting
Granule (SSG) detector for cold dark matter and neutrinos. The response of SSG
devices to nuclear recoils has been explored irradiating SSG detectors with a 70MeV
neutron beam. The aim of the experiment was to test the sensitivity of Sn, Al and
Zn SSG detectors to nuclear recoil energies down to a few keV. The detector consisted
of a hollow teflon cylinder (0.1cm\textsuperscript{3} inner volume) filled with tiny superconducting
metastable granules embedded in a dielectric medium. The nuclear recoil energies
deposited in the SSG were determined measuring the neutron scattering angles with a
neutron hodoscope. Coincidences in time between the SSG and the hodoscope signals
have been clearly established. In this paper the results of the neutron irradiation
experiments at different SSG intrinsic thresholds are discussed and compared to Monte
Carlo simulations. The results show that SSG are sensitive to recoil energies down to
\sim 1keV. The limited angular resolution of the neutron hodoscope prevented us from
measuring the SSG sensitivity to even lower recoil energies.
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1 Introduction

Superheated Superconducting Granule (SSG) detectors are presently being developed for the detection of neutrinos and cold dark matter candidates [1]. Various astronomical observations on the dynamics of spiral galaxies and galaxy clusters seem to suggest that most of the matter (\(\sim 90\%\)) in the universe is in the form of dark matter. Models of large structure formations combined with the COBE discovery of anisotropies in the cosmic microwave background predict a dark matter scenario made of a mixture of relativistic (hot) and non-relativistic (cold) particles. Possible cold dark matter candidates are weakly interacting massive particles (WIMPs) with masses between 30GeV and some TeV. A recent review on dark matter can be found in Ref. [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 a direct detection of WIMPs via elastic neutral current scattering with nuclei. Assuming a dark matter halo gravitationally trapped in the galaxy, appreciable counting rates can be reached with recoil energy thresholds of a few keV [5].

The interest in superconducting devices for dark matter detection is based on the very small quantum energies involved to break a Cooper pair (\(\sim 1\)meV) compared to conventional ionization (\(\sim 20\)eV) and semiconductor detectors (\(\sim 1\)eV). Superheated Superconducting Granule (SSG) detectors [6] consist of a collection of tiny (some \(\mu\)m diameter) spheres embedded in a dielectric medium. The granules, made of a type I superconductor having a superheating and supercooling phase transition, are kept at a constant temperature in the metastable state. The detection principle is based on the phase transition from the metastable to the normal conducting state (flip) of a single granule due to the energy deposited by the interacting particle. The detection threshold is given by the minimum energy needed to raise the granule temperature from the operating to the transition temperature. Due to the disappearance of the Meissner effect, the magnetic field enters the normal conducting granule, and therefore the phase transition can be sensed with a pickup loop around the detector. In principle, very low energy thresholds (\(\sim 100\)eV) can be obtained with an appropriate choice of the granule size, the superconducting material, the operating temperature and the strength of the applied magnetic field.

The sensitivity of SSG detectors to minimum ionizing particles [7], x-rays [8] and \(\alpha\) particles [9] has been proven in the past. To study the response of the detector to nuclear recoil energies in the keV range, a set of experiments has been performed by our group irradiating Sn, Al and Zn SSG detectors with a 70MeV neutron beam at the Paul Scherrer Institute in Villigen (Switzerland). The investigated range of nuclear recoil energies was from 1keV up to some hundred keV and is in turn comparable with the recoil energies expected in WIMP-nucleus interactions. Due to the fast transition time of the granules (\(\sim 100\)ns [10]), coincidences in time between the SSG signals and the neutron beam were clearly established, making irradiation tests a powerful probe to evaluate the response to small recoil energy depositions.
In this paper, the results of the irradiation experiments are discussed and compared to Monte Carlo simulations. In the investigated range of nuclear recoil energies, we have found good agreement between the performance of Al SSGs at different detector thresholds and the theoretical expectations. In the case of Sn SSG detectors, the measured response to nuclear recoils (sensitivity) was found to be higher than expected. The sensitivity of Zn SSGs was found to be correlated to the time difference between the scattering interaction and the onset of the resulting phase transition. Energy thresholds down to \( \sim 1 \text{keV} \) were reached in Sn and Zn SSG detectors. Due to the limited angular resolution of the neutron hodoscope we were not able to test the SSG sensitivity to lower recoil energies. The presented results are encouraging for possible applications of SSGs for a dark matter detector.

2 Experimental Setup

We performed neutron irradiation experiments on SSG detectors made of Al, Sn and Zn granules with diameters of 20-25\( \mu \text{m} \), 15-20\( \mu \text{m} \) and 28-30\( \mu \text{m} \), respectively. The setup used in the experiments is sketched in Fig.1 and the characteristics of the different SSG detectors are listed in Table 1.

The SSG detectors consisted of a hollow teflon cylinder of 4mm inner diameter and 8mm length, filled with a collection of granules selected in size by ultrasonic sieving. A scanning electron microscope analysis of a sample of sieved granules showed a rather narrow distribution (Table 1). The Al granules were embedded in an Al\(_2\)O\(_3\) powder, the Sn and Zn granules were embedded in plasticine. The volume filling factors were between 6% and 11%. The detectors were operated in the mixing chamber of a \(^3\)He-\(^4\)He dilution refrigerator \[11\]. The measurements on the Zn and Sn SSGs were done at a temperature of 40±5mK using a pair of identical SSG detectors mounted one behind the other along the beam axis in order to increase the statistics. The irradiation tests with Al SSGs were performed at 120±10mK and are described in Ref. \[12\].

Each SSG target was surrounded by one pickup coil (180-228 windings, depending on the sample) connected to a J-FET preamplifier working at room temperature. The signal due to the phase transition of a single granule was a damped oscillation with a period of about 1.5\( \mu \text{s} \) as shown in Fig 2. The signal was well above the electronic noise, and we were able to clearly recognize the phase transition of a single granule in SSG detectors made of more than 1 million granules. The magnetic field was generated by a Helmholtz coil outside the cryostat and the uncertainty in the absolute field strength was evaluated to be 1%.

The neutron beam was produced by irradiating a Be target with 72MeV protons from the Injector I at the Paul Scherrer Institute \[13\]. The residual protons were swept away by a bending magnet downstream of the Be target. The neutron beam was collimated to a diameter of 3.2mm by a copper collimator of 150cm length aligned with the SSG detectors. The energy distribution of the neutrons was sharply peaked
at 70MeV with a small shoulder towards lower energies $^{13}$. The beam repetition rate was 17MHz with a bunch length of 2ns.

The scattered neutrons were detected with a counter hodoscope located 2m behind the SSG. The neutron hodoscope consisted of 18 scintillator bars with a length of 150cm and a cross section of $5 \times 5 \text{cm}^2$. The bars were arranged in three successive planes of six elements each. The position of the interacting neutron inside a single element was determined measuring the time difference between the signals of two photomultipliers located at the ends of the bar with a resulting spatial resolution of $\pm 4 \text{cm}$ corresponding to an angular resolution of $\pm 20 \text{mrad}$. The hodoscope covered scattering angles from 20mrad up to about 0.45rad.

In the earlier Al runs $^{12}$, the neutron beam was monitored using a 5cm thick scintillation counter behind the hodoscope preventing an absolute evaluation of the beam intensity. To discriminate against charged particles, two veto counters were installed between the cryostat and the hodoscope. The first counter was a 5mm thick scintillator located 20cm behind the SSG and covering an area of $20 \times 20 \text{cm}^2$. The energy threshold was set to 0.15MeV. The second veto counter was a 2cm thick scintillator located close to the hodoscope covering the full acceptance.

In the Zn and Sn irradiation tests, we improved the setup using concrete blocks covering the sides and the top of the neutron hodoscope to shield against background from the surrounding. In addition, the neutron flux was measured using a thin CH$_2$ target positioned after the collimator and a telescope at 13 degrees to detect protons coming from $n - p$ reactions in this target. To discriminate against charged particles entering the SSG detector an additional 5mm scintillator veto counter was located in front of the cryostat window.

## 3 Irradiation experiments

The distribution of the superheating field of the granules within the detector was measured without irradiation by simply ramping the field and recording the rate of phase transition signals as a function of the applied field. The superheating field distributions of the SSG detectors used in the irradiation experiments are shown in Fig.3. Previous works on single granules $^{9}$ have shown a modulation in the superheating field related to the orientation of the granule with respect to the magnetic field. The crystalline structure of the granules, deviations from spherical shape and magnetic field distortions across the granules were found to be responsible for the observed superheating field distributions.

### 3.1 Irradiation cycles

The irradiation experiments consisted of many consecutive cycles. In each cycle, the magnetic field was changed with time as shown in Fig.4. The detector threshold was
set ramping the magnetic field up to a reference value $B_1$. Then the field was reduced to a lower value $B_2$ and maintained constant for 5 or 10 minutes during which the beam induced phase transitions were recorded. Finally, the field was raised to 50mT in order to flip the remaining superconducting granules into the normal state. The detector magnetic threshold was defined as $h = 1 - B_2 / B_1$, the values of the reference field $B_1$ being listed in Tab.1. Due to the superheating field distribution only granules with an individual field $B_{sh} > B_1$ were sensitive to the neutron beam. Data were taken at detector thresholds $h$ in the range from 0.5% up to 10%, which correspond to recoil energy thresholds (see chapter 4.2) as shown in Fig.5. To align the SSG detectors to the beam, the cryostat was moved perpendicular to the beam axis to find the maximum SSG counting rate without selecting coincidences with the hodoscope. The measured beam profile was a gaussian with a standard deviation of $\sigma \sim 2\text{mm}$ as it is shown in Fig.6. The fraction of the total neutron flux impinging on the SSG detector was 35±5%.

The decrease of the counting rate within an irradiation cycle is shown in Fig.4 for a Sn SSG detector at two magnetic thresholds. This is due to the loss of sensitive granules during irradiation. At high detector thresholds, the decay is less pronounced because only a small fraction of the granules is sensitive to the impinging particles.

Due to the small neutron cross section and the small size of the target, the probability of having multiple elastic scatterings within the SSG is rather small. Neutrons mainly produce the phase transition of a single granule. Charged particles instead can cause more than one granule to flip. Single flip events were clearly distinguished from events with higher multiplicity using the pulse height of the phase transitions signals of the SSG detectors (Fig.8).

### 3.2 Selection cuts

In order to select a neutron induced event, coincidences in time between the injector radio frequency, the SSG detector and the hodoscope signals had to be established. The SSG trigger was defined by the first zero crossing of the SSG signal (Fig.2).

Typical time distributions between the SSG and hodoscope signals are shown in Fig.4 for the Al, Zn and Sn SSG detectors. The SSG signals in coincidence were well above the accidental background and only events within the hatched regions were selected for the analysis. The events outside the time window were used to evaluate the accidental background, which was subtracted from the selected events after normalization. The standard deviations from the means of the distributions of the SSG signals in coincidence above background were about 25ns in Sn, 45ns in Al and 150ns in Zn.

In contrast to Sn, the coincidences in the Zn irradiation test lie within a wide range of time differences ($\simeq 800\text{ns}$) between the hodoscope trigger and the SSG flip signals, as shown in Fig.4. Recent investigations [18] have shown that the observed time distributions are not affected by the speed of the magnetic field penetration inside
the granule, but are due to the thermal relaxation of the quasiparticles and phonons produced by the recoil event. The time scale of the thermal diffusion is shorter in Sn than in Zn due to the shorter quasiparticle relaxation times [19].

To reduce the background from charge exchange reactions, which produced a fast proton in the final state, only events with no signal in the veto counters were considered. The kinetic energy of the interacting neutron was determined from the time of flight between the neutron production target and the hodoscope. A cut on the scattered neutron time of flight of $\pm 1.5\text{ns}$ was introduced as shown in Fig.10. Due to the bunch width of the beam, the accuracy on the energy measurement of a 70MeV neutron was $\pm 8\text{MeV}$.

After the cuts, the number of events used in the final analysis was approximately 300 in Al and 1500 in Zn and Sn for each detector threshold.

4 Simulation of the experiment

To evaluate the SSG response to nuclear recoils, the measurements were compared to a Monte Carlo simulation of the experiment. The SSG response to the beam was calculated considering only elastically scattered neutrons.

4.1 Nuclear recoil energies

The distribution of the scattering angles ($\vartheta$) was evaluated by a partial wave expansion using the optical model [14]. This approximation can be safely used because the de Broglie wave length of a 70MeV neutron (0.54fm) is smaller than the nuclear radius $R = 1.37A^{1/3}\text{fm}$ with $A$ the atomic number. Because the neutron kinetic energy of 70MeV is higher than the nuclear potential of about 30MeV [13], the neutron wave enters the nucleus with a propagation vector shifted by $k_1 \simeq 0.3\text{ fm}^{-1}$ and is absorbed by neutron-nucleon-scattering with an absorption coefficient of $K=(0.25-0.29)\text{ fm}^{-1}$, depending on the nuclear neutron-proton-ratio [14]. The differential elastic cross section is given by:

$$\frac{d\sigma_{el}}{d\vartheta} = \frac{\pi}{2k^2} |f(\vartheta)|^2 \sin(\vartheta)$$

$$f(\vartheta) = \sum_{l=0}^{l+1/2<kR} (2l+1) \left[ 1 - \exp(-K + 2i k_1 sl) \right] P_l(\cos \vartheta)$$

$$sl = 1/k \left[ (kR)^2 - (l + 1/2)^2 \right]^{1/2}$$

with $k$ the de Broglie propagation vector of the neutron and $P_l$ the Legendre polynome of degree $l$. Due to nuclear absorption, the total elastic cross section differs from the geometrical cross section $\pi R^2$, depending on the value of $KR$, leading to total cross sections at 70MeV of 0.82barn, 1.39barn and 1.85barn for Al, Zn and Sn, respectively.
The scattering probabilities listed in Tab.1 are calculated considering an effective target thickness $d$ of 0.5mm, 1.9mm and 0.9mm for the Al, Zn and Sn SSG, respectively. The recoil energy $E_r$ deposited inside a granule by an elastically scattered neutron was evaluated from the scattering angle $\vartheta$.

4.2 Energy threshold

The energy threshold $E_{th}$ for a single granule is given by the energy needed to raise the granule temperature from the bath temperature $T_b$ to the transition temperature $T_{sh}$. From the phase diagram, this change in temperature can be related to the magnetic threshold $h_g = 1 - B_2/B_{sh}$ with $B_2$ and $B_{sh}$ the applied and the superheating field respectively. The transition temperature $T_{sh}$, evaluated from the approximated temperature dependence of the superheating field $B_{sh} = B_0(1 - t^2)$ is:

$$T_{sh}(h_g) = T_c \sqrt{t^2 + h_g(1 - t^2)}$$ (2)

with $T_c$ the critical temperature at zero magnetic field and $t = T_b/T_c$ the reduced temperature of the bath.

For a granule of volume $V$, the energy density threshold $q_{th} = E_{th}/V$ required to produce a phase transition can be defined as:

$$q_{th} = \int_{T_b}^{T_{sh}(h_g)} C(T) \,dT$$ (3)

where the superconducting specific heat $C(T)$ is given by:

$$C(T) = \beta \frac{T^3}{\theta^3} + \gamma T \, u(t)$$ (4)

using the parameterization [6]:

$$u(t) = \begin{cases} 3.33 \exp(-1.76/t) \, t^{-3/2} & ,0 < t < 0.1 \\ 26 \exp(-1.62/t) & ,0.1 < t < 0.161 \\ 8.5 \exp(-1.44/t) & ,0.161 < t < 1 \end{cases}$$

and $\beta = 1944$ $J/mol^{-1}K^{-1}$. The values of the Sommerfeld constant $\gamma$, the Debye temperature $\theta$ and the critical temperature $T_c$ are listed in Tab.2 for the three materials of interest [7].

In eq. 3, the energy deposited by the interacting particle is assumed to be uniformly distributed over the whole granule. Such a scenario is usually referred to as global heating model [1]. The calculated energy thresholds for 25$\mu$m Al, 29$\mu$m Zn and 17$\mu$m Sn granules are shown in Fig.5. The recoil energies due to neutral-current scattering of dark matter are expected to be of the order of a few keV [4]. Note that such energy
thresholds can be reached with the presently used superconducting granules and in principle even lower ones could be reached using smaller granules.

In the irradiation experiments, the detector threshold $h$ was set by ramping the magnetic field as shown in Fig.4 and discussed in section 3. Only granules with an individual field $B_{sh} \geq B_1$ were sensitive. The probability of having a phase transition in the Sn SSG for a given energy deposition, shown in Fig.11, can be evaluated from eq.3 using the measured granule size and the superheating field distributions. The slow increase of the flip probability with increasing recoil energy is due to the superheating field distribution.

4.3 Occurrence of neutron induced phase transitions

In the simulation program, a phase transition was triggered depending on the energy deposit by an elastically scattered neutron inside a granule. This granule was selected from a pool of granules with a flat size distribution within the range given in Tab.1 and a superheating field distribution obtained from the measurements. The distribution of scattering angles was derived from eq.4. A phase transition occurred whenever the deposited energy density $q=E_r/V$ exceeded the threshold value $q_{th}$ (eq.3). All the flipped granules ($q \geq q_{th}$) were made insensitive to later interactions. After each phase transition, the path of the scattered neutron was tracked to the hodoscope. Events with no hits in the hodoscope were discarded. The scattering angles and recoil energies associated to the selected events were stored. For each of these events the hit pattern of the hodoscope was evaluated. The spatial resolution of the neutron hodoscope was properly taken into account. During the irradiation, the probability of having a phase transition inside the SSG detector for a given recoil energy changes with time because of the decrease in the number of sensitive granules (Fig.7). To account for this effect, the Monte Carlo program generated the same number of phase transitions as measured in a typical cycle for each detector threshold. The total number of scattering events generated in the simulations was used to normalize the calculated distributions at different detector thresholds.

5 Experimental results

5.1 Normalization

To evaluate the absolute SSG efficiency to nuclear recoils, the rate of coincidences was normalized to the beam monitor counts and divided by the hodoscope counting rate. To estimate the hodoscope counting rate due to neutrons scattered by the SSGs, additional runs with bulk material were performed using a thick Sn target replacing the SSG detector. Elastically scattered neutrons were selected requiring a trigger in the hodoscope with the same selection cuts on the neutron time of flight, on the
hodoscope and on the veto counters as used in the SSG irradiation runs. The bulk runs were done with two different target thicknesses (2mm and 10mm). After subtraction, the resulting hodoscope counting rate for an effective 8mm thick Sn bulk was about 3.2±0.3(stat) events per beam monitor count. The expected hodoscope counting rate $n_{Sn}$ due to elastic scatterings from the Sn SSG detectors was evaluated from the bulk runs considering the ratio between the effective thicknesses of the SSG and the bulk target. Since the neutron flux impinging the SSG detectors was only 35±5% of the total beam flux, the hodoscope counting rate $n_{Sn}$ normalized to the beam monitor was evaluated to be $n_{Sn}=0.13±0.02$. The error contains the statistical and systematical errors of the bulk runs and the uncertainty in the beam coverage of the SSG detectors. The Sn bulk measurements were also used to evaluate the hodoscope counting rate $n_{Zn}$ due to neutrons elastically scattered from the Zn SSG detectors. The probability $S$ for an incoming neutron to be elastically scattered is higher in the Zn than in the Sn detectors (see table 1). From the Monte Carlo simulations, the mean geometrical acceptance of the hodoscope for elastically scattered neutrons on Zn nuclei turned out to be about 10% higher than on Sn nuclei. The hodoscope counting rate is with $n_{Zn}=0.39±0.06$ about three times higher than $n_{Sn}$.

In the irradiation runs, the rates of coincidences between the SSG detectors and the neutron hodoscope have been measured. The loss of sensitive granules during irradiation (Fig.7) was taken into account. The ratio between the SSG coincidence rate and the hodoscope counting rate defines the detection efficiency. It reflects the ability of the SSG detector to detect events with a scattered neutron in the hodoscope. The efficiency will never reach 100% since a fraction of the granules is never sensitive due to the width of the superheating curve and the choice of the magnetic threshold.

### 5.2 Aluminum

The recoil energies of the selected events for three detector thresholds are compared with the Monte Carlo results using the global heating model in Fig.12.

The experimental uncertainty in the determination of the recoil energy is due to the neutron kinetic energy resolution of the time of flight measurement and the scattering angle resolution of the hodoscope. The uncertainty in the counting rate is due to statistical and systematic errors in the selection cuts. In the full range of applied detector thresholds, the experimental data agree well with the global heating model. The distributions shift to higher values when the detector threshold is increased. These shifts are not clearly seen due to the different magnetic thresholds of the sensitive granules and to the limited recoil energy resolution which corresponds to the bin width in Fig.12.

The agreement between experimental data and Monte Carlo results also appears in the comparison of the Monte Carlo detector efficiency (for scattering events with the final neutron being detected in the hodoscope) and the experimental efficiency, as
shown in Fig. 13. The hodoscope counting rate $n_{Al}$ in this case was determined by a calibration run with a 4cm thick Al bulk in the beam. Its thickness was chosen so, that most of the neutrons in the beam are scattered within the bulk. The counting rates were normalized to a 5cm thick scintillation counter placed in the beam behind the hodoscope.

As expected, the measured detector efficiency decreases with increasing detector threshold. Due to the distribution of recoil energies and the spread of superheating fields, not every elastic scattering releases enough energy to flip the granule, so that even at zero detector threshold the efficiency does not reach 100%.

The experimental results show that the behaviour of Al SSGs is consistent with global heating.

5.3 Zinc

The Zn data were divided into two sets selecting events with either short (1.2-1.6 $\mu$s) or long (1.6-2.0 $\mu$s) time differences between the hodoscope and the SSG signals. In Fig. 14, the recoil energy distributions of the two sets of data are compared to the global heating Monte Carlo simulation. For clearness, the Monte Carlo and the data have been normalized to the same total number of events. Fig. 14 exhibits a clear correspondence between a fast (slow) response to a large (small) recoil energy.

In Fig. 15 the measured efficiency considering both slow and fast triggers is compared to the Monte Carlo simulations. The Monte Carlo results agree in general well with the experiment, but the decrease of efficiency with increasing detector threshold is steeper in the experimental data than in the Monte Carlo simulations. This disagreement still remains when only the slow signals are considered.

5.4 Tin

Previous experiments on Sn SSG irradiated with $\alpha$ particles [9] and minimum ionizing particles [7] have shown that the detector sensitivity is higher than expected by the global heating model (eq. 3). To evaluate the SSG sensitivity to nuclear recoils, the measurements were compared to the Monte Carlo simulations using the global heating model.

The comparison between the measured and the calculated recoil energy distribution is shown in Fig. 16 for four detector thresholds. The observed sensitivity of Sn SSG to nuclear recoils of some keV demonstrates the ability of such devices to detect also nuclear recoils due to WIMP interactions. The data seem to indicate that Sn granules are more sensitive to nuclear recoils than expected using the global heating model.

Fig. 17 compares the measured efficiencies to detect a neutron scattering with the final state neutron being registered in the hodoscope at six different detector thresholds with the predictions from the Monte Carlo algorithm using the global heating model.
The higher sensitivity of Sn SSGs is still under investigation. It may be explained by a heat diffusion effect which takes into account the location of the nuclear recoil inside the granule together with the minimum size of the nucleation center at the surface of the granule \[20\].

6 Conclusions

Irradiation measurements of Al, Zn and Sn superheated superconducting granule (SSG) detectors exposed to a 70MeV neutron beam have been performed to study the sensitivity to nuclear recoils of defined energy down to some keV. The limited angular resolution of the experiment prevented us to measure the sensitivity of the SSG to recoil energies below 1keV. In the case of Al SSGs, the measured recoil energies follow the theoretical predictions of the global heating model, while the Sn SSGs show a higher sensitivity to nuclear recoils than predicted by this model. In the case of Zn SSGs a large time difference between the interaction and the occurrence of the flip signal has been observed. This delay could be attributed to the heat diffusion mechanism, which reflects the long quasiparticle relaxation time in Zn.

The experiments confirmed that SSG detectors can be successfully used to detect recoil energies even below 1keV, depending on the material and the granule size. By improving the readout circuit in order to detect signals from smaller granules, even smaller energy thresholds (in the eV region) could be reached. The detector efficiency does not saturate above the energy threshold because of the shape of the superheating curve and the size distribution of the granules. The obtained sensitivities encourage the use of SSG detectors for WIMP searches.

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Tables

Table 1: SSG detector characteristics.

| material | $B_1$ [mT] | $T_b$ [mK] | grain diameter [$\mu$m] | Filling factor [%] | scattering prob. S [%] |
|----------|-------------|------------|-------------------------|-------------------|----------------------|
| Al       | 10.4        | 120        | 20-25                   | 6                 | 0.24                 |
| Zn       | 6.5         | 40         | 28-30                   | 11                | 1.73                 |
| Sn       | 31.5        | 40         | 15-20                   | 6                 | 0.60                 |

Table 2: Properties of the used SSG materials.

| material | $T_c$ [K] | Sommerfeld constant [mJ/mol/K$^2$] | Debye Temp. [K] |
|----------|-----------|-----------------------------------|-----------------|
| Al       | 1.2       | 1.36                              | 426             |
| Zn       | 0.9       | 0.63                              | 310             |
| Sn       | 3.7       | 1.75                              | 195             |

Figure Captions

Fig. 1: Experimental setup.

Fig. 2: Signal output of the readout electronics for a beam induced phase transition of a single granule in a Zn detector.

Fig. 3: The superheating curves of the a) Al, b) Zn and c) Sn SSG detectors as measured in the experiment.

Fig. 4: Magnetic field versus time during one irradiation cycle.

Fig. 5: The corresponding recoil energy thresholds $E_{th}$ versus the SSG detector thresholds $h$ for: a) Al granules with $23\mu$m diameter at $T_b=120$mK, b) Zn granules with $29\mu$m diameter at $T_b=40$mK, c) Sn granules with $17\mu$m diameter at $T_b=40$mK.

Fig. 6: The neutron beam profile measured with the Sn SSG detector across the horizontal beam axis.
Fig. 7: Time evolution of the Sn SSG detector counting rate during irradiation at two magnetic thresholds, not requiring coincidence with the hodoscope.

Fig. 8: Signal amplitudes of grain flips in the Sn SSG detector without requiring a coincidence with the neutron hodoscope. Single grain flips can be clearly distinguished from multiple (2,3,4 etc) flips.

Fig. 9: Distribution of the time difference between SSG and hodoscope signals for: a) Al, b) Zn and c) Sn SSG detectors. The selected events are within the hatched regions. The time scale is offset by a constant value due to electronic delays.

Fig. 10: Time of flight (TOF) spectrum of incident neutrons for the Sn detector. The selected events are within the hatched regions.

Fig. 11: Calculated phase transition probability as a function of the deposited recoil energy inside a granule for the Sn SSG detector with the thresholds $h=0.5\%$ and $h=3.5\%$.

Fig. 12: Recoil energy distribution of the Al SSG for three detector thresholds: a) 2\%, b) 5\%, c) 10\%. Line: Monte Carlo prediction using the global heating model, points: data from the irradiation runs.

Fig. 13: Al SSG detection efficiency for an event with the elastically scattered neutron passing the hodoscope. Points: Data from irradiation runs, line: Monte Carlo prediction using the global heating model.

Fig. 14: Recoil energy distributions of the Zn SSG for two detector thresholds, for either short (1.2-1.6$\mu$s, Figs. a and b) and long (1.6-2.0$\mu$s, Figs. c and d) time differences between hodoscope and SSG signals. Line: Monte Carlo prediction using the global heating model, points: Data from the irradiation runs.

Fig. 15: Zn SSG detection efficiency for an event with the elastically scattered neutron passing the hodoscope. Points: Data from irradiation runs, line: Monte Carlo prediction using the global heating model.

Fig. 16: Recoil energy distribution of the Sn SSG for four detector thresholds: a) 0.5\%, b) 1.0\%, c) 2.5\%, d) 3.5\%. Points: Data from irradiation runs, line: Monte Carlo prediction using the global heating model.

Fig. 17: Sn SSG detection efficiency for an event with the elastically scattered neutron passing the hodoscope. Points: Data from irradiation runs, line: Monte Carlo prediction using the global heating model.