# ON THE USE OF SSC AS A DETECTOR OF CERTAIN DARK MATTER CANDIDATES*

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Following the proposal of Goodman and Witten we consider the use of superheated superconducting colloid (SSC) as a detector for supersymmetric particle candidates for the dark matter. The expected count-rates and energy depositions suggest that the SSC detector should be able to detect scalar neutrinos with $m > 5$ GeV, providing that they are the lightest supersymmetric particles. The background due to solar neutrinos is estimated to be 0.002 counts/(kg$\times$day) and the signal to background ratio of a few thousands is expected.

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## *Introduction*

Astronomical evidences suggest the existence of dark matter halo [1]. Many dark matter candidates have been proposed, e.g. black holes, gas clouds, monopoles, axions, neutrinos and massive SUSY-particles. Recently, Goodman and Witten [2] proposed new ways of detecting some candidates, exploiting elastic neutral currents scattering on heavy nuclei [3]. The detector will consist of superconducting grains with a radius of a few microns embedded in a dielectric material and placed in a magnetic field. The grains are maintained just below their superconducting transition temperature. A scattered particle, e.g. SUSY partner of neutrino will impart a small recoil kinetic energy to the nucleus it scatters from. For example, particles with masses of 10–100 GeV give the recoil of 10–100 keV. Such a small energy deposit can make a tiny superconducting grain go normal, permitting the magnetic flux to collapse into the grain and producing an electromagnetic signal in a read--out electronics [3].

We want to point out that the superheated superconducting colloid can detect particles, only if the deposed energy is bigger than some energy threshold, $E_{\mathrm{th}}$. This leads to a strong dependence of the count-rate on the particle mass, type of detector, temperature in which it operates and the noise of read-out electronics. In the following, we discuss the various

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components of the detection system and their effects on the detection capabilities. Furthermore, we find a strong dependence of the detector response on the velocity of incoming particle, count-rate $\sim v^7$. The realistic model of the local distribution of velocities of weakly interacting, massive particles in the galactic halo and their effect on detection capabilities is discussed elsewhere (see Ref. [8]).

### *Detection of scalar neutrinos*

We first assume that the unknown dark matter candidate has vector couplings to Z bosons and scatters from nuclei. One particle with this property is the scalar partner of neutrino in supersymmetric theories. There is no cosmological argument against sneutrinos as the lightest supersymmetric particle [4]. In other models [5] the sneutrino is lightest and therefore stable.

The count-rate to be expected is [2]

$$R \approx 5.8 \times \left(\frac{\bar{\sigma}}{10^{-38}\ \mathrm{cm}^2}\right)\left(\frac{\varrho}{10^{-24}\ \mathrm{g/cm}^3}\right)\left(\frac{v}{200\ \mathrm{km/sec}}\right)\Big/(\mathrm{kg} \times \mathrm{day}) \tag{1}$$

where

$$\bar{\sigma}[\mathrm{cm}^2] = 2 \times 10^{-35} \frac{4mM}{(m+M)^2} \tilde{\gamma}^2 \left(\frac{\bar{N}}{100}\right)^2 \tag{2}$$

and: $m$ — mass of the particle in GeV, $\varrho$ — mass density of halo particles, $v$ — particle's mean velocity, $M$ — mass of the target nuclei, $\bar{N}$ — number of neutrons in the target nuclei, $\tilde{\gamma} \simeq O(1)$. For justification of formulae (1) and (2) and for definition of $\tilde{\gamma}$ see Ref. [2]. The cross-section for $1.0 < m < 100$ GeV and three superconductors, Al, Sn and Pb is plotted in Fig. 1.

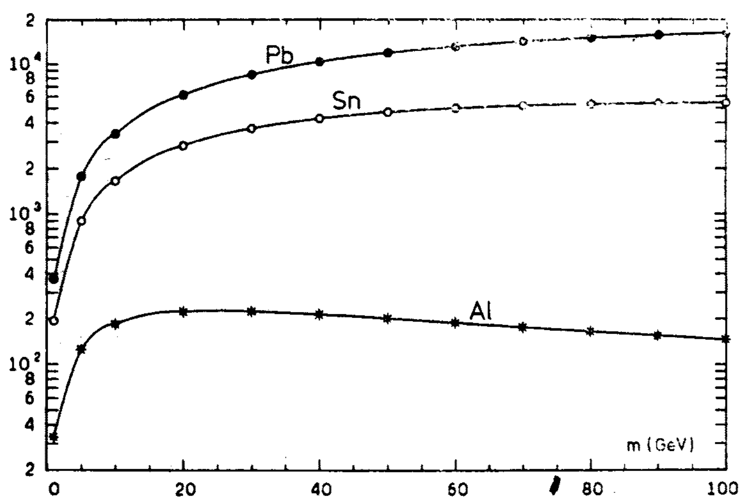


Fig. 1. Cross-section for sneutrino coherent scattering on Al, Sn, Pb (in units $1.0^{-35}$ cm$^2$)

In many SUSY models, photinos are the lightest i.e. stable particles. Goodman and Witten consider the case when photinos interact with quarks via exchange of scalar quarks. If there is important mixing between left- and right-handed scalar quarks, the photino gets coherent couplings to quarks. However, this is unfortunately not the case in most models. There is the possibility of interaction (see Ref. [2], page 9) but in most models

$$\frac{(M_1^2-M_2^2)^2}{M_1^4 M_2^4} \approx O(M_1^{-4}) \approx O(M_2^{-4}) \tag{3a}$$

and

$$\sin 2\beta \approx O(m_q/M_q) \tag{3b}$$

which leads to

$$\frac{\sigma_{\text{photino}}}{\sigma_{\text{sneutrino}}} \approx 0.24\times\left(\frac{m_q}{M_Q}\right)^2\left(\frac{100\ \text{GeV}}{M_Q}\right)^4\left(\frac{q}{\frac{2}{3}e}\right)^4 \approx O(10^{-6}) \tag{3c}$$

for $m_q > 10$ MeV and $M_Q > 40$ GeV.

Thus, the cross-section for coherent interaction of photino is very small, and only photinos with mass > 100 GeV can be detected in a few kilogram detector if one assumes $v = 200$ km/sec. However, it is not the realistic model of the local distribution of velocities of photinos in the galactic halo. When the velocity distribution is taken into account, even a few GeV photinos can be detected in a few kilograms SSC detector (see Ref. [8]).

The recoil kinetic energy is angle dependent and the maximum energy recoil is

$$E_{\max} = \frac{1}{2}\frac{(2mv)^2}{M}\left(\frac{M}{M+m}\right)^2. \tag{4}$$

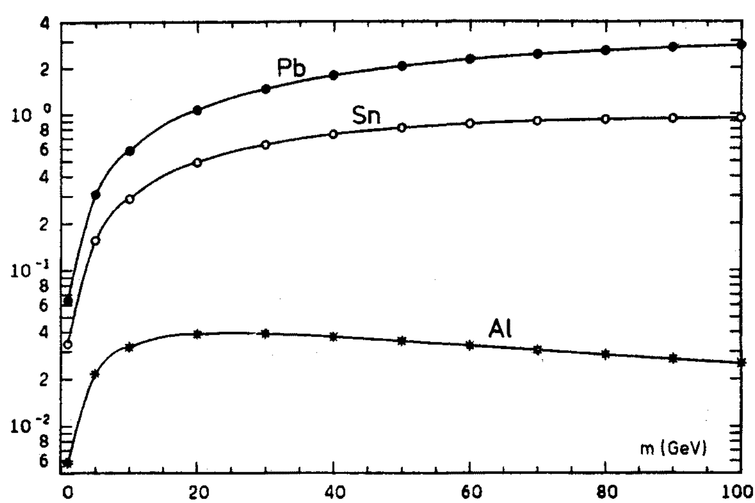


Fig. 2. Count-rate per kg×day for sneutrinos using Al, Sn and Pb detector. Assuming $\varrho = 10^{-24}$ g/cm$^3$ and $v = 200$ km/sec

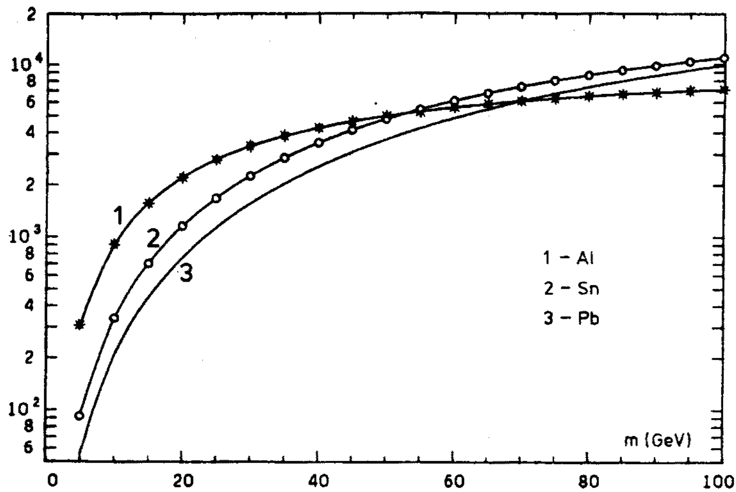


Fig. 3. Typical energy deposition, $E_{th}$ [eV] = 0.5 $E_{max}$, of sparticle with mass $m$ [GeV] on Al, Sn, Pb

Experimentally, we have to assume that the SSC detector is sensitive to energy recoils bigger than $E_{th}$, and our calculations show that optimal $E_{th} = \frac{1}{2} E_{max}$ (see following discussion and Fig. 7). In Fig. 3 this energy transfer $E_{th}$ is plotted vs. particle mass for different superconductors.

Obviously, as we assumed a given energy threshold, $E_{th}$ for grain, we expect somewhat smaller count-rate. For small energy transfers, e.g. if $m \ll M$ or $\cos 2\beta \ll 1$ we expect that cross-section is only weakly dependent on the momentum transfer and

$$R(E_{th}, E_{max}) = R \times (1 - E_{th}/E_{max}). \tag{5}$$

It is plotted in Fig. 2 for $E_{th} = 0.5\, E_{max}$.

The SSC is not the detector but a class of detectors which can be based on any of over twenty elements which are type I superconductors. The following material parameters influence the performances of SSC as sparticle detector:

— specific heat which at low temperatures, $T < 0.5$ K, is dominated by electrons specific heat;
— atomic number;
— density;
— critical temperature;
— critical and superheated magnetic fields.

It should be pointed out that these parameters vary widely, e.g.

— electronic specific heat from $\gamma$ (mJ/(mole × $K^2$)) = 0.171 to 2.99 for Be and Pb;
— $A$ = 4 to 207 for Be and Pb;
— $\varrho$ (g/cm³) = 1.8 to 22.48 for Be and Os;
— $H_c$ (Gauss) = 5 to 1340 for Be and V.

In this paper we considered three superconductors, Al, Sn and Pb.

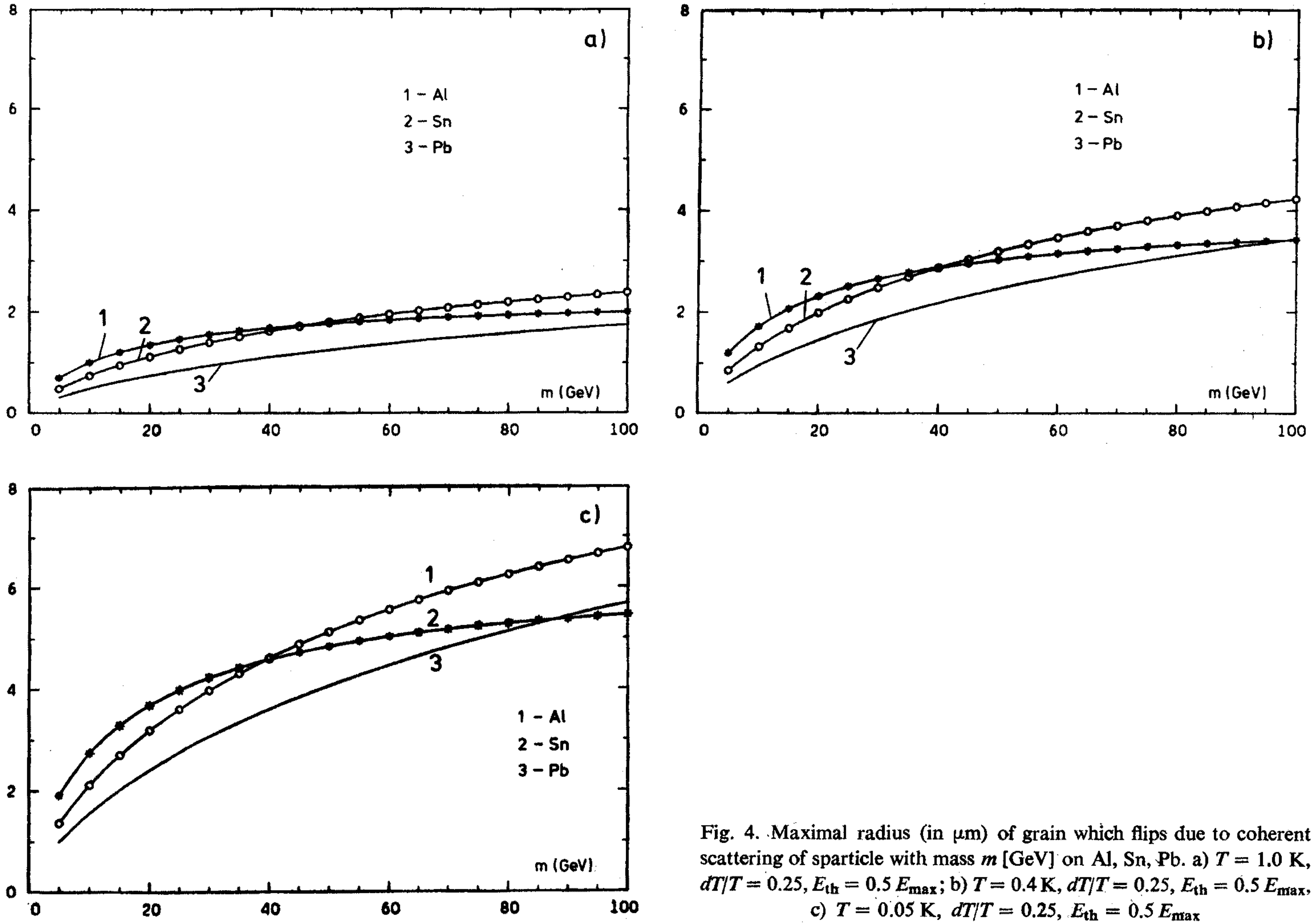


Fig. 4. Maximal radius (in μm) of grain which flips due to coherent scattering of sparticle with mass $m$ [GeV] on Al, Sn, Pb. a) $T = 1.0$ K, $dT/T = 0.25$, $E_{th} = 0.5\ E_{max}$; b) $T = 0.4$ K, $dT/T = 0.25$, $E_{th} = 0.5\ E_{max}$, c) $T = 0.05$ K, $dT/T = 0.25$, $E_{th} = 0.5\ E_{max}$

Using the conservative model of grain flipping (see Ref. [3]) we estimate the maximal size of the grain which change state due to the coherent scattering of the particle with mass $m$. We assumed that energy deposition is $E_{th} = 0.5 \times E_{max}$ and that the grains are in the temperature of 1.0 K whereas the temperature jump of $dT/T = 25\%$ is sufficient to flip the grain. Results are shown in Fig. 4a. Please note that the size of grain should be much bigger than the penetration depth, i.e. $R > 1$ μm. We observe that at $T = 1.0$ K only sparticles with $m > 20$ GeV can be detected. In Fig. 4b, c we show the maximal size of grain at temperatures of 0.4 K and 0.05 K, respectively. We observe that at $T = 0.4$ K sparticles with $m > 5$ GeV can be detected and that the limit of detectability is $m < 1$ GeV at $T = 0.05$ K. These results suggest that in the search for heavy sparticles one can use pumped liquid helium-4 but that for most interesting low mass sparticles the dilution refrigerators have to be used.

It should be pointed out that in the design of the SSC-detector the main difficulty and cost is in the read-out electronics. We suggest to use the DC-SQUID for detection of single grain flipping. The technicalities of the read-out are described elsewhere [6]. Our calculations suggest that

- — the SQUID read-out look should have $R < 20$ cm to diminish the pick-up of external magnetic noise;
- — the mass of the detector to be placed inside a read-out loop is strongly dependent on the size of used grains;
- — appropriate shaping of the SSC, one can exclude all the events when more than one grain flips.

The result of our calculations, i.e. a mass of the detector to be placed inside one SQUID vs. incident particle mass, is plotted in Fig. 5. Furthermore, we should point out that there are two main contributions to the electronic noise using DC-SQUID:

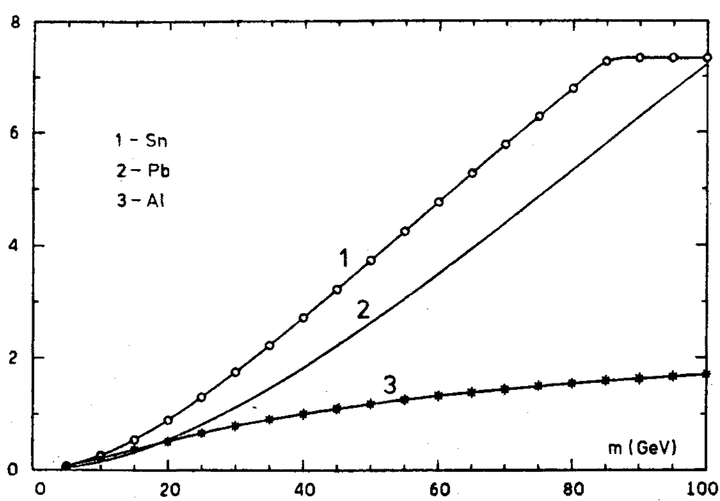


Fig. 5. Mass of SSC detector which can be placed inside one DC-SQUID loop. Assuming $E_{th} = 0.5\,E_{max}$, $T = 0.4$ K and $dT = 0.1$ K

— intrinsic noise of DC-SQUID;
— pick-up noise due to magnetic field fluctuations.
In searches for a low mass $m < 20$ GeV sparticles, relatively small diameter ($R_{loop} < 5$ cm) loops have to be used and the intrinsic noise of DC-SQUID dominates.

The above described calculations of count-rate and the grain thermodynamics permit us to calculate the expected count-rate per day for SSC detector with one DC-SQUID as read-out (see Fig. 6). We assumed $v = 200$ km/sec and $\varrho = 10^{-24}$ g/cm$^3$. It should be

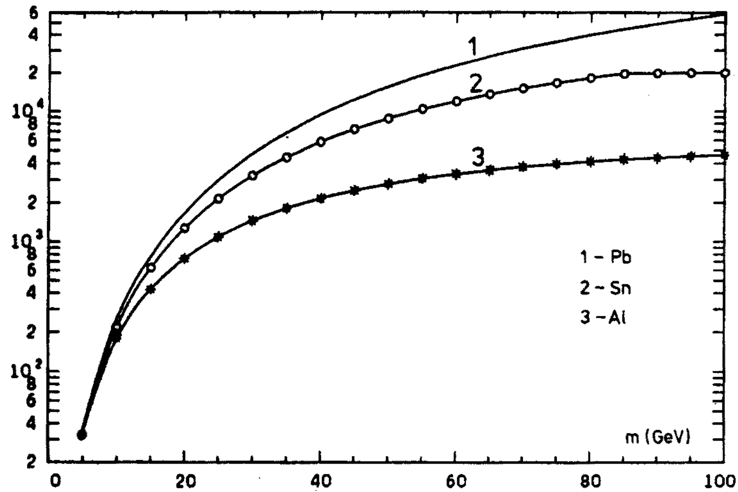


Fig. 6. Count-rate per day for one DC-SQUID detector for Al, Sn and Pb. ($E_{th} = 0.5\,E_{max}$, $T = 0.4$ K, $dT/T = 0.25$)

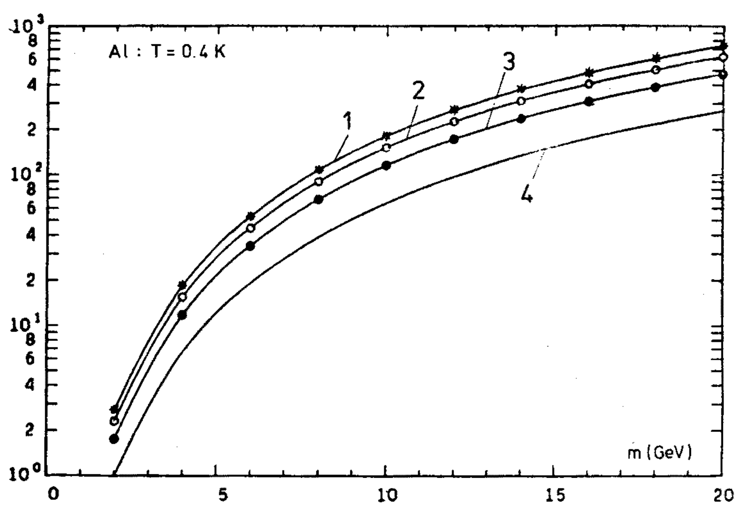


Fig. 7. Count-rate per day for one DC-SQUID detector for different assumptions about $E_{th}$ : $E_{th}/E_{max} = 0.5$, 0.3, 0.2 and 0.1 are shown in curves *1*, *2*, *3* and *4*, respectively

pointed out that for low particle masses the use of low atomic number target, e.g. Aluminium may be better. We expect count-rates of about 30/day for $m = 5$ GeV and 200/day for $m = 10$ GeV. For high masses, use of high atomic number targets is better and for Pb and $m > 40$ GeV count-rate of ca. $10^4$ counts/day is expected.

We should note that decrease of the count-rate for $m < 10$ GeV is only partially due to the decreasing cross-section. With $E_{th} \ll E_{max}$ we observe the fast decrease of the mass of detector which can be placed on a single DC-SQUID. Actually, it may be better to increase $E_{th}$ and thus be able to use bigger grains. The count-rates for $E_{th}/E_{max} = 0.5$;

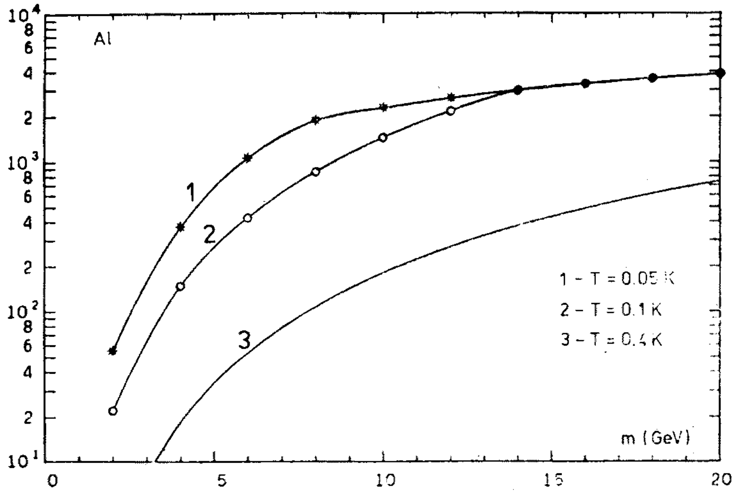


Fig. 8. Count-rate per day for one DC-SQUID detector for different assumptions about temperature ($E_{th} = 0.5\,E_{max}$, $dT/T = 0.25$, Aluminium)

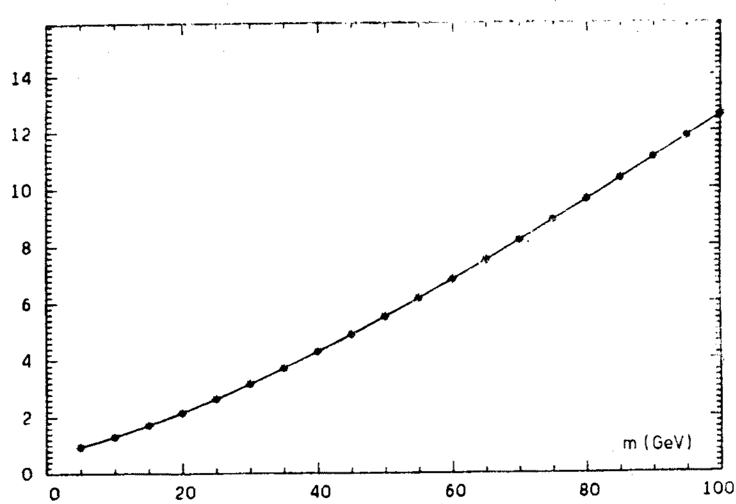


Fig. 9. Ratio of count-rates for Pb and Al detector

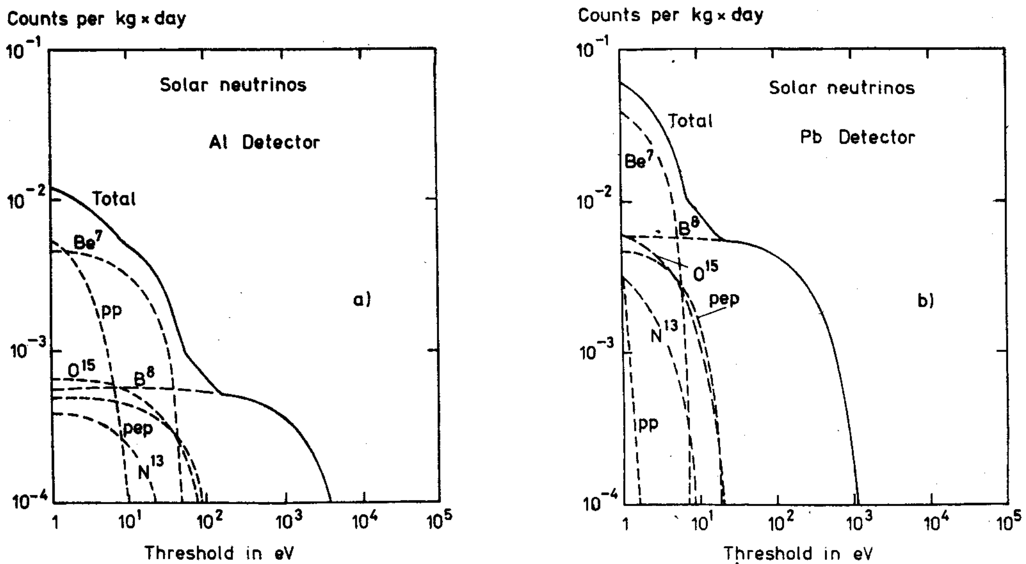


Fig. 10. Background due to coherently interacting solar neutrinos (see Ref. [3]); a — aluminium; b — lead

0.3; 0.2 and 0.1 are shown in Fig. 7. Actually, it decreases for $E_{th} > 0.5\,E_{max}$, i.e. $E_{th} = 0.5\,E_{max}$ is optimal.

For small sneutrino masses, $m < 10$ GeV, much higher count-rates can be obtained by further cooling of the detector. In Fig. 8 we show that the expected count-rates for $dT/T = 0.25$ and $T = 50$, 100 and 400 millikelvin, respectively.

It should be pointed out that by using two SSC detectors with a very different atomic number, say Al and Pb one can get some information on the sneutrino mass. The ratio of count-rates vs. particle mass is plotted in Fig. 9 ($T = 0.4$ K, $dT/T = 0.25$).

## Background

The preliminary estimates show that SSC detector with energy theshold of, say 1 keV and mass of a few kilograms can be built within two years. It would require only two read-out electronic channels based on DC-SQUID's and would be relatively unexpensive, say a few hundred thousand dollars. Thus the proper estimate of background is of considerable importance. It should be reminded that in SSC detector, a very good background rejection is possible due to:

— microseconds time resolution;
— micron granularity;
— modest energy resolution.

The signature of the neutral scattering event is that *one and only one grain* flips. In our paper [3] we discussed in some detail the most important background sources, and concluded that natural radioactivity is dominating. We believe that a background smaller than $5 \times 10^{-3}$ event/(kg × day) is possible, when detection of solar neutrino is attempted. However, when detecting the dark matter candidates, the solar neutrinos are the background and have to be accounted for. Let us first consider the background for coherent scattering of neutrinos. The data for Al and Pb are given in Fig. 10a and 10b respectively. It can be seen that the neutrino count-rate is strongly dependent on the energy threshold, $E_{th}$, i.e. minimum energy deposed in grain necessary to change the state. For $E_{th} > 200$ eV, only the $B^8$ solar neutrinos can be detected. Furthermore, the background in lower atomic number targets is higher than in high atomic number targets. It can be seen that for $E_{th}$ of a few keV, the background due to coherent interacting solar neutrinos is $B_1 < 5 \times 10^{-4}/(\mathrm{kg} \times \mathrm{day})$.

However, there is also a possibility of neutrino scattering from electrons. In this case the most abundant pp neutrinos dominate. The scattering of neutrinos on Silicon were discussed in Ref. [7]. The number of electrons per kilogram of material is only a slowly changing function of atomic number, $x = (Z/A) \times 6 \times 10^{26}$ electrons/kg where $Z/A = 0.498$, 0.482, 0.427, 0.427, 0.396 for Si, Al, Cd, In and Pb, respectively. The pp neutrinos interacting in metal will give about $10^{-3}$ event/(kg × day). When crossing metal, the minimum ionization particles losses are $\bar{E}2R \times (-dE/dx)$ with $\frac{-dE}{dx} = 1.8$ and 1.5 keV/μ, for Cd and In, respectively. Thus even the neutrino scattering in plastic may lead to about 10 keV energy deposition in the grains. The total background due to scattering of solar neutrinos on electrons should be $< 2 \times 10^{-3}$ event/(kg × day). Thus, if the count-rate for cosmological relics of sparticles is given by formulae (5), i.e. a few per kg × day for $m > 5$ GeV, we should have a very favorable signal/background of a few thousands.

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## REFERENCES


[1] S. Faber, J. S. Gallagher, *Ann. Rev. Astron. Astrophys.* 1979; F. Takahara, KEK Report 84-12, p. 149, September 1984; see however J. P. Lafon, in Proc. Moriond Workshop on massive neutrinos, January 1984; edition Frontières, Paris 1985.

[2] M. W. Goodman, E. Witten, *Phys. Rev.* **D13**, June (1985).

[3] A. K. Drukier, L. Stodolsky, *Principles and applications of a neutral current detector* ..., preprint MPI-PAE/PTh 36/82; also *Phys. Rev.* **30**, 2295 (1984).

[4] J. Ellis et al., *Nucl. Phys.* **B238**, 453 (1983); J. Ellis et al., *No-scale supersymmetric standard model*, preprint TH 3734-CERN, September 1983.

[5] J. S. Hagelin et al., *Perhaps Scalar neutrinos are the LSP's*, Los Alamos preprint LA-UR 83-3711 (1983).

[6] A. K. Drukier, A. Kotlicki, B. Turrell, *Electronic read-out of SSC detector using DC-SQUID's*, in preparation.

[7] B. Cabrera et al., *Bolometric detection of neutrinos*, preprint HUTP-84/A077.

[8] A. K. Drukier, K. Freese, D. N. Spergel, *Detecting cold dark matter candidates*, preprint Harvard-Smithsonian Center for Astrophysics, May 1985, to be published in *Phys. Rev.* D.