NEW IDEAS ON THE DETECTION OF LOW ENERGY SOLAR NEUTRINOS

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Abstract:

$^{115}$In provides an extremely interesting target for real time solar neutrino detection [1]. Its use was proposed by Raghavan [2], based on the reaction:

$$\nu (E > 128 \text{ keV}) + ^{115}\text{In} \rightarrow ^{115}\text{Sn}^{**} + e^- (E_p - 128 \text{ keV})$$

where the $^{115}\text{Sn}^{**}$ decays to the ground state of $^{115}\text{Sn}$ with a lifetime of 3.3 $\mu$s emitting two $\gamma$ rays (497 keV and 116 keV)[3]. The delayed coincidence should provide a specific signature of solar neutrino events, sharp enough to overcome background problems related to $^{115}\text{In}$ $\beta$ radioactivity.

Real time detection of solar neutrinos with $^{115}\text{In}$ has been proposed by several techniques [4]. We discuss here the possibility of performing such an experiment, focusing on superconducting granules and special scintillators. The concept of "localized micro-avalanche" should introduce crucial improvements in superheated superconducting granules (SSG) devices and, eventually, make feasible a 4 ton In solar neutrino experiment. The possible use of dedicated scintillating crystals of In compounds is also dealt with, as feasibility studies are under way.
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1. SUPERHEATED SUPERCONDUCTING INDIUM GRANULES

Superheated superconducting granules [5] were proposed for particle detection [6] by a Orsay group [7,8] and further studied in Rennes [9], where irradiation tests with a low energy electron beam were first performed. Subsequent attempts to build transition radiation detectors [10] or X-ray imaging devices [11] failed. The main problems for SSG development have been until now:

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.

More recently, the development of a SSG indium solar neutrino detector [12] encountered the same difficulties. In particular, the signal produced by a 116 keV photon (about 6 granules of 2 μm diameter would change state) is too weak to be read by conventional fast amplifiers in a full size experiment with a realistic number of electronic channels ($10^5$ for 5mm wide read-out loops). Furthermore, the intrinsic energy resolution is degraded by the inhomogeneity in grain size.

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, $10^4$ 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 any In solar neutrino experiment. Also, sensitivity of existing SSG prototypes is at least as good as predicted by naive theoretical calculations (global heating). It can actually be much better, as exhibited in Fig.1, where a local heating mechanism [6, 13] allows $10 \mu m < \Phi(\text{diameter}) < 25 \mu m$ tin granules to be sensitive to $6$ keV γ's [13, 14]. All irradiation experiments [14, 15] 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.

2. AMPLIFICATION BY THERMAL MICRO-AVALANCHE

It was first noticed by the Garching group [16] 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 [13, 14], 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.
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b. When going down in temperature from the point where $q'$ (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 $t_\tau$ is set below this domain, $q'$ 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, $\delta H$ 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 $\Delta E$, we assume $V$ to be the volume of an isothermal sphere of radius $R(t) = (4t/D)^{1/2}$ ($t$ = time, $D$ = detector heat diffusion coefficient). Taking for all granules a universal dependence of the effective superheated critical field in terms of temperature:

$$H_{sh}^{eff}(T) \approx H_{sh}^{eff}(0) f(T) \quad \{2\}$$

we can write a relation between the increase of temperature $\Delta T$ inside the isothermal hot sphere, and the equivalent threshold in magnetic field $\Delta H$ [6]:

$$\Delta H = H_{test} [f(T) - f(T + \Delta T)] [f(T + \Delta T)]^{-1} \quad \{3\}$$

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

$$dV_{flip}/dV = \int_{H_{test} + \delta H}^{H_{test} + \Delta H} d\psi/dH_0 \ dH_0 \quad \{4\}$$

Where $\psi$ is the filling factor in volume and $d\psi/dH_0$ the differential superheating curve in filling factor [6, 13].

Finally, $\Delta T$ is related to $\Delta E$, $V_{flip}$ and $V$ through the equation:

$$\Delta E + V_{flip} q' = V \int_T^{T + \Delta T} c_{det} \ dT' \quad \{5\}$$

where $c_{det}$ is the average specific heat of the SSG colloid. A first consequence of equations {2-5} is that $\Delta E$ simply sets an overall scale for volume, time and distance in the evolution of a localized micro-avalanche. This can be seen writing:

$$x = V \Delta E^{-1}, \ y = V_{flip} \Delta E^{-1} \quad \{6\}$$

Then, expressing the above equations in terms of $x$ and $y$ removes all explicit dependence on $\Delta E$. If the total flipping volume $V(t = +\infty)$ 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-avalanches 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 risetime $\tau$ 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.
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Using very small granules (about 1\(\mu\)m diameter), the new concept of localized thermal micro-avalanche allows to:

1. Increase the electronic signal by one or two orders of magnitude;
2. Obtain a better linearity for very low energy particles (e.g. the 116 keV \(\gamma\));
3. Eliminate problems related to the lack of uniformity in grain size;
4. Produce, for the first time in a SSG detector, a linear response to the recoil energy of a nucleus (e.g., dark matter detection);
5. Use the dielectric material as an active target (e.g., hydrogen target for dark matter searches).

Fig.2 shows the solution of [2-6] in a simplified version of the SSG In detector with \(\psi = 0.3\), at \(t_r = 0.3\). The detector response for several values of \(\delta H/H_{test}\) (0\%, 0.1\%, 0.5\%, 1\%, 5\%), and for a 100 keV energy deposit, is exhibited in Fig.2a. Fig. 2b shows, for \(\delta H = 0.005 H_0\), the response to an energy deposit of: 50 keV, 100 keV, 200 keV, 500 keV and 1 MeV. Even at \(q^\ell = 0\), the solution of (2) - (5) 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 \(\delta H \rightarrow 0\). When \(q^\ell > 0\), this divergence becomes power-like but remains regularized by the cutoff \(\delta H\) if \(q^\ell\) does not exceed a certain value. If \(q^\ell\) 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 [17]. Also, at the beginning of the micro-avalanche phenomenon, Kapitza resistances can play a significant role. We have checked that, using Varnish GE 7031 [14] and taking a standard value of Kapitza resistivity for this material [18], heat exchanges between granules and the dielectric would occur in about 10 nsec. In 200 nsec (the time resolution required for a solar neutrino experiment), a point like deposit of heat would have spread to a radius of about 30 \(\mu\)m.

3. DEDICATED SCINTILLATING INDIUM CRYSTALS

More conventional would be the approach based on scintillators [4, 19]. The key idea is to develop a new scintillating crystal, based on some indium compound. If the new scintillator exhibits performances similar to those of NaI(Tl), it may be possible to build a 4 ton In experiment with 10\(^5\) to 10\(^6\) crystals. A X-Y read out can in principle be used, connecting 25 to 50 crystals to the same photomultiplier, but requires a very careful design. Each crystal would then be connected to at least two P.M.'s which allows to get position information by coincidence. The total number of required P.M.'s would be of 8000 for 10\(^5\) crystals and 40000 for 10\(^6\) crystals.

Other read-out systems may be considered: low temperature photodiodes or CCD's, photosensitive wire chambers, multi-photomultipliers... but the crucial issue is whether a performant In scintillator can actually be obtained. InBO\(_3\) powder is known [20] to be a high quality phosphor when doped with Tb\(^{3+}\) or Eu\(^{3+}\), and transparent crystals of InBO\(_3\) have been obtained in the laboratory [21]. Scintillation properties of undoped InBO\(_3\) have been studied [22] and no significant light
yield was found, but the preparation of new crystals doped with Tb$^{3+}$ and Ce$^{3+}$ is now under way [23].

InBO$_3$ is far from being the only In compound of which transparent crystals have been obtained. Indium sesquioxide, In$_2$O$_3$, exhibits transparency if prepared in a suitable way [24]. Transparent crystals have been obtained of: gallates (In$_2$GaO$_4$ [25]), silicates (NaInSi$_2$O$_6$, [26] or In$_2$SiO$_7$ [27]) germanates (In$_2$Ge$_2$O$_7$ [28]), and several other substances like fluorite InF$_3$ [23]. It therefore seems conceivable to find an indium compound fitting with our requirements.

Even if a high light yield is reached, a scintillator In experiment would have to face intrinsic limits in segmentation (it seems difficult to go beyond $10^6$ crystals and 40000 P.M.'s), which can make difficult the rejection of background due to coincidence between a $\beta$ decay of $^{115}$In and an erratic $\gamma$ that would fake the two photons of $^{115}$Sn* decay. Very low background, at the level of the best existing Ge experiments [29], will be required in order to avoid such coincidences.

4. CONCLUSION AND COMMENTS

The improved version of SSG may provide a leap forward in the feasibility study of a $^{115}$In solar neutrino experiment. Dedicated scintillators are also an interesting technique and should not be discarded prematurely.

The above techniques can also be considered for a real time thallium experiment [1]. Thallium is a good type I superconductor [30] and scintillating transparent crystals of thallium compounds exist as well [31]. Moreover, thallium is not radioactive. However, the lifetime of the excited state (2.3 keV) of $^{203}$Pb produced in the neutrino reaction is not well known and must be determined before further investigations.

References

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[22] We have checked luminescence properties of a InBO4 crystal at room temperature. Low temperature studies were performed by B. Jacquier (University of Lyon). In both cases, no significant light yield was seen for an undoped crystal produced at Electrotechnical Lab. (Sakuramura).

[23] A study along these lines is being performed by J.P. Chaminade (C.N.R.S. Bordeaux).


[27] J. Loriers (C.N.R.S., Meudon) and J.P. Denis (Baikowski, Annecy), unpublished.


[29] See, for instance, F.T. Avignone and D.O. Caldwell these Proceedings.


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Fig. 1: Irradiation results (total number of counts after a certain time in terms of the magnetic field gap $\Delta H$) for: a) Granules made with a Sn$_{99}$Sb$_1$ alloy; b) 998% pure tin grains. See [13, 14]

Fig. 2: $V_{flip}$ versus $V$ for several values of: a) The sweep in magnetic field $\delta H/H_{test}$ (0.0, 0.001, 0.005, 0.01, 0.05) for $\Delta E = 100$ keV; b) A point-like energy deposit (50, 100, 200, 500, 1000 keV) for $\delta H/H_{test} = 0.005$. Volumes are in $\mu$m$^3$. 