

The Luminescent Bolometer As a Dark Matter Detector

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Abstract

Direct detection of WIMP dark matter candidates has to face many difficult challenges. In particular, it requires an extremely high level of background rejection. The only way out seems to be particle identification which, for experiments based on nucleus recoil, is most efficiently performed by simultaneously detecting ionization or light and phonons. When comparing different approaches, it is necessary to keep in mind the potential requirement of building large detectors and the difficulties that this condition may raise for some cryogenic devices. It is claimed that the luminescent bolometer (simultaneous detection of light and phonons) red by arrays of superconducting tunnel junctions, as proposed by the author some years ago, ultimately provides the most appropriate WIMP detector. Solar neutrino detection and other applications are also briefly discussed.

1 The Luminescent Bolometer

Simultaneous detection of light and phonons in a single crystal scintillator cooled to very low temperature was proposed (Gonzalez-Mestres, & Perret-Gallix, 1988a) as a new tool for high-performance particle detection, expected to: a) provide slow thermal detectors with a fast light strobe, giving a much better timing without crucially spoiling energy resolution; b) make possible particle identification through the phonon/light ratio, thus improving background rejection. As bolometers evolve towards the detection of nonequilibrium phonons, fluorescence appears as a natural complement. Many crystals are expected to produce an important light yield at very low temperature. The device operating simultaneous detection of light and phonons at very low temperature was called the *luminescent bolometer* (Gonzalez-Mestres, & Perret-Gallix, 1988b). Simultaneous detection of fluorescence light and nonequilibrium phonons would combine (Gonzalez-Mestres, 1991a and 1991b) good energy resolution, fast timing, position information and high background rejection. Several extremely difficult experiments may become feasible, and others would be seriously improved.

A number of well-known scintillators (BGO, CdWO₄, CaWO₄, GSO:Ce, CeF₃, YAG:Ce, CaF₂:Eu...) exhibit fast luminescence at low temperature and are candidates for absorbers. But other substances, which do not scintillate at room temperature, become efficient luminophores when cooled down. Two examples:

a) PbMoO₄ green fluorescence is known (Bernhardt, 1985; Van Loo, & Wolterink, 1974) to increase by four orders of magnitude between room temperature and LN₂ temperature. It has been studied down to He₄ temperature (Van Loo, & Wolterink, 1974). Following a proposal to use cooled PbMoO₄ in double beta experiments (Gonzalez-Mestres, & Perret-Gallix, 1989a), a PbMoO₄ 2 × 2 × 2 cm³ single crystal read by a photomultiplier through a quartz light guide was characterized down to LN₂ temperature and showed a photopeak pulse height equal to 16% of that of room temperature NaI:Tl (M. Minowa et al., 1992).

b) Some indium oxides studied by J.P. Chaminade (see Gaewdang, T., 1993) following a proposal (Gonzalez-Mestres, & Perret-Gallix, 1987 and 1989b) to develop scintillating single crystals of In compounds, exhibit scintillation at low temperature. In₂Si₂O₇ has been characterized down to 4K (Gaewdang, 1993), but other compounds can be considered (Gonzalez-Mestres, & Perret-Gallix, 1987; Gaewdang, 1993).

If the properties of the absorber (Debye temperature, phonon propagation, low temperature scintillation, light yield and decay time...) are crucial to the quality of a luminescent bolometer, the sensors are equally key elements. The first design of the device proposed (Gonzalez-Mestres, & Perret-Gallix, 1988 a and 1988b) the use of separate sensors for the light and the phonons. Semiconductors, thin black bolometers and superconductors were considered as photon sensors (Gonzalez-Mestres, & Perret-Gallix, 1988a, 1988b and 1989a). The first successful feasibility study, made by the Milano group, adopted such an approach (Alessandrello et

al., 1991 and 1992) using a photodiode as the cryogenic photosensitive device. The results were naturally limited in threshold and energy resolution, as has been discussed in more recent reviews (Fiorini, 1993; Sadoulet, 1993) but the situation can be technically improved. In 1991, we proposed (Gonzalez-Mestres, 1991a and 1991b) a new design incorporating a common sensor for both the light strobe and the delayed phonon signal, and suggesting also the use of arrays of superconducting tunnel junctions (STJ) as the new sensor.

2 Superconducting Sensors

Superconductors are natural sensors for both phonons and photons, and should perform better than semiconductors due to the comparatively low gap for quasiparticle excitation. Low impedance superconducting films already provide the best phonon sensors (f.i. Ferger, 1994), and photosensitive superconducting devices are an active research subject (f.i. Barone, & Russo, 1993). A performant superconducting sensor, sensitive to the light strobe followed by the delayed pulse of phonons, would considerably simplify and improve the architecture of the luminescent bolometer. This seems feasible nowadays due to the success of arrays of superconducting tunnel junctions (f.i. Goldie, 1990) and of other superconducting sensors. The new device, made of a single crystal low temperature scintillator with an appropriate superconducting sensor implanted on each of its faces, may become the *ultimate* detector for several physics goals (Gonzalez-Mestres, 1991b).

2.1 STJ Arrays In a very important work, with a series array of 432 Al-Al STJ, implanted on a Si wafer with an area of $12 \times 12 \text{ mm}^2$ and a thickness of 0.5 mm, the Oxford group obtained (Goldie, 1990) at $T \simeq 360 \text{ mK}$ (base temperature of the cryostat) a resolution of 700 eV FWHM on a 25 keV X-ray peak produced from the fluorescence of an indium foil. A naive extrapolation suggests (Gonzalez-Mestres, 1991a and 1991b) that a similar STJ array could be sensitive to $\approx 1 \text{ keV}$ of scintillation photons absorbed near the array, which corresponds to the light yield of a $\approx 10 \text{ keV}$ electron or photon in an efficient scintillator. According to the Oxford group, most of the 25 keV peak width was due to drifts in the cryostat temperature and to electronic noise. These considerations motivated our proposal to use arrays of STJ for the detection of both photons (the fast strobe) and phonons (the delayed pulse). To absorb the scintillation light we considered (see also Gonzalez-Mestres, 1994), either implanting a thin layer between the radiation absorber and the STJ array (but care must be taken of phonon propagation through the layer), or to use blackened STJ arrays covering a large fraction of the crystal surface (which requires working in an optical cavity).

An interesting possibility would be to deposit the STJ arrays on a superconducting substrate of higher critical temperature, covering the full crystal surface (an array per face). Nb or Sn can be the substrate for a Al STJ array. Thus, both the photons and the phonons from the absorber would be converted into quasiparticles by the substrate layer in an efficient way. Such quasiparticles would subsequently be detected by the STJ array. The photon signal would immediately originate in the substrate, whereas phonons would first undergo a number of scattering processes depending on the size and quality of the crystal. With an ADC and a DSP after the electronic chain, for each face of the crystal, digital analysis would allow to reach a very low threshold for both the fluorescence and the phonon signal. When the expected signal is a sum of exponentials, on-line digital filtering allows for iterative algorithms leading to very performant trigger schemes (Gonzalez-Mestres, 1992a), which apply to fluorescence in a straightforward way and can be adapted to phonon detection. Energy resolution would also be very good, as total energy can be reconstructed from light and phonon pulses. Digital analysis of the phonon pulse would lead to excellent space resolution inside the crystal, and we can expect to reach fast timing (down to 100 ns) with suitable choices. However, the crystal size and phonon scattering properties will necessarily set an intrinsic limit to the detector performance. Phonons reaching the crystal surface with an energy $E < 2\Delta$ (the gap of the STJ superconducting material) cannot contribute to the signal.

Perryman et al. have proposed (Perryman, Foden, & Peacock, 1993) optical photon counting with a superconducting substrate in combination with an array of widely spaced STJ of lower energy gap. STJ are indeed being successful in the field (Perryman et al., 1999). In our case, we are not interested in optical photon counting but in the detection of $10^2 - 10^5$ optical photons produced by a particle interacting with the

cooled scintillator. On the other hand, we must face the extra requirement of efficient phonon detection from large absorbers. For the phonon yield, the fact that several intrinsic scintillators work at low temperature is encouraging, as doped scintillators may exhibit poor phonon propagation.

2.2 Alternatives Superconducting films are very successful and solutions based on this technique, others than STJ arrays (e.g. transition edge sensors, see Cabrera et al., 1998), deserve serious consideration. But efficient detection of scintillation light is likely to limit the freedom of the design. It is possible to consider superheated superconducting dots when only four faces of the crystal need to be used (allowing for a magnetic field parallel to the four faces), or for cylinder structures. Sensitivity may, however, be a problem for this kind of detectors. It seems difficult to simultaneously detect light and external phonons using superheated microspheres, but we may hope for technical progress in the interface between the granules and the scintillating absorber. As compared to other techniques, STJ arrays present, for large detectors, the advantage of operating with excellent performances at He₃ and even at He₄ temperatures, which considerably simplifies cryogenics with respect to large dilution refrigerators which would be difficult to handle. Simultaneous detection of light and phonons presents a similar advantage as compared to simultaneous detection of ionization and heat.

3 Proposed Applications

The luminescent bolometer is an exceptionally versatile device, with many possible applications involving large (especially if it can be operated at He₃ temperature) and small detectors.

3.1 Non-Baryonic Dark Matter This was the first proposed application of the luminescent bolometer (Gonzalez-Mestres, & Perret-Gallix, 1988a and 1998b), in view of background rejection and nucleus recoil identification. The approach was criticized on the grounds of the high threshold of existing prototypes, but as explained above the situation can be considerably improved introducing superconducting sensors: then, the threshold of the luminescent bolometer will become as low as that of any device performing simultaneous detection of ionization and heat. The possibility to work well above dilution temperatures will then become a definite advantage of dark matter experiments using the luminescent bolometer. The reliability of a large scale experiment would be much better with our approach, where 100 kg to 1 ton detectors can indeed be cooled to the operating temperature with existing and well established cryogenic techniques. Detector stability would also be a crucial advantage. Furthermore, targets such as ⁷Li, ¹⁹F, ²⁷Al, ¹²⁷I, ¹⁸³W... can be incorporated in the cold scintillator approach. If particle physics and cosmology still provide a ground to experiments aiming at the direct detection of dark matter WIMPs (there is to date no evidence for new particles!), the luminescent bolometer with a superconducting read-out is to be the right technique for that purpose. However, many basic studies remain to be performed on the low temperature behaviour of the relevant scintillators.

3.2 Double Beta Applications to double beta experiments were proposed in 1989 (Gonzalez-Mestres, & Perret-Gallix, 1988a), with the basic idea of rejecting the alpha background in high Q materials. CdWO₄ and PbMoO₄ were then explicitly considered. The use of CdWO₄ seems indeed to be a promising way (Zdesenko et al., 1992; Alessandrello et al., 1991a), and Mo would be a very performant target. To our original proposal, the Milano group has added the successful development of a CaF₂ luminescent bolometer (Alessandrello et al., 1991a and 1991b). After suitable technical developments, the luminescent bolometer can potentially incorporate any double beta target. The elementary cells of a double β experiment can be $\approx 2 \times 2 \times 2$ cm³ crystals, which amounts to ≈ 25 crystals and ≈ 150 electronic channels per Kg of detector.

3.3 Solar and Reactor Neutrinos (Indium Target) This may become the most important and far-reaching application of the luminescent bolometer, as no technique allows by now to detect in real time low energy neutrinos. Several indium compounds seem to scintillate mainly at low temperature. To the indium germanates, silicates and other oxides presently under study, some of which (e.g. In₂Si₂O₇) give excellent results at low temperature, InCe oxides should be added in order to possibly exploit the fluorescence of trivalent cerium. Fluorides deserve further consideration (Gaewdang, 1993; Gonzalez-Mestres and Perret-Gallix, 1987), as some of them can scintillate and crystal growth seems easier than with oxides. A large scale, real

time solar neutrino experiment based on Raghavan's reaction, with a luminescent bolometer made of an indium compound, has already been described (Gonzalez-Mestres, 1991a, 1991b, 1992b and 1994) and nothing to date contradicts its potential feasibility. A neutrino-antineutrino oscillation experiment at a reactor would be ~ 100 times smaller. It must therefore be considered as a suitable intermediate step.

3.4 Other Applications Basic physics and chemistry, (f.i. study of relaxation phenomena), nuclear physics and technology (f.i. nuclear spectroscopy, heavy-ion physics), astrophysics... are generating potential applications of the luminescent bolometer (Gonzalez-Mestres, 1994). Neutron detection at low counting rate (e.g. with a lithium target, Gonzalez-Mestres 1991a; de Marcillac et al., 1993), low radioactivity measurements, long lived isotopes... present increasing interest in both scientific and industrial domains.

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