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An active electron polarized scintillating GSO target for neutrino physics

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ABSTRACT

The feasibility of an electron-polarized, active target to be used as detector in neutrino scattering experiments, suggested by several theoretical papers, has been investigated. We report on the properties of the paramagnetic crystal Gd_2SiO_5 (GSO), in which 7.7% of the total number of electrons present can be polarized by lowering the temperature and applying an intense external magnetic field.

The material magnetic susceptibility has been measured down to cryogenic temperatures showing that for $H=5$ T and $T=4$ K about 80% of the maximum allowed magnetization can be attained. Also the spectral and time response of the crystal have been characterized and the scintillation process has been studied using a photomultiplier to measure the response to gamma rays irradiation and cosmic rays operating the GSO crystal at 13.5 K. An avalanche photodiode (APD) readout of the scintillation signal from the GSO crystal has also been performed, since the magnetic field-independent response of this device allows it to be placed close to the crystal in the cryogenic environment.

1. Introduction

The standard model of the electro-weak interaction [1] is based on a Lorentz structure with the exchange of vector–axial (V-A) current [2,3], where left-handed neutrinos can interact mainly with left-handed electrons (or nuclei). When a detecting material is prepared in a spin polarized state, this feature provides a mean to control the contribution of the weak interaction to the total cross-section of the process. If the target is polarized by an externally applied magnetic field, it is possible to change the rate of the interaction by inverting the field direction.

A new generation of neutrino experiments could stem using detectors based on this mechanism, as suggested in several theoretical papers [4–6]. It has been pointed out that investigation of the flavor composition of a (anti)neutrino beam could be possible by studying their scattering from polarized electrons in a polarized target [7]. A polarized electron target was suggested also to improve the sensitivity of the search for the neutrino magnetic moment in the scattering process (anti)neutrino – electron [8]. Compared to traditional detection techniques, in this approach – that makes use of polarizable material – the electromagnetic background limit should not be relevant, since it could be subtracted from the spectra as a measurable noise contribution.

A cubic meter detector for low energy neutrinos, with an equivalent mass of about 10 tons, could be developed using the scintillating crystal studied in this work as active material. Crystals of GSO are in fact commercially available and the level of radioactivity has been measured to be sufficiently low [9]. Installed at about 20 m distance from a 1 GW (thermal) power nuclear reactor would yield an antineutrino-*e* event rate of the order of 0.1/day/kg. A 10% variation in the total number of registered events is expected when inverting the direction of the magnetic field in which the active material is placed. This last expedient has also been suggested to improve the measurement of the magnetic moment of the neutrino [8].

Besides, switching the direction of the field will permit discrimination against cosmic-ray induced detector response, removing much of the noise limiting the currently used detectors.

A neutrino telescope has been proposed in which the active detecting material is based on *nuclei* originally polarized with spin antiparallel to the spin of the incoming neutrinos [10]; absorption of neutrinos from the In^{115} nucleus is suggested, and the fully polarized detector is described as being twice as sensitive as the unpolarized detector.

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The research of polarized matter may be of interest also for other research subjects such as axions [11], CP violation through the study of the electric dipole moment [12], and spin-spin interaction in gravitation [13].

In this paper we present measurements that confirm the possibility to realize an active polarized target crystal of Gd_2SiO_5 (GSO) doped with Cerium (GSO:Ce), as proposed in Ref. [14]. Within the herewith described approach, the detected output signal carrying information about interactions is scintillation. It is worth noticing, however, that it has also been proposed to use paramagnetic materials to build a magnetic adiabatic calorimeter [15], which would open the way to the use of several different types of materials, also in powder form, and likely characterized by higher degree of attainable electron polarization. Investigations on this calorimetric approach are under way in our group and will be the subject of a forthcoming paper.

GSO:Ce is a well known scintillator and its properties have been extensively studied (see for instance [16] and references therein). It has a density of 6.71 g/cm^3 and, at room temperature, its light yield is about 9000 photons/MeV. Its recombination time, measured at room temperature [16], is of approximately 60 ns for excitation energies in excess of 4.51 eV (Gd^{3+} levels), while it is about 26 ns in the UV region (Ce absorption).

The magnetic properties of Gd_2SiO_5:Ce are due to the rare earth element Gd in the oxidation state Gd^{3+}; the electronic configuration of trivalent Gd is $4f^7$, with seven localized unpaired electrons, responsible for the Curie paramagnetic behavior. The magnetization of a Curie paramagnet at a given temperature T and applied field H is described by the Brillouin function [17], according to which a high degree of magnetization is obtained at low temperature and high magnetic field. It is worth noticing that even when all the unpaired $4f^7$ electrons have a spin parallel to the applied magnetic field, only 7.7% of total number of electrons present in the target are polarized.

Taking into account the behavior of Gd^{3+} paramagnetic salts reported in Ref. [18], the magnetic polarization of Gd within GSO can be as high as 6.3 Bohr magnetons/Gd atom for a unitary ratio between the applied magnetic field H and the temperature T. Therefore, a magnetic field of about 4 T should be sufficient to fully polarize the material at a temperature of 4.2 K.

It is the aim of the present work to check the possibility of obtaining the desired high degree of polarization in GSO crystals for ordinary laboratory values of H and T and to characterize the scintillating response under these conditions.

This paper is divided into two parts. The first is devoted to characterize the magnetic behavior of GSO, through the study of the temperature dependence on the magnetic susceptibility $\chi = M/H$ and of the field dependence of the magnetization. Measurements of the optical response to short laser pulses in the UV range, conducted with the material kept at cryogenic temperatures and with an external magnetic field, are also reported.

In the second part of the paper the scintillation properties of magnetically polarized GSO under gamma ray irradiation are discussed. For this characterization, two different methods were used, one using a photomultiplier tube (PMT) for the read-out and one using a silicon avalanche photodiode (APD) operated at cryogenic temperatures.

2. Material characterization: susceptivity, spectral response and time response

2.1. Magnetic characterization

The DC (i.e., static field) magnetization measurements were performed using a SQUID-based Magnetic Property Measurement System (Model MPMS-XL5 by Quantum Design Inc.). The SQUID magnetometer has a sensitivity of 10^{-8} emu; the system is equipped with a superconducting magnet producing fields up to 50 kOe and calibrated using a Pd standard. The residual field during the zero field cooling was less than 5×10^{-2} Oe.

A small, cube shaped GSO crystal was cut from a prismatic single crystal and the magnetic susceptibility was measured in the field cooling mode for $H=100$ Oe applied along the three cube edges. Since no differences was detected among the three measurements, Fig. 1 reports one of the three obtained $\chi(T)$ curves.

As shown in Fig. 1, the susceptibility follows a Curie–Weiss law behavior $\chi = C/(T-\theta)$, with $C = p_{eff}^2 N_a B^2/3k_B$, in which N_a is the Avogadro number, μ_B is the Bohr magneton, k_B is the Boltzmann constant and p_{eff} is the effective number of Bohr magnetons for each magnetic ion. A linear fit of the $\chi^{-1}(T)$ plot is displayed as inset to Fig. 1. The fit gives $\theta = -8.9(2)$ K and $C=16.13(7)$ emu K/(Oe mol), from which we obtain for p_{eff}, the effective number of Bohr magnetons for the Gd atom, the value of 8.02(2) μB/Gd atom, in good agreement with what reported in literature for Gd^{3+} species. The negative sign of the Weiss temperature indicates antiferromagnetic correlations between Gd^{3+} ions in GSO. However, no sign of transition towards a magnetically ordered phase was detected down to the lowest measured temperature of 2 K.

The field dependence of the magnetization, measured after zero field cooling to 4 K is shown in Fig. 2, which displays M as a function of the internal field B acting on the Gd magnetic moments, obtained from the applied field H (corrected for the normalized magnetization factor N taken from Ref. [19]) and the GSO magnetization M (magnetic dipole moment per unit volume) as $B = H + 4\pi(1-N)M$ in CGS units.

The upper curve in Fig. 2 is the theoretical one, calculated by the Brillouin function, which describes the behavior of a collection of $4f^7$ independent ions, i.e. in the absence of exchange interactions. It is seen that the experimental data deviate appreciably from the expected behavior. In search of the source of the deviation, one may consider in particular the antiferromagnetic $Gd^{3+}O^{2-}Gd^{3+}$ super-exchange interaction opposing the parallel alignment of the gadolinium moments at 4 K, as shown by the Curie–Weiss behavior of the susceptibility with negative θ, which likely constitutes the major source of deviation from the independent ion approximation. On the contrary, since $L=0$ for Gd^{3+} (S state), incomplete orbital quenching or the effect of crystalline field splitting cannot be invoked. Regardless, the results show that

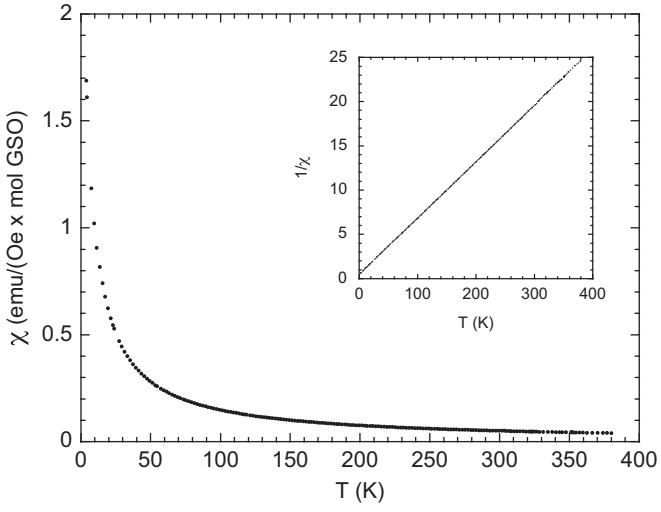

Fig. 1. Magnetic susceptibility of a cube shaped GSO single crystal measured with $H=100$ Oe applied along the three cube edges. The inset shows the inverse susceptibility as a function of T, showing the linear Curie–Weiss behavior.

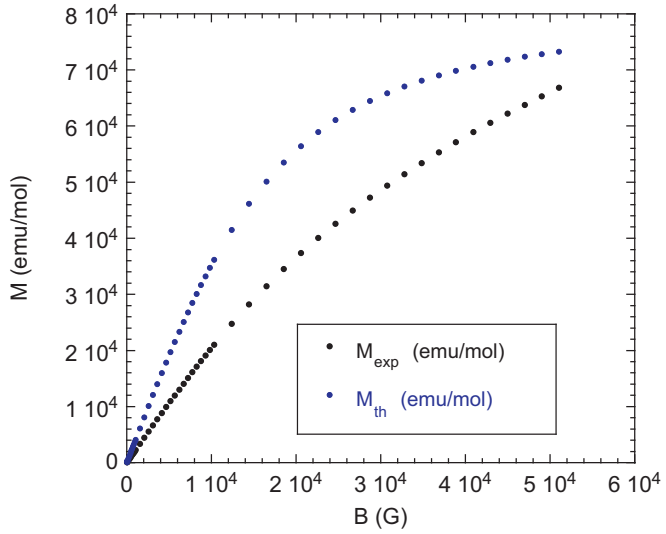

Fig. 2. M (B) curve at $T=4$ K for GSO. The theoretical curve (upper one) is calculated by the Brillouin function for the $4f^7$ electronic configuration of free Gd^{3+} ions. This curve asymptotically saturates to the value of 7 μ_B/Gd atom.

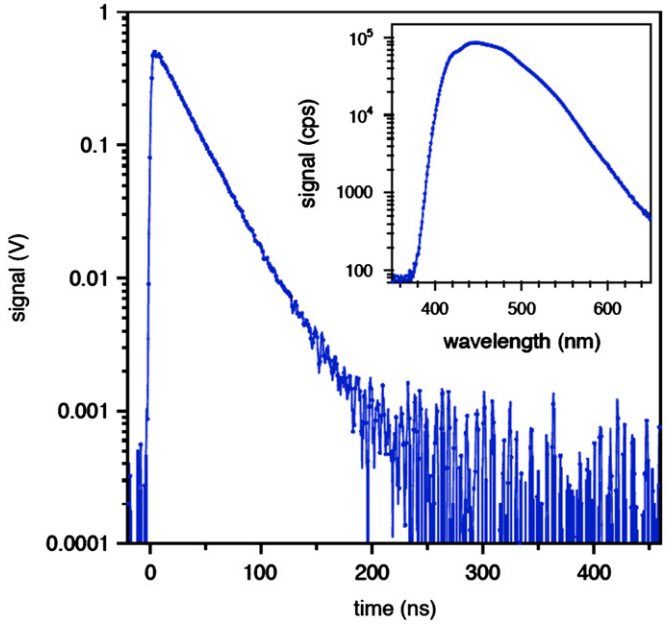

Fig. 3. Scintillation signal and emission spectra (upper insert) at room temperature and $B=0.9$ T.

almost 80% of the saturation magnetization can be induced in GSO by $H=5$ T at $T=4$ K.

2.2. Optical spectral response and timing

The optical properties of GSO:Ce have been measured both under magnetic field and at cryogenic temperatures, using a GSO crystal of $(2\times2\times250)$ mm^3 size. The crystal was inserted inside a small permanent magnet giving a magnetic flux of 0.9 T and next placed in a cryostat into a liquid He bath. The cryostat had an optical window allowing the crystal to be irradiated with a laser beam (YAG 355 nm, 200 Hz, 25 nJ/pulse).

Fig. 3 shows the timing and the emission spectra of the photoluminescence signal at room temperature and $B=0.9$ T. The signal decay characteristic time is measured to be $\tau=(25\pm0.8)$ ns. This value is in good agreement with what reported in Ref. [16].

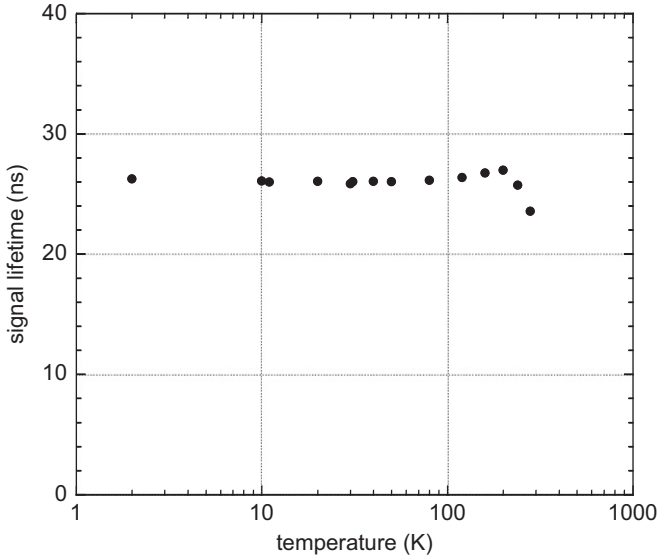

Fig. 4. Signal lifetime τ at different temperatures.

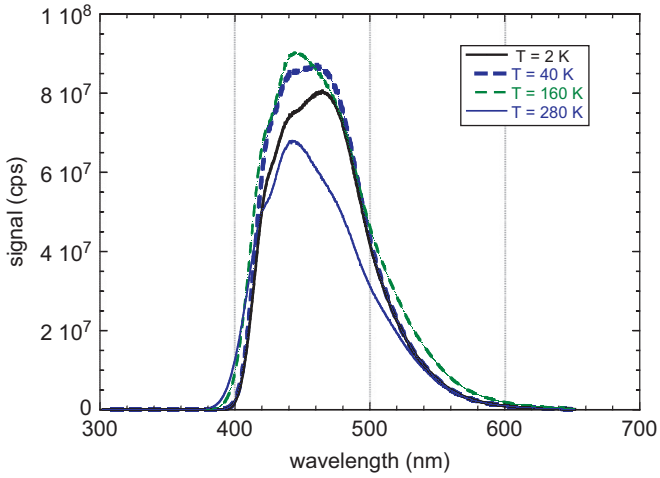

Fig. 5. Emission spectra at different temperatures.

Figs. 4 and 5 respectively show the lifetime and the photoluminescence emission spectra at different temperatures, ranging from 2 K to 280 K. No important variations are observed for the signal lifetime with respect to temperature. Minor systematic variations in proximity of the emission peak can be noticed but the emission bandwidth is not changed.

In summary, the measurements show that the photoluminescence properties of the GSO crystal are not significantly altered by temperature from 300 K down to 2 K nor are they altered by the presence of a magnetic field.

3. Scintillation properties of the polarized material under gamma irradiation

In the measurements presented in this section the GSO crystal is kept at low temperature and is under the influence of the magnetic field. As already stated in the introduction, this is one of the necessary tests to check the feasibility of a scintillating neutrino detector based on a scintillating polarized material.

The GSO:Ce scintillation under irradiation of 511 keV gamma source was studied both using a PMT and an APD. Note that, since the aim of these measurements is to check if the scintillating

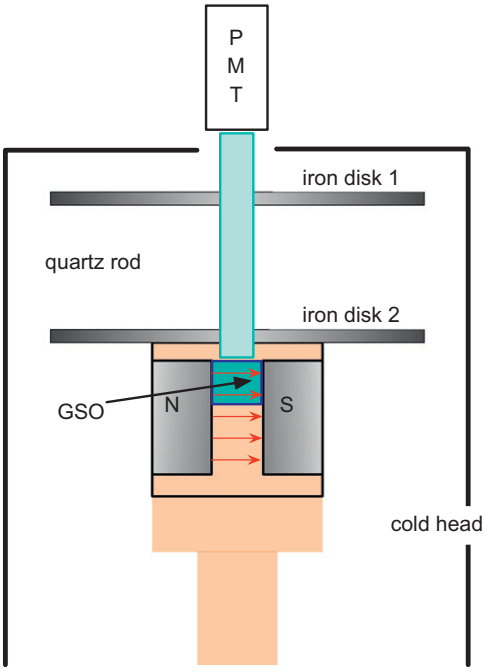

Fig. 6. Scheme of the experimental setup used to study the GSO scintillation signal.

properties change at low temperature and under the influence of the magnetic field, particular care in reducing noise contributions has not been taken. The main noise contribution in the observed spectra is the microphonic noise originating from the cryocooler.

The GSO:Ce crystal $(1\times1\times1)\,\mathrm{cm}^3$, 0.5% Ce doped, was provided by the Hitachi Chemical Company. Its surface is optically polished and it was laterally wrapped with Teflon to prevent escaping of light.

3.1. Scintillation response of the polarized GSO read at a PMT

To study the polarized GSO scintillation signal under gamma rays irradiation, the experimental setup shown in Fig. 6 has been arranged.

The crystal was enclosed into a double-C-shaped copper mounting fixed on a cryocooler head. Inside the copper mounting it is possible to accommodate also two permanent magnets, generating a measured magnetic field of 0.98 T in a 1 cm gap (measurement done at 77 K). The photomultiplier tube (Hamamatsu R2027)) is operated at room temperature, protected against magnetic field disturbances by two soft iron plates; a 10 cm long quartz waveguide couples the light signal from the irradiated crystal to the PMT. The stability of the PMT during measurements has been monitored sending 10 ns duration light pulses through an optical fiber. The scintillation signals have been processed through a shaping amplifier (Silena mod. 7612), before entering an MCA (Ortec mod. 926). The spectra from a Na^{22} radioactive source, placed under the GSO crystal, are shown in Fig. 7.

The results demonstrate that the light yield is not influenced by a magnetic field of 1 T. The same result has been obtained with the GSO crystal kept at 13.5 K. As can be seen in Fig. 7, we observed a significant decrease (of the order of 40%) of the light signal at low temperature, that can be possibly attributed to the dependence of the light on temperature, as reported in Ref. [16] for GSO crystals under X ray irradiation.

3.2. Scintillation time response of the GSO crystal

The same setup shown in Fig. 6 with the addition of a layer of plastic scintillator positioned above the cryocooler was used to

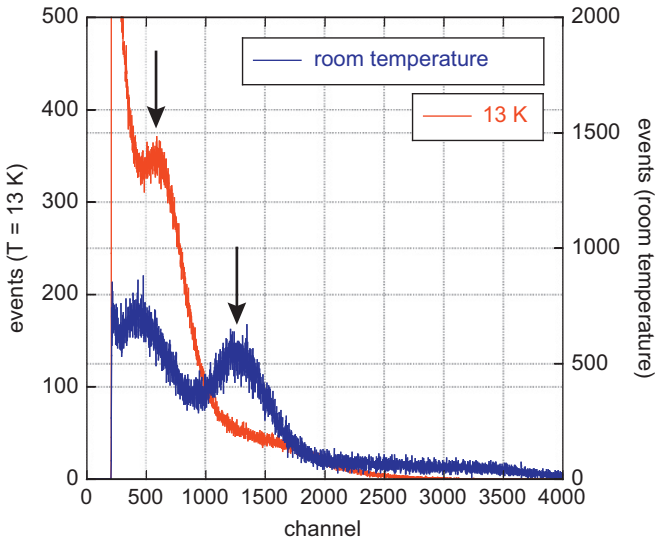

Fig. 7. The 511 keV gamma energy deposition events at room temperature and at 13.5 K. The arrows indicate the full-energy peaks corresponding to absorption of the 511 keV photons.

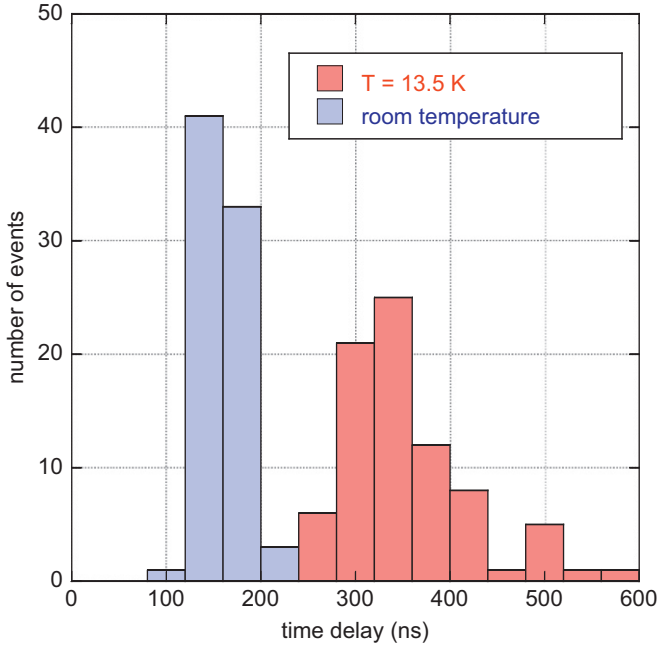

Fig. 8. Distributions of measured time decays at room temperature and $T=13.5$ K.

check the possible dependence of the scintillation time upon temperature and applied magnetic field.

Signals from the scintillation of the GSO produced when the crystal is traversed by cosmic rays were acquired in coincidence with signals in the plastic scintillator. Typically, more than one hundred PMT waveforms from the GSO were recorded on a 1 GHz bandwidth digital oscilloscope, both at room temperature and at $T=13.5$ K. The observed signals decay exponentially with a decay time τ_m which depends on the temperature, as shown in Fig. 8, where the distributions of the measured signal decay time at the two temperatures are plotted. The time decays (τ_m) of 163 ± 10 ns and of 330 ± 20 ns were obtained at $T=300$ K and $T=13.5$ K respectively, averaging over a sample of 90 events at each value of temperature. The observed decay time τ_m is related both to the response time of the apparatus τ_a, defined as the delay of the light

signal due to the quartz waveguide and the PMT, and the scintillation time of the GSO. Since the measured scintillation time of the GSO crystal is $\tau_s = 60$ ns [16], τ_a is obtained through expression $\tau_a = \sqrt{\tau_m^2 - \tau_s^2} = 152 \pm 20$ ns at room temperature. Also it is reasonable to expect that this value is temperature independent and therefore, assuming the same response time for the two temperatures, a scintillation time of (293 ± 20) ns is inferred at $T = 13.5$ K.

Time measurements, at both temperatures, were repeated without magnetic field and no observable variations were observed at the 10% level. It should be noted that the longer decay time at lower temperatures may be attributed to a temperature effect on the physical mechanism of emission of scintillation light, as already reported by Mori et al. [16].

3.3. Measurements using APD

The signal from GSO crystals in a magnetic field could be detected using APDs. It is not obvious however that these devices work properly at cryogenic temperatures, since it is believed that their functioning at temperatures below 77 K is limited by the so-called freeze-out effect 20,21, especially if the material (n or p-type) is heavily doped.

On the other hand, improvements are expected when the APD is made of high purity silicon, as suggested by recent results that were obtained with semiconductor detectors [22].

Therefore we carried out preliminary measurements on bare beveled silicon APDs from Advance Photonics, 16 mm diameter, UV sensitive.

The gain of the APD was measured at $T = 300$ K and $T = 13.5$ K, using a 5.9 keV X-ray source (Fe), as function of the applied voltage. The results are shown in Fig. 9, in which the temperature dependence of the energy required to produce an electron-hole pair has also been taken into account to calculate the APD gain.

At the lower temperature, a limit of approximately 10^3 in the gain is set by discharges, which appear when the applied voltage exceeds ~ 1400 V.

Nevertheless, the values of the gain allowed the acquisition of the spectrum of a Cs^{137} γ-ray source, positioned just above the GSO crystal, directly coupled to the APD which collected the light produced in the scintillation process. No optical grease was used to minimize reflections at interfaces, therefore the amount of light collected would be smaller than expected if that precaution was adopted.

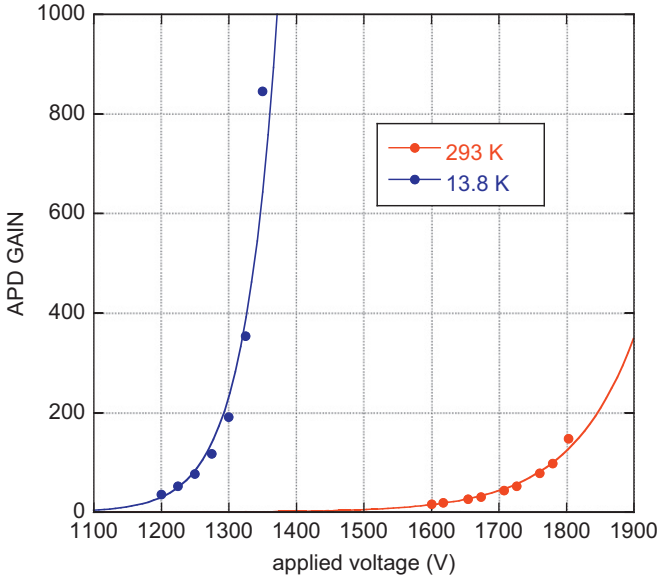

Fig. 9. The measurement of the APD gain versus applied voltage at room temperature and at 13.5 K.

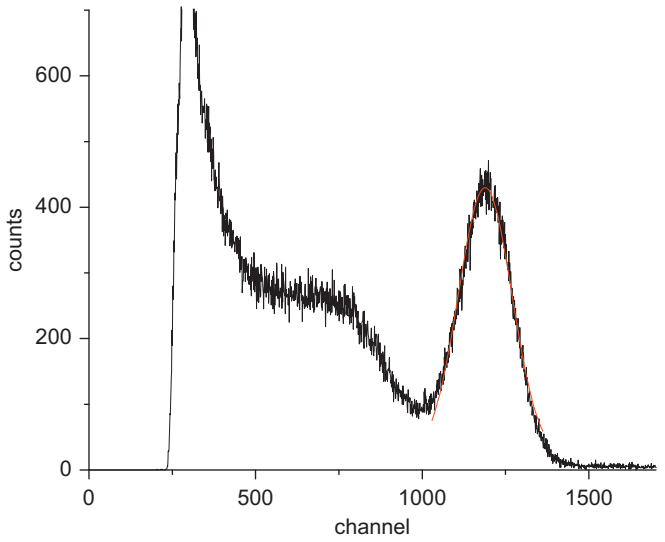

Fig. 10. Cs^{137} source spectrum at room temperature. The voltage applied to the APD is 1800 V.

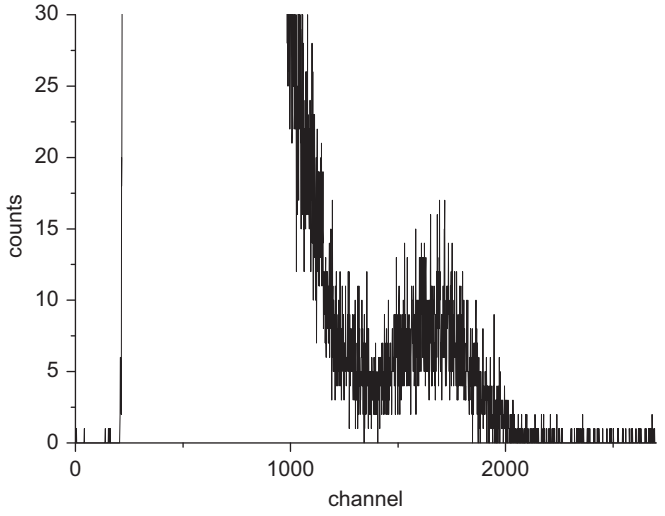

Fig. 11. Cs^{137} source spectrum at 13 K. The voltage applied to the APD is 1325 V.

The spectra taken at two different temperatures ($T = 300$ and 13 K) are shown in Figs. 10 and 11. As it was the case with PMT readout, in this experimental configuration as well, the light yield at $T = 13.5$ K is measured to be a factor of two lower than at room temperature, thus confirming previously obtained results [16].

These measurements show that indeed it is possible to collect the scintillation light from GSO crystals using APDs kept at cryogenic temperatures.

4. Conclusions

In this work the feasibility of a new generation detector for neutrino physics has been investigated. It has been demonstrated that a GSO crystal kept at low temperatures and in a high magnetic field is a suitable active material. This was achieved through the systematic study of its magnetic properties and optical response at cryogenic temperature and in the presence of a magnetic field up to

5 T. The scintillation properties of the polarized material under gamma irradiation have been studied, and the possibility to collect the light signal with a photomultiplier tube or an avalanche photodiode kept at low temperature has been successfully tested.

Cosmic ray events have also been used to measure the time response of the GSO crystal at low temperatures, which is about a factor of five longer than the value at room temperature [16].

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