Particle Dark Matter and Solar Axion Searches
with a small germanium detector at the
Canfranc Underground Laboratory

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Abstract

A small, natural abundance, germanium detector (COSME) has been operating recently at the Canfranc Underground Laboratory (Spanish Pyrenees) in improved conditions of shielding and overburden with respect to a previous operation of the same detector \cite{1,2}. An exposure of 72.7 kg day in these conditions has at present a background improvement of about one order of magnitude compared to the former operation of the detector. These new data have been applied to a direct search for WIMPs and solar axions. New WIMP exclusion plots improving the current bounds for low masses are reported. The paper also presents a limit on the axion-photon coupling obtained from the analysis of the data looking for a Primakoff axion-to-photon conversion and Bragg scattering inside the crystal.

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1 Introduction

Substantial evidence and well-founded arguments exist pointing out that the Universe may well consist of a suitable mixture of cold dark matter (CDM), hot dark matter (HDM) and baryons (in the amount required by the primordial nucleosynthesis), which together with a large component of dark energy could complete the proper gravitational balance of the Universe. Regarding the nature of the dark matter, there are compelling reasons to believe it consist mainly of cold non-baryonic particles. Among these candidates, Weakly

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Interacting Massive Particles (WIMPs) and axions are the front runners. The lightest stable particles of supersymmetric theories, like the neutralino, describe a particular class of WIMPs. On the other hand, axions, the light pseudoscalar bosons emerging from the spontaneous breaking of the Peccei-Quinn symmetry proposed to solve the strong CP problem, are also favorite candidates to provide the dark matter density for masses of the order of microelectronvolts.

The direct detection of WIMPs relies on the measurement of their elastic scattering off the target nuclei of a suitable detector. The non-relativistic and heavy (GeV – TeV) WIMPs supposedly filling (at least partially) the galactic haloes could hit a Ge nucleus producing a nuclear recoil of a few keV. Because of the small WIMP-matter interaction cross sections the rate is extremely low ranging from 1 to \(10^{-26}\) c/kg/day according to the type of interaction and type of WIMP. The detection of such small and rare signals requires ultra-low background detectors with very low energy thresholds. Many experiments are underway using a variety of techniques to achieve both goals. Germanium ionization detectors have reached one of the lowest raw background levels of any type of detector and have a reasonable ionization yield(\(\sim 0.25\)). Should they have sufficiently low energy thresholds, they would be attractive devices for WIMP direct detection. This paper presents the case of one of such germanium detectors of rather low energy threshold and fairly low background rate.

As it is well known, solar axions can been searched for with crystal detectors through the axion-to-X ray Primakoff conversion with coherent Bragg diffraction. This paper also deals with a search for such axions with the same germanium detector, COSME.

## 2 Experimental setup

The COSME detector is a p-type coaxial hyperpure natural germanium crystal, of dimensions 22 mm (length) \(\times\) 52.5 mm (diameter) corresponding to an active volume of 44 cm\(^3\) and a mass of 234 g which has a long-term resolution of 0.43 keV full width at half maximum (FWHM) at 10.37 keV. The detector was specially built for dark matter searches, i.e., with a low energy threshold and ultralow background materials. The cryostat, of 1.5 mm thick electroformed copper, was made by Pacific National Northwest Laboratory (PNNL). The field effect transistor (FET) is shielded with 450 year old (Spanish) lead.

The COSME detector was formerly used in the Canfranc tunnel in one of the first dedicated searches for WIMPs. Now it has been placed in a deeper location in the same tunnel within a significantly improved shielding, the same as the IGEX experiment. The innermost shield of the IGEX and COSME detectors consists of 2.5 tons of archaeological lead 2000-year-old forming a 60 cm cube. The detector fits into a precision-machined hole in this lead block to minimize the empty space around the detector available to radon. Nitrogen gas, at a rate of 140 liters per hour, evaporating from liquid nitrogen, is forced into the detector chamber to create a positive pressure and to further avoid radon intrusion. The archaeological lead block is located inside of another shield made of bricks of low-activity-lead (\(\sim 10\) tons) forming all together a cube of 1 m on a side.
2-mm-thick cadmium sheet surrounds the external lead shield, and two layers of plastic seal the assembly tightly. A cosmic ray muon veto covers the top and two sides of the shielding. Finally, an external polyethylene neutron moderator 20 cm thick (1.5 tons) covering the six sides of the cube complete the shield. The entire set-up is supported by an iron structure resting on noise-isolation blocks. The experiment is located in a room isolated from the rest of the laboratory which has an overburden of 2450 m.w.e., reducing the muon flux to a (measured) value of $2 \times 10^{-7} \text{cm}^{-2}\text{s}^{-1}$.

Further details about the detector are given in Ref.\[2\] whereas the setup and shielding are described in the IGEX papers \[9, 10\]. The data acquisition and filtering techniques are similar to the previous experiment \[1, 2\] but with the addition of muon vetoes working in anticoincidence as in IGEX \[10\].

3 Experimental Results
3.1 Spectrum

The COSME detector has been running during the years 1998 and 1999 in these new conditions, and has accumulated data corresponding to a statistics of 72.7 kg days of exposure. Figure 1 gives the experimental differential rate corresponding to this acquisition (thick line) compared to the previous set of data from 1990 to 1992 (thin line). A significant decrease of the background with respect to the former data is clearly shown. It is also worth noticing the near disappearance of the peaks at 8.98 keV and 10.37 keV corresponding to cosmogenically induced $^{65}$Zn and $^{68}$Ge isotopes ($T_{1/2}$ = 244.3 d and 288 d EC X-rays from $^{65}$Cu and $^{68}$Ga respectively) after the long-term underground storage of the detector. Also the 46.5 keV peak of $^{210}$Pb shows a significant decrease.

The energy threshold achieved in this new setting is 2.5 keV and the long-term energy resolution obtained in the visible low energy peaks (Pb and Bi X-rays and 46.5 keV from $^{210}$Pb) was the same as in the previous run. The background in the low energy region (2.5 - 10 keV) is 0.7 c/keV/kg/day, an improvement of almost one order of magnitude compared with the previous run. The background goes down to 0.4 c/keV/kg/day in the 12–20 keV region, and 0.3 c/keV/kg/day in the 20–30 keV region. Although this background is not as low as that obtained in the other detectors sharing the same shielding (IGEX), its better threshold leads to an improved bound for low mass WIMP exclusion.

3.2 WIMP exclusion plot

As previously stated, the new data have been analyzed first to get a limit on the WIMP-nucleon cross section as a function of the WIMP mass. The exclusion plot is derived from the recorded spectrum in 0.5-keV bins (from the 2.5 keV threshold up to 50 keV), by requiring the theoretically predicted signal in an energy bin to be less than or equal to the (90% C.L.) upper limit of the (Poisson) recorded counts. The derivation of such an interaction rate signal assumes standard hypothesis and parameters, i.e., that the WIMPs form an isotropic, isothermal, non-rotating halo of density $\rho = 0.3$ GeV/cm$^3$, which has a maxwellian velocity distribution with $v_{rms} = 270$ km/s (with an upper cut corresponding to an escape velocity of 650 km/s), and a relative Earth-halo velocity of $v_r = 230$ km/s). Other, more elaborated halo models, as well as other kinematical parameters would lead to different results. The cross sections are normalized per nucleon assuming a dominant scalar interaction, as the most likely observable coupling with the current experimental sensitivities:

$$\sigma_{N\chi} = \sigma_{n\chi} A^2 \frac{\mu_{W,N}^2}{\mu_{W,n}^2}$$

(1)

where $A$ is the target (germanium) mass number, $\mu_{W,N}$ is the WIMP-nucleus reduced mass, and $\mu_{W,n}$ the WIMP-nucleon reduced mass. The Helm parameterization [11] is used for the scalar nucleon form factor. The quenching factor has been assumed to be equal to 0.25, which is a good approximation if the relevant bins for the calculation of the exclusion plot are below $\sim$ 10 keV, as is the case of COSME.
The exclusion plot derived from the data reported here following such a procedure is shown in figure 2 by a thick solid line. This result is compared with the limit obtained with the previous data of COSME (thick dashed line) as well as a combined contour obtained from several previous germanium experiments \[2, 12, 13\] (thin dotted line) and two recent germanium results, IGEX-DM \[10\] (thin dashed line) and Heidelberg-Moscow \[14\] (thin dot-dashed line). All the curves have been computed from the raw data with the same set of assumptions (except for those for which a 0.25 quenching factor was not a good approximation, for which an appropriate energy dependence has been used \[14\]). The DAMA region corresponding to its reported annual modulation effect \[15\] is also shown. As can be seen, the new COSME plot improves other germanium bounds in the 12–30 GeV region and together with the other Canfranc results from Ge detectors (COSME I and IGEX-DM) provide the best bound below 200 GeV obtained. up to now with conventional germanium ionization detectors. Better exclusion contours have been obtained with NaI scintillators which use statistical pulse shape background discrimination \[16\], as well as with germanium bolometers which simultaneously detect ionization and allow an event-by-event background rejection \[17\].

### 3.3 Limit on axion-photon coupling

If axions exist they could be copiously produced in the core of the stars from where they can extract energy efficiently competing with other conventional mechanisms. The cooling of stars by axionic energy emission could affect the star’s properties and its evolution and so, to avoid conflict with the experimental observation, strong constrains on the coupling strength or mass of the stellar axion follow \[3\]. The discovery of axions, if they exist, –either galactic or stellar– is one of the challenges of current astrophysics and various efforts are underway. As far as this second category of axions is concerned, a nearby and powerful source of stellar axions would be the Sun.

Crystal detectors provide a simple mechanism for solar axion detection \[7, 8\]. In fact, axions can pass in the proximity of the atomic nuclei of the crystal where the intense electric field can trigger their conversion into photons. In the process the energy of the outgoing photon is equal to that of the incoming axion. The axion production rate in the Sun –through Primakov conversion of the blackbody photons in the solar plasma– can be easily estimated \[13, 8\] within the standard solar model, resulting in an axion flux of an average energy of about 4 keV that can produce detectable X-rays when reconverted again in a crystal detector. Depending on the direction of the incoming axion flux with respect to the planes of the crystal lattice, a coherent effect can be produced when the Bragg condition is fulfilled, with the ensuing strong enhancement of the signal.

A useful parametrization\[8\] of the solar axion flux at Earth is the following:

\[
\frac{d\Phi}{dE_a} = \sqrt{\lambda} \frac{\Phi_0}{E_0} \left(\frac{E_a}{E_0}\right)^3 e^{E_a/E_0 - 1}
\]

where \(\lambda=(g_{a\gamma\gamma} \times 10^8/\text{GeV}^{-1})^4\) is a dimensionless coupling introduced for later convenience, \(\Phi_0=5.95 \times 10^{14} \text{ cm}^{-2} \text{ sec}^{-1}\) and \(E_0=1.103 \text{ keV}\).
Figure 2: Exclusion plot for spin-independent interaction where bounds coming from different experiments are drawn. The thick line shows the exclusion obtained with the data reported in this paper, obtained with 72.7 kg-days of exposure with COSME detector. The thick dashed line shows the one from the previous running of the same detector for comparison. Limits from a recent result of IGEX-DM experiment (thin-dashed), from the Heidelberg-Moscow experiment (dot-dashed) and from a combination of previous germanium experiments (dots) are also shown. The closed region corresponds to the (3σ) annual modulation effect reported by the DAMA collaboration (including NaI-1,2,3,4 runnings).

Making use of eq. as well as the cross-section of the process and appropriate crystallographic information, we have calculated the expected axion-to-photon conversion count rate \( R(t) \) in a germanium detector (See ref.[19, 8] for further details). An example of the expected count rate is shown in figure as a function of time during one day. As expected, the signal shows a strong time dependence throughout the day, due to the motion of the Sun in the sky. This correlation of the expected rate with the position of the Sun in the sky is a distinctive signature of the axion which can be used, at the least, to improve the signal/background ratio.

To extract all this information from a experimental set of data we introduce, following
Figure 3: Expected axion signals for coherent Primakoff conversion in a germanium crystal as a function of time for $\lambda = 1$, for two different energy windows: a) $2 \text{ keV} \leq E_{ee} \leq 2.5 \text{ keV}$; b) $4 \text{ keV} \leq E_{ee} \leq 4.5 \text{ keV}$.

Ref. [20], the quantity:

$$\chi = \sum_{i=1}^{n} \left[ \bar{R}(t_i) - < \bar{R} > \right] \cdot n_i \equiv \sum_{i=1}^{n} W_i \cdot n_i$$  \hspace{1cm} (3)

where $\bar{R}(t) = R(t)/\lambda$, the $n_i$ indicates the number of measured events in the time bin $t_i, t_i + \Delta t$ and the sum is over the total period $T$ of data taking. The brackets indicate time average.

By definition the quantity $\chi$ is expected to be compatible with zero in absence of a signal, while it weights positively the events recorded in coincidence with the expected peaks.

The time distribution of $n_i$ is supposed to be Poissonian, with mean:

$$< n_i > = \left[ \lambda \bar{R}(t_i) + b \right] \Delta t.$$  \hspace{1cm} (4)

Assuming that the background $b$ dominates over the signal the expected average and variance of $\chi$ are given by:

$$< \chi > = \lambda \cdot A$$  \hspace{1cm} (5)

$$\sigma^2(\chi) \simeq b/A$$  \hspace{1cm} (6)

with $A \equiv \sum_i W_i^2 \Delta t$. Each energy bin $E_k, E_k + \Delta E$ with background $b_k$ provides an independent estimate $\lambda_k = \chi_k/A_k$ so that one can get the most probable combined value of $\lambda$:

$$\lambda = \sum_k \frac{\chi_k}{\sum_l A_l}$$
\[ \sigma(\lambda) = \left( \sum_k A_k / b_k \right)^{-\frac{1}{2}}. \] (7)

This method provides an estimation of the axion-photon coupling \( g_{a\gamma\gamma} \) if an axion signal is present in the experimental data (and is accessible to the sensitivity of the experiment), or an upper limit to \( g_{a\gamma\gamma} \) in case of a negative result. If the exact orientation of the crystal is not known we must repeat the calculation for all possible ones, and take the most conservative result. We know only the direction of one of the crystallographic axis of COSME, which is vertical with respect to the laboratory frame, so we have repeated the calculation for all possible rotations around the fixed vertical axis. The different values for \( \lambda \) so obtained are shown in figure 4 with the corresponding 90\% error derived from \( \sigma(\lambda) \). All of them are compatible with absence of signal, so taking the most conservative value, we obtain an upper limit \( \lambda < 0.006 \) at 95\% C.L., which corresponds to a limit on \( g_{a\gamma\gamma} \):

\[ g_{a\gamma\gamma} < 2.78 \times 10^{-9} \text{GeV}^{-1} \] (8)

The application of the statistical analysis described above can be viewed as a background rejection technique, which in our case results in a reduction of about two orders of magnitude. The limit presented here is practically equal to that obtained by the SOLAX Collaboration with another Ge detector[20]. These limits are the mass independent (although solar model dependent) most stringent laboratory bounds for the axion-photon coupling obtained so far. A recent result, however, obtained with the Tokyo helioscope [21] (a \( \sim 2 \text{ m} \) long superconducting magnet which converts axions into photons in a \( \sim 4 \text{ Tesla} \) magnetic field), improves by a factor 3-5 the COSME and SOLAX bounds for axion masses below 0.26 eV.

4 Conclusion

A small (234 g) germanium detector of natural isotopic abundance, with an energy threshold of 2.5 keV and an energy resolution of 430 eV at the 10.37 keV X-ray \(^{68}\text{Ga} \) peak, has collected data up to a statistics of 311 days, in a search for WIMPs. The timing information of the same set of data has allowed also a search for the characteristic time pattern of an hypothetical solar axion signal as expected from the relative motion of the detector with respect to the Sun along the day. Both searches have provided bounds for the couplings \( \sigma_W(m) \) and \( g_{a\gamma\gamma} \) of both types of hypothetical particles to matter and radiation respectively. The obtained results have been proven to be competitive (or superior) with other current searches of such types of particles, which use similar techniques.

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Figure 4: Values of $\lambda$ obtained for different assumed rotations around the fixed vertical axis.

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