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$ZnWO_4$ anisotropic scintillator for Dark Matter investigation with the directionality technique

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Abstract. The $ZnWO_4$ crystal scintillator has unique features that make it very promising to realize a pioneering experiment to pursue Dark Matter investigation with the directionality technique. In particular in this detector the light output and the scintillation pulse shape for heavy particles (p, α, nuclear recoils) depend on the direction of the impinging particle with respect to the crystal axes, while the response to γ/β radiation is isotropic. The anisotropy of the light output can be considered to point out the presence in the diurnal counting rate of a Dark Matter signal produced by candidate particle inducing just nuclear recoils. In addition this crystal detector has also other important characteristics for a Dark Matter experiment: high light output, high level of radiopurity. In this paper the present performances of the developed $ZnWO_4$ crystal scintillator will be summarized together with the possible future improvements. Some reachable sensitivities – under given assumptions – in the investigation of DM candidate particles with the directionality technique will also be addressed.

1 Introduction

In Dark Matter (DM) direct experiments, in order to point out the presence of a signal of Galactic origin, it is mandatory to pursue a signature for signal identification. The most important one is the model independent DM annual modulation that has been successfully exploited by the DAMA/NaI and DAMA/LIBRA experiments obtaining, cumulatively, an annual modulation effect at 9.3σ C.L. over 14 annual cycles [1–3].

An independent evidence can be obtained by pursuing a different approach, but effective for those DM candidate particles able to induce just nuclear recoils: the directionality [4]. This strategy is based on the correlation between the arrival direction of the DM particles (and thus of the induced nuclear recoils) and the Earth motion in the Galactic rest frame. Because of the rotation of the Milky Way, the Galactic disc passes through the halo of DM and the Earth is crossed by a wind of DM particles apparently flowing along a direction opposite to that of solar motion. Since the Earth rotates around its axis, the average direction of DM particles with respect to an observer fixed on the Earth changes during the sidereal day. Thus, the directions of the induced nuclear recoils are expected to be strongly correlated with the impinging direction of the considered DM candidates while the background events are not.

In principle, an experiment able to measure the nuclear track might be suitable to investigate the directionality. One possibility is to use low pressure gas detector (such as Time Projection Chambers, TPC) where the range of recoiling nuclei is of the order of mm. However, a realistic experiment with low pressure TPC can be limited e.g. by the necessity of an extreme operational stability, of large detector size and of a great spatial resolution in order to reach a significant sensitivity. The limitations affecting experiments aiming to measure recoil tracks, can be overcome by using the anisotropic scintillation detectors [5, 6]. In this case there is no necessity of a track detection and recognition (in solid detectors the range of recoiling nuclei is typically of the order of μm). In these detectors the detector response for heavy particles and scintillation pulse shape depend on the incoming direction of the heavy particles relatively to the crystal axes and the information on the presence of DM induced recoils is given by a peculiar variation of the measured counting rate during the sidereal day [7].

2 The main features of the $ZnWO_4$ anisotropic scintillator

Recently, measurements and R&D works have shown that the $ZnWO_4$ scintillators can offer suitable features for a DM experiment based on the directionality. In this crystal scintillator the light output for heavy particles (p, α, nuclear recoils) depends on the direction of such particles with respect to the crystal axes while the response to γ/β radiation is isotropic; the scintillation decay time also shows the same property. In addition to the anisotropy, the recently developed $ZnWO_4$ scintillators have very good level of radiopurity [8], and can work at energy threshold of few keV [9]. The $ZnWO_4$ offers also a high atomic weight and the possibility to realize crystals with masses of some kg [10]. Moreover, three target nuclei with very different masses are present in this detector (Zn, W and O), giving sensitivity to both small and large mass for the considered DM candidates.

The luminescence of $ZnWO_4$ was studied sixty years ago [11]. Large volume $ZnWO_4$ single crystals of reasonable quality were grown [12] and studied as scintillators in the eighties [13]. Further developments for high quality radiopure $ZnWO_4$ have been performed and described in [10, 14, 15].

The first low background measurement with a small $ZnWO_4$ sample (mass of 4.5 g) was performed in the Solotvina underground laboratory (Ukraine) at a depth of $\approx$ 1000 m of water equivalent in order to study its radioactive contamination, and to search for double beta decay of zinc and tungsten isotopes [17]. A possibility to search for diurnal modulation of WIMP direction with $ZnWO_4$ scintillators was also pointed out in [17]. More recently, radiopurity and double beta decay processes of zinc and tungsten have been further studied also at LNGS using new developed $ZnWO_4$ detectors with masses $0.1 - 0.7$ kg [8, 9, 18, 19]. The growth of the crystals, the scintillation properties, the pulse shape discrimination capability, the anisotropic properties, the residual radioactive contamination and the possible applications have been deeply studied [8, 10, 14, 15, 17–20]. The obtained results are very promising and an R&D to produce $ZnWO_4$ crystals having higher radiopurity is still ongoing. In particular, an R&D to improve $ZnWO_4$ crystals radiopurity by re-crystallization (recently demonstrated for $CdWO_4$ crystal [20]) is in progress.

In the measured $ZnWO_4$ scintillators the radioactive contamination is: $<$ 0.002 mBq/kg for ^{228}Th and ^{226}Ra ($\sim$ 0.5 ppt for ^{232}Th and $\sim$ 0.2 ppt for ^{238}U, assuming the secular equilibrium of the ^{232}Th and ^{238}U chains), $<$ 0.02 mBq/kg for ^{40}K; the total α activity is 0.18 mBq/kg [8].

As previously mentioned, the study of the directionality with the $ZnWO_4$ detectors is based on the anisotropic properties of these scintillators. In particular the light output of the detector for α and β

particles of the same energy is different; in addition the response of the detector to α's depends also on the direction of the particels with respect to its crystallographic axes. In Fig. 1 the behaviuor of the light output ratio for α and β (α/β ratio) is reported as a function of the energy and the direction of the α beam in a $ZnWO_4$ crystal [17]. As shown in Fig. 1, the response of the detector for α particles

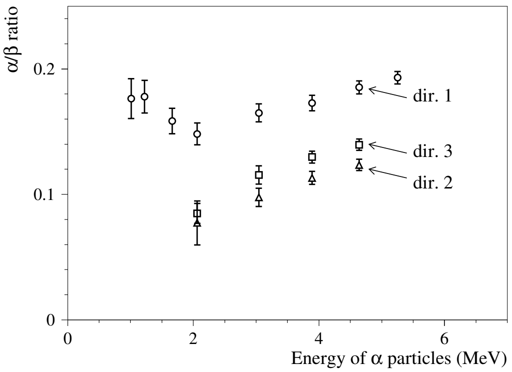

Figure 1. Dependence of the α/β ratio (ratio of the light output measured in the crystal for α and β particles) on the energy of α particles measured with $ZnWO_4$ scintillator. The crystal was irradiated in the directions perpendicular to (010), (001) and (100) crystal planes (directions 1, 2 and 3, respectively). The anisotropic behaviour of the crystal is evident [17].

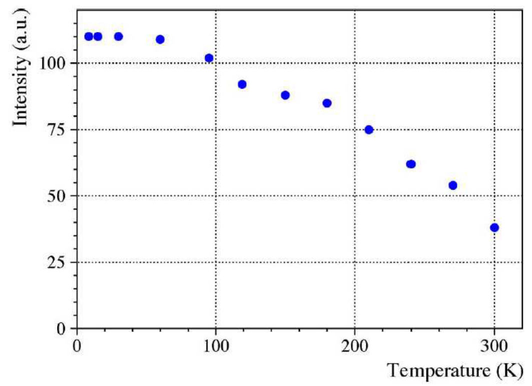

Figure 2. Dependence of the light output of the $ZnWO_4$ as a function of the temperature, for excitation with ^{241}Am α particles [15].

measured along direction 1 is about 1.5 times larger than that measured along direction 2, and about 1.4 times larger than that measured along direction 3. On the contrary, the anisotropy of the light response of the $ZnWO_4$ scintillator disappears in case of electron excitation. The same behaviour have been recently reported also for the anthracene in Ref. [16]. Moreover for $ZnWO_4$, as reported in Ref. [17], also the shape of the scintillation pulse depends on the type of irradiation; this feature allows one to discriminate $\gamma(\beta)$ events from those induced by α particles. This pulse shape discrimination capability can be of interest not only for a DM experiment but also for double beta decay searches. Measurements with a neutron beam to study the anisotropy response of the crystal for recoils at keV energy range will be performed in near future [21].

Another feature of this scintillator, important for a DM experiment, is the relatively high light output which is about 13-20% of the Na(Tl) scintillator. It has been observed that the light output largely increase when the crystal scintillator working temperature is decreased [15] (see Fig. 2).

3 Estimated sensitivity in some given scenarios

In case of a DM candidate interacting via elastic scattering with ordinary nuclei, by pursuing the directionality technique with anisotropic scintillators, the DM signal can be pointed out by studying the diurnal variation of the counting rate as a function of the sidereal time. In a laboratory on the Earth, the DM particles are expected to arrive preferentially from the opposite direction of the Sun velocity in the Galaxy. Due to the Earth rotation around its axis, the orientation of the crystallographic axes of the scintillator with respect to the arrival direction of the particle (and thus of the nuclear recoils) changes during the day. Because of the anisotropy of the scintillator, the response of the detector varies during the day. Thus the DM signal is expected to have a peculiar variation during the sidereal day [7]. On the contrary, the light response of the detector to e/γ background will be isotropic and its counting rate will show a flat behaviour as a function of the time. For this reason the observation of a peculiar diurnal variation can offer indication for the presence – in the Galactic halo – of DM candidates inducing just nuclear recoils.

To estimate the reachable sensitivity – in some given scenarios – of an experiment exploiting the directionality technique with the help of $ZnWO_4$ scintillators, we can consider a set-up composed by a matrix of detectors (as DAMA/LIBRA set-up) installed deep underground in a sealed low radioactive copper box, continuously flushed with high purity N_2 gas and placed in the center of a multi-ton, multi-component low radioactive passive shield. By considering 200 kg of $ZnWO_4$, in 5 years of data taking and with an energy resolution FWHM = 2.4 $\sqrt{E[keV]}$), the sensitivity reported in Fig. 3 can be reached [7]. In particular, two software energy thresholds have been considered: 2 keVee for Fig. 3-left and 6 keVee for Fig. 3-right. The sensitivity curves have been calculated considering four possible time independent background levels in the low energy region: 10^{-4} cpd/kg/keV (solid black lines), 10^{-3} cpd/kg/keV (dashed lines), 10^{-2} cpd/kg/keV (dotted lines) and 0.1 cpd/kg/keV (dotted-dashed lines). The response of the detector to Zn, W and O recoils for the three crystal axes have been estimated by considering the method described in Ref. [22], taking into account the data on the anisotropy obtained with the α particles (see Fig. 1). As shown in Fig. 3 the directionality approach can reach – for DM candidates inducing just nuclear recoils and the given scenarios – a sensitivity to spin-independent cross sections at level of $10^{-5} - 10^{-7}$ pb, depending on the candidate mass between few GeV and hundreds GeV. However, it is worth noting that these plots are model dependent and, thus, always affected by several uncertainties; to obtain this sensitivity plot the scenario described in details in Ref. [7] has been considered. In Fig. 3 the allowed regions (7.5σ from the null hypothesis) obtained by performing a corollary analysis of the DAMA model independent result in term of the scenarios described in Ref. [23] are also reported.

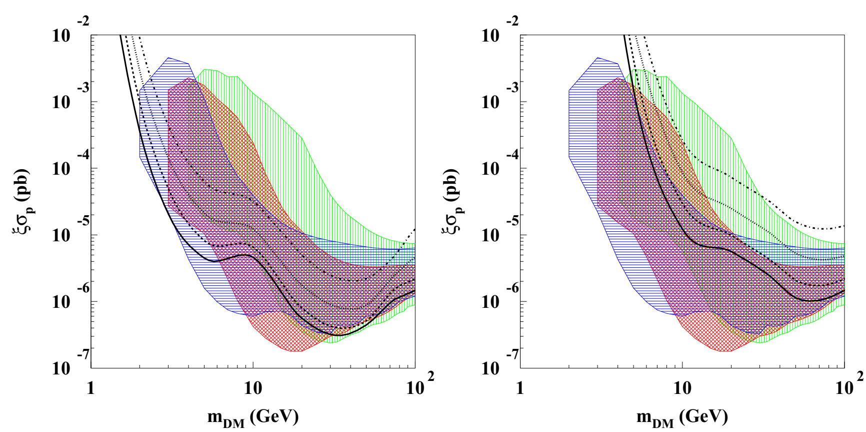

Figure 3. Sensitivity curves at 90% C.L. reachable by the set-up described in the text, for DM candidates inducing just nuclear recoils in the given scenario by exploring the directionality approach. Four possible background levels in the low energy region are considered (see text) and two software energy thresholds: 2 keVee in (a) and 6 keVee in (b). There m_{DM} is the particle mass, σ_p is the spin-independent elastic scattering cross section on nucleon and ξ is the fraction of the DM local density of the considered candidate. In the figures there are also shown (green, red and blue online) allowed regions obtained in Ref. [23] by a corollary analysis of the 9σ C.L. DAMA model independent result in terms of scenarios for DM candidates inducing just nuclear recoils.

4 Conclusions

The perspectives of a pioneering experiment with anisotropic $ZnWO_4$ detectors to further explore, with the directionality approach, those DM candidate particles inducing just nuclear recoils have been addressed. The features of these detectors can permit to reach, in some of the many possible scenarios, sensitivities not far from that of the DAMA/LIBRA positive result [2, 3]. In case of success the experiment can obtain an evidence for the presence of such DM candidate particles in the galactic halo with a new approach and will provide complementary information on the nature and interaction type of the DM candidate(s). In case of negative results the experiment would favor other kinds of astrophysical, nuclear and particle physics scenarios or other DM candidate particles, interaction types which can account as well for the 9.3σ C.L. DM model independent annual modulation effect already observed by the DAMA experiments. In all cases such an experiment would represent a first realistic attempt to investigate the directionality through the use of anisotropic scintillators and it could also represent a further activity in the application of highly radiopure $ZnWO_4$ detector in the field of rare processes.

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