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The ADAMO Project and developments

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Abstract. In the anisotropic scintillators the light output and the pulse shape for heavy particles (p, α, nuclear recoils) depend on the direction with respect to the crystal axes; the response to γ/β radiation is isotropic instead. This feature offers the possibility to study the directionality approach, which is applicable in the particular case of those Dark Matter candidate particles inducing just nuclear recoils. Among the anisotropic scintillators, the $ZnWO_4$ has unique features, which make it an excellent candidate for this type of research, and there is still plenty of room for the improvement of its performances. Studies on the exploitation of further possibilities are also considered and will be shortly mentioned. In this paper the possibility of a low background pioneer experiment (named ADAMO: Anisotropic detectors for DArk Matter Observation) to exploit the directionality approach by using anisotropic $ZnWO_4$ scintillators is discussed.

1. Introduction

Astrophysical observations have given evidence for the presence of Dark Matter (DM) on all astrophysical scales and many arguments have also suggested that a large fraction of the DM should be in form of relic particles. In the direct search for DM, a positive model independent result has been obtained at 9.3σ C.L. for the presence of DM particles in the galactic halo by the DAMA/NaI and DAMA/LIBRA experiments [1][2][3] exploiting the DM annual modulation signature [4] in highly radio-pure NaI(Tl) target over 14 annual cycles.

A different possible approach is the directionality [5], in principle effective just for those DM candidate particles able to induce nuclear recoils. This approach studies the correlation between the arrival direction of the DM particles, through the induced nuclear recoils, and the Earth motion in the galactic rest frame. In fact, the dynamics of the rotation of the Milky Way galactic disc through the halo of DM causes the Earth to experience a wind of DM particles apparently flowing along a direction opposite to that of solar motion relative to the DM halo. However, because of the Earth's rotation around its axis, the average direction of those DM candidates with respect to an observer fixed on the Earth changes during the sidereal day. The nuclear recoils induced by the DM candidates considered here are expected to be strongly correlated with the impinging direction of such DM candidates, while the background events are not.

Anisotropic scintillators are considered as promising detectors sensitive to the recoils direction because of the dependence of their scintillation properties (quenching and scintillation decay kinetics) on the direction of the heavy particles relatively to the crystal axes. Zinc tungstate ($ZnWO_4$) anisotropic crystal scintillator is proposed as a promising choice to build a realistic directionality sensitive set-up. Here, the ADAMO (Anisotropic detectors for DArk Matter Observation) project, based on the use of $ZnWO_4$ crystal scintillators, is presented and an example of the reachable sensitivity for a given scenario is discussed.

2. Directionality sensitive detectors

In principle low pressure Time Projection Chamber (TPC), where the range of recoiling nuclei is of the order of mm (while in solid detectors the range is typically of order of μm) might be suitable to investigate this directionality (see e.g. [6]) through the detection of the tracks directions. However, a realistic experiment with low pressure TPCs can be limited e.g. by the necessity of an extreme operational stability, of an extremely large detector size and of a great spatial resolution in order to reach a significant sensitivity. These practical limitations can be overcome by using the anisotropic scintillation detectors. In this case there is no necessity of a track detection and recognition, since the information on the presence of those candidate particles is given by the variation of the measured counting rate during the sidereal day when both the light output and the pulse shape vary depending on the direction of the impinging particles with respect to the crystal axes (see the Ref. [7]). The use of anisotropic scintillators to study the directionality approach was proposed for the first time in Ref. [8] and revisited in [9], where the case of anthracene detector was preliminarily analysed. Recently, measurements and R&D works have shown that the $ZnWO_4$ scintillators can offer suitable features: they have already a very good radio-purity [10], and an energy threshold at a level of a few keV is reachable [11]. Thus, the $ZnWO_4$ can be an excellent candidate for this type of research due to its unique features. In fact, not only the light output of 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, but also the scintillation decay time shows this property. Both the anisotropic features of the $ZnWO_4$ detectors can provide two independent ways to exploit the directionality approach.

3. The $ZnWO_4$ anisotropic scintillator, features and pulse shape analysis (PSA)

In addition to the mentioned properties, the $ZnWO_4$ offers a high atomic weight and the possibility to realize crystals with masses of some kg. 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 [12]. Large volume $ZnWO_4$ single crystals of reasonable quality were grown [13] and studied as scintillators in the eighties [14]. Further development of large volume high quality radiopure $ZnWO_4$ crystal scintillators is described in [15][16][17]. The main properties of the $ZnWO_4$ scintillators are given in Table 1 of Ref. [7].

The material is non-hygroscopic and chemically resistant. 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 [18]. In this work a possibility to use the dependence of $ZnWO_4$ scintillation pulse shape on direction of irradiation by high ionizing particles to search for diurnal variation of DM particles inducing just nuclear recoils was pointed out for the first time. More recently, radiopurity and double beta decay processes of zinc and tungsten have been further studied also at LNGS using $ZnWO_4$ detectors with masses $0.1 - 0.7$ kg [10][11][20][21].

R&D developments have been recently performed with the aim to develop highly radiopure $ZnWO_4$ crystals [10]. The growth of the crystals, the scintillation properties, the pulse shape discrimination capability, their anisotropic properties, their residual radioactive contamination, their possible applications have been studied [10][15][16][17][20][21]. Different $ZnWO_4$ prototypes have been investigated; the results are very promising and the R&D is still ongoing.

The measured radioactive contamination is [10]: less than 0.002 mBq/kg for ^{228}Th and ^{226}Ra (~ 0.5 ppt for ^{232}Th and ~ 0.2 ppt for ^{238}U, assuming the secular equilibrium of the ^{232}Th and ^{238}U chains), less than 0.02 mBq/kg for ^{40}K; in particular, a total α activity of 0.18 mBq/kg has been measured. The radioactive contamination of the samples of $ZnWO_4$ crystals approaches that of specially developed low background NaI(Tl); moreover, $ZnWO_4$ crystals having higher radiopurity could be expected in future realizations. As previously mentioned, the study of the directionality with the $ZnWO_4$ detectors is based on the anisotropic properties of these scintillators. Measurements with α particles have shown that the light response and the pulse shape of a $ZnWO_4$ scintillator depend on the impinging direction of α particles with respect to the crystal axes [18]. Fig. 1 shows the dependence in a $ZnWO_4$ crystal of the α/β light ratio (quenching factor) on energy and direction of the α beam relatively to the crystal planes. The $ZnWO_4$ crystal was irradiated in the directions perpendicular to the (010), (001) and (100) crystal planes (directions 1, 2 and 3, respectively in Fig. 1). As shown in Fig. 1, the quenching

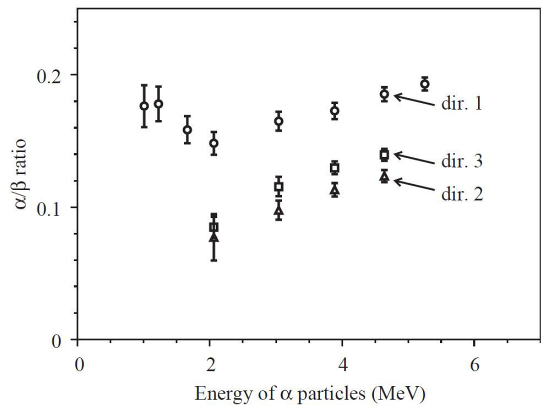

Figure 1. Dependence of the α/β ratio on energy of α particles measured with $ZnWO_4$ scintillator. The crystal was irradiated in the directions perpendicular to (010), (001) and (100) crystal planes (directions 1, 2 and 3, respectively). The anisotropic behaviour of the crystal is evident [18].

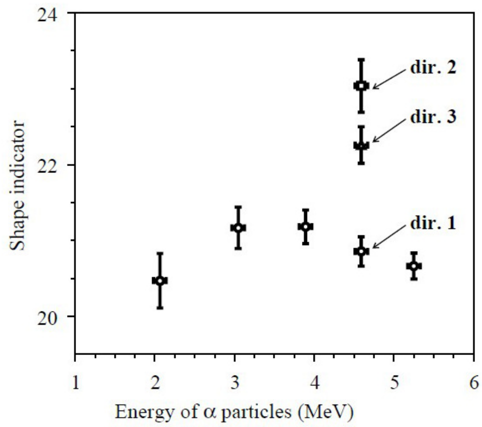

Figure 2. Dependence of the shape indicator (see text) on the energy and on the directions of α particles relatively to the main (010), (001) and (100) crystal planes of $ZnWO_4$ (directions 1, 2 and 3, respectively) [18]. Similar behavior has been observed also with $CdWO_4$ scintillators [19].

factor for α particles 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. Instead, the anisotropy of the light response of the $ZnWO_4$ scintillator disappears in case of electron excitation. Moreover, as demonstrated in Ref. [18], the dependence of the pulse shapes on the type of irradiation in the $ZnWO_4$ scintillator allows one to discriminate $\gamma(\beta)$ events from those induced by α particles. The PSA can be realized by using the optimal filter method proposed in Ref. [22] and developed in Ref. [18] for $ZnWO_4$ crystal scintillators. The so-called shape indicator (SI) should be calculated for each signal to obtain a numerical characteristic of scintillation pulse. One can found an example of the method application in Ref. [10].

As an example, we show in Fig. 2 the dependence of the SI on the energy and on the impinging direction of the α particles obtained with a $ZnWO_4$ scintillator irradiated in the directions 1, 2 and 3 [18]. Also in this case, the anisotropic behaviour of the crystals response is evident. By the PSA analysis it is also possible to point out the anisotropic behaviour of the pulse shape in case of heavy particles impinging on a $ZnWO_4$ detector.

4. The ADAMO project

Profiting of the experience of the DAMA collaboration with the DAMA/LIBRA set-up [23] and of the proved success of this detector configuration and of the shielding for the background reduction, a similar scheme can be adopted also for the proposed experiment. Hence, a matrix of 25 detectors (as DAMA/LIBRA set-up) can be installed in a sealed low radioactive copper box. Such copper box, continuously flushed with high purity N_2 gas, can be placed in the centre of a multi-ton, multi-component low radioactive passive shield (similar to the one described in Ref. [23]) deep underground (see Ref. [7] for details).

The sensitivity reachable - for the model scenario described in [7] - by the ADAMO project (200 kg of $ZnWO_4$, 5 years of data taking and an energy resolution FWHM = $2.4\sqrt{E[keV]}$), exploring the directionality approach, is reported in Fig. 3. In particular, two software energy thresholds have been considered: 2 keVee for Fig. 3 (a) and 6 keVee for Fig. 3 (b). The reachable sensitivity has 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). For the Zn, W and O quenching factors with respect of the three axes of the $ZnWO_4$ crystal we have considered here the values obtained by the method described in Ref. [25] taking into account the data of the anisotropy to α particles (see Fig. 1). As shown in Fig. 3 the directionality approach can reach - for the DM candidates investigated here and under the given model scenario - 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; here, for simplicity, the same scenario described in [7] has been considered (isothermal halo model, Maxwellian velocity distribution, spin independent interaction, and related assumptions; see Ref. [7] for details). 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. [24] are also reported.

5. Conclusions

The possibility of a pioneering experiment with anisotropic $ZnWO_4$ detectors to further explore, with the directionality approach, DM candidate particles that scatter off target nuclei has been addressed. The features and the potentiality of these detectors can permit to reach in some of the many possible scenarios and for the DM candidates considered here sensitivities not far from that of the DAMA/LIBRA positive result [2][3]. In case of success such an 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 favour other kinds of astrophysical, nuclear and particle physics scenarios for the DM candidates considered here and/or other DM candidate particles, interaction types and scenarios which can account as well for the 9.3σ C.L. DM model independent evidence already observed by the DAMA experiments.

In all cases the ADAMO experiment would represent a first realistic attempt to investigate the directionality approach through the use of anisotropic scintillators and it could also represent a further activity in the application of highly radio-pure $ZnWO_4$ detector in the field of rare processes.

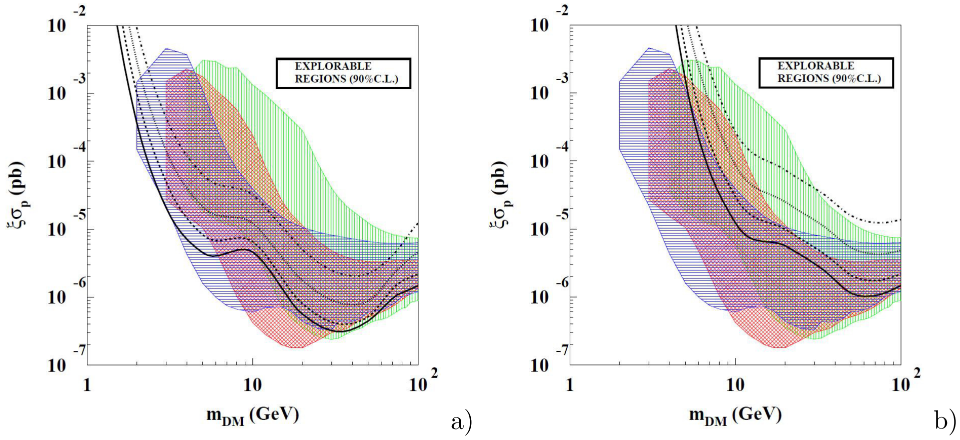

Figure 3. Sensitivity curves at 90% C.L. reachable by the ADAMO project for DM candidates inducing just nuclear recoils in the model scenario given in the text by exploring the directionality approach. Four possible background levels in the low energy region are considered as given in the text as well as two possible 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 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. [24] by performing a corollary analysis of the 9σ C.L. DAMA model independent result in terms of scenarios for DM candidates inducing just nuclear recoils.

References

[1] Bernabei R *et al* 2003 *La Rivista del Nuovo Cimento* **26** 1
[2] Bernabei R *et al* 2008 *Eur. Phys. J. C* **56** 333
[3] Bernabei R *et al* 2010 *Eur. Phys. J. C* **67** 39; Belli P *et al* 2011 *Phys. Rev. D* **84** 055014; Bernabei R *et al* 2012 *J. Instrum.* **7** P03009, Bernabei R *et al* 2012 *Eur. Phys. J. C* **72** 2064; Bernabei R *et al* 2013 *Eur. Phys. J. A* **49** 64; Bernabei R *et al* 2013 *Eur. Phys. J. C* **73** 2648; Bernabei R *et al* 2013 *Int. J. Mod. Phys., A* **28** 1330022; Bernabei R *et al* 2014 *Eur. Phys. J. C* **74** 2827
[4] Drukier K *et al* 1986 *Phys. Rev. D* **33** 3495, Freese K *et al* 1988 *Phys. Rev. D* **37** 3388
[5] Spergel D 1988 *Phys. Rev. D* **37** 1353
[6] Lehner M *et al* 1988 in *Heidelberg, Dark matter in astrophysics and particle physics* 767, *Preprint* [astro-ph/9905074]; Alner G *et al* 2005 *Nucl. Instrum. Meth. A* **555** 173
[7] Cappella F *et al* 2013 *Eur. Phys. J. C* **73** 2276
[8] Belli P *et al* 1992 *Il Nuovo Cim. C* **15** 475
[9] Bernabei R *et al* 2003 *Eur. Phys. J. C* **28** 203
[10] Belli P *et al* 2011 *Nucl. Instrum. Meth. A* **31** 626
[11] Belli P *et al* 2011 *J. Phys. G* **38** 115107
[12] Kroger F 1948 *Some Aspects of the Luminescence in Solids*, Elsevier Pub. Co, Amsterdam, p.109
[13] Grabmaier B 1984 *IEEE Trans. Nucl. Sci.* **31** 372
[14] Zhu Y *et al* 1986 *Nucl. Instrum. Meth. A* **244** 579; Danevich F *et al* 1989 *Prib. Tekh. Eksp.* **5** 80 [1989 *Instrum. Exp. Tech.* **32** 1059]
[15] Nagornaya L *et al* 2008 *IEEE Trans. Nucl. Sci.* **55** 1469
[16] Nagornaya L *et al* 2009 *IEEE Trans. Nucl. Sci.* **56** 994
[17] Galashov E *et al* 2009 *Functional Materials* **16** 63
[18] Danevich F *et al* 2005 *Nucl. Instrum. Meth. A* **544** 553
[19] Danevich F *et al* 2003 *Phys. Rev. C* **67** 014310
[20] Belli P *et al* 2008 *Phys. Lett. B* **658** 193
[21] Belli P *et al* 2009 *Nucl. Phys. A* **826** 256
[22] Gatti E and De Martini F 1962 *Nuclear Electronics* **2** 265
[23] Bernabei R *et al* 2008 *Nucl. Instrum. Meth. A* **592** 297
[24] Belli P *et al* 2011 *Phys. Rev. D* **84** 055014
[25] Tretyak V 2010 *Astropart. Phys.* **33** 40