Study of Dark Matter with Directionality Approach Using $ZnWO_4$ Crystal Scintillators

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Abstract

Developing low-background anisotropic scintillators can provide a completely unique manner to have a look at the Dark Matter (DM) particle issue withinside the galactic halo, which is capable of setting off nuclear recoils, via the directionality technique. In particular, the $ZnWO_4$ crystal scintillator is an excellent candidate for this sort of research, thanks to its distinctive characteristics. In fact, both the light output and the shape of the scintillation pulse rely on the arrival direction of heavy particles (α particles and nuclear recoils) with relation to the crystal axes and might provide two separated modes to study the directionality and distinguish the γ/β radiation. In addition, because of the difference in mass of the three target nuclei, Zn, W, and O, the detector is sensitive to small and large DM candidates masses. Considering this, the ADAMO project performed new measurements to study the anisotropy of a $ZnWO_4$ scintillator to α particles and to nuclear recoils induced by neutron scattering. These are here presented.

Keywords: dark matter, anisotropic scintillator, $ZnWO_4$
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1. INTRODUCTION

Astrophysical studies have proved the presence of Dark Matter (DM) on all the astrophysical scales. Several statements have indicated that a big fraction of it ought to be within the sort of relic particles. Nowadays, many approaches are working in order to study DM particles in the galactic halo; here, we are going to consider a certain strategy: the directionality approach. A model-independent signature is a reliable method to provide a DM signal marker with respect to the background in direct detection investigations. The rate of events caused by a physical interaction in a target detector actually results from the halo model, the cross section of the process, and the relative velocity between the incident DM particle (DMp) and the target, as was initially suggested in [1, 2] and studied in [3, 4]. A typical time behavior for such an interaction rate is the DM yearly modulation, which the DAMA collaboration has effectively tapped into [5, 6, 7, 8, 9, 10, 11].

In addition to this primary signature, other possible ones are predictable, including a diurnal modulation caused by the Earth's rotation around its axis [12], a daily variation of the interaction rate caused by the DMp's different depths [13], and a directionality signature caused by the correlation between the DMp's impinging direction and the Earth's galactic motion [14]. In fact, the Earth encounters a wind of DM particles that appears to move in opposition to the solar motion with regard to the DM halo due to the rotation dynamics of the Milky Way galactic disc through the DM halo. In order to further support and provide specifics for some DMp candidates and associated astrophysical scenarios, it may be possible to see a distinctive anisotropy in the distribution of nuclear recoil orientations.

2. STUDY OF THE $ZnWO_4$ ANISOTROPIC RESPONSE

In anisotropic scintillators, the detector response to particles that can cause a nuclear recoil, in terms of quenching factor (Q.F.) and pulse shape, relies on the orientation in which the particles are striking with respect to the crystallographic axes. In light of this, it is anticipated that in the case of nuclear recoils, the measured energy spectrum at low energy will change during the sidereal day as a result of the shifting orientation of the crystallographic axes with respect to the DMp direction. Due to these characteristics, the counting rate observed in a specific low energy window along the sidereal day exhibits a unique variation, and it is possible to highlight the DM events relative to the electromagnetic background (for more information, see, e.g., [3, 4, 14, 15]). These types of detectors were initially proposed in [3] and were updated in [4] to analyze the directionality signature. The anthracene scintillator was initially explored; however, various operational issues with such scintillators' vi-

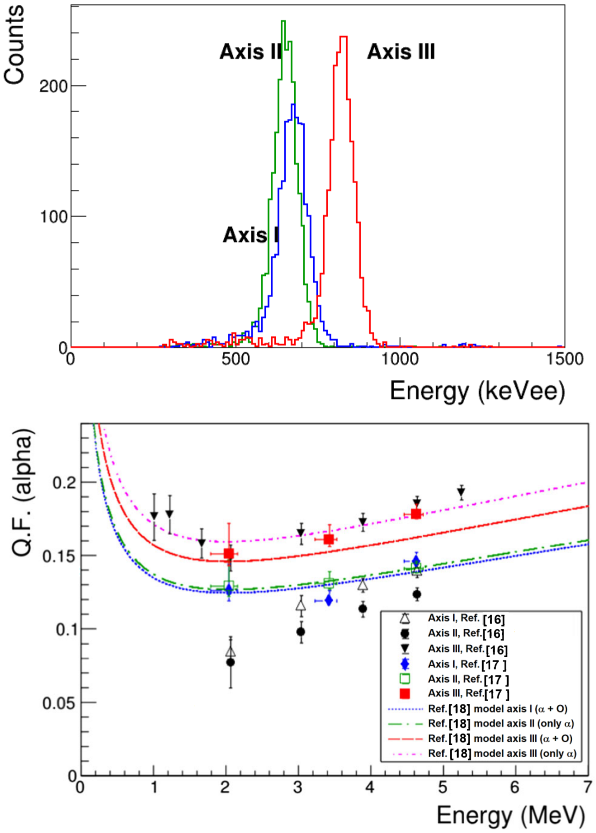

FIGURE 1: Up: Alpha energy spectra of 4.63 MeV (expressed in keVee) with the arrival direction along the three axes of the crystal. Down: α/β ratio as a function of the energy of the α particles found with a $ZnWO_4$ scintillator in [16] (black points) compared with those reported in [17] (colored points). The anisotropic behavior of the crystal is evident. The models for each crystallographic axis, which were derived as global fits on all the data (from recoils and α's; see text) of [17] in accordance with [18], are also reported.

ability were noted. The authors suggested using a $ZnWO_4$ crystal scintillator to overcome these problems [14].

2.1. *Studies with α Particles*

Using α particles, the first measurements of the Q.F.s of $ZnWO_4$ and the associated anisotropic behavior were investigated in [16]. In [17], further measurements were made using a little $ZnWO_4$ crystal and a ^{241}Am source with various sets of thin mylar films to lower the energy of the α particles. ^{137}Cs and ^{22}Na γ sources were used to calibrate the crystal's energy scale for each measurement.

Figure 1(up) displays the energy profiles of the α particles striking the crystal along the three crystallographic axes. In Figure 1, the $ZnWO_4$ crystal was beamed in the directions orthogonal to the (100), (001), and (010) crystallographic planes, which are referred to as crystallographic axes I, II, and III, respectively.

The dependency of the Q.F. as a function of energy for the three various orientations of the α beam connected to the crystallographic axes is depicted in Figure 1(down). The Q.F. for α particles recorded along crystallographic axis III is, in particular, nearly 1.2 times bigger than that measured along crystallographic axes I and II. Instead, the values of the Q.F. along crystallographic axes I and II are remarkably close.

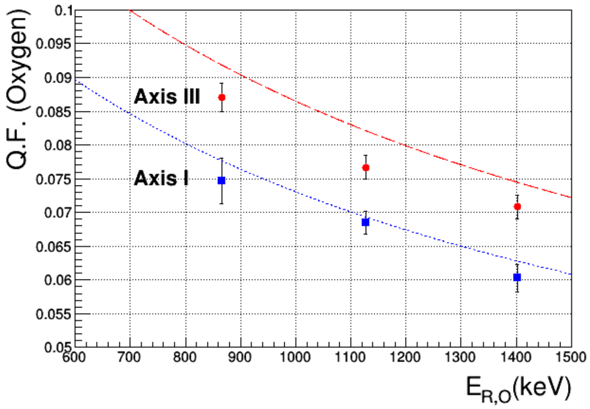

FIGURE 2: Values of the Q.F. measured for oxygen nuclear recoils in $ZnWO_4$ for the crystallographic axes I and III versus the expected recoil energies $E_{R,O}$. The predicted Q.F. behavior for the under consideration crystallographic axes is also depicted in the plot; it was derived by performing global fits on the α and oxygen recoil data in accordance with [18] (for more information, see [17]).

According to Figure 1(down), the Q.F. values and anisotropic impact stated in [17] are appropriately in agreement with those of [16]. The behavior of the Q.F. for each crystallographic axis, as predicted by the model in [18], is also reported in the same image. As a result, the data support $ZnWO_4$ crystal scintillator's anisotropic properties for α particles with energies up to a few MeV.

2.2. *Studies with a Neutron Generator*

The oxygen nucleus's recoil energies have been examined using the same crystal and a monochromatic neutron generator. Specifically, a set-up scheme and a thorough description of the data analysis are shown in Figure 4 of [17] and in that paper. The calculated quenching factors are presented in Figure 2 with models for the relevant crystallographic axes taken from [18] (see [17] for more details). In [17], we make a note of the fact that the anisotropy is also noticeably evident for oxygen nuclear recoils in the energy range down to around 100 keV at 5.4σ of the C.L. (see also Table 1 of [17]).

3. OPTICAL AND SCINTILLATION PROPERTIES OF ADVANCED $ZnWO_4$ CRYSTALS

A prolonged R&D using a Czochralski growing process was done to address the high optical and scintillation properties of $ZnWO_4$ crystals. The research and development was focused on varying the compound stoichiometry of an initial WO_3 provided by various suppliers; a further process while using a single or double crystallization with and without annealing of the generated boules was applied. In the temperature range from 85 K to room temperature, the luminescence of the produced $ZnWO_4$ crystals was studied, including emis-

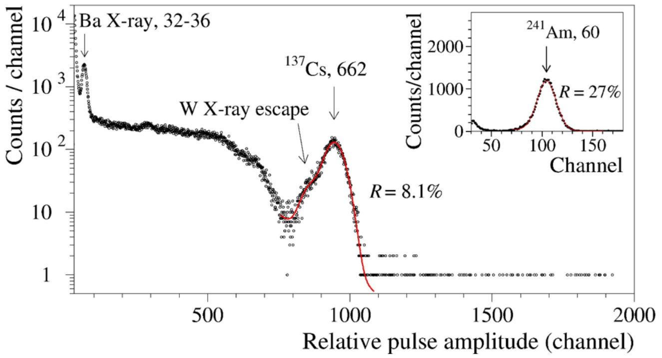

FIGURE 3: The energy spectra of γ-ray quanta of ^{137}Cs as determined by scintillation detector using the $ZnWO_4$ crystal sample No. 84 of [19]. The inset presents the energy spectrum of γ-ray quanta of ^{241}Am. X-ray and γ-ray quanta have energies expressed in keV.

sion spectra, temperature and dosage dependencies of the luminescence intensity, phosphorescence, and thermally induced luminescence. Up to 350 K, thermally stimulated luminescence was examined in particular. Using γ-ray sources such as ^{60}Co, ^{137}Cs, ^{207}Bi, ^{232}Th, and ^{241}Am, the scintillation characteristics of $ZnWO_4$ crystals were examined. In the wavelength range of 300–700 nm, the crystals' optical transmission spectra were studied. The $ZnWO_4$ crystals generated by single crystallization from the $ZnWO_4$ compound of the stoichiometric composition prepared by a deeply purified WO_3, annealed in an air atmosphere, gave the best optical and scintillation characteristics (more details in [19]).

As an illustration, Figure 3 shows the energy spectrum of the γ-ray quanta from the ^{137}Cs and ^{241}Am sources as measured with the $ZnWO_4$ crystal sample that produced the most light (see [19]). It should be emphasized that $ZnWO_4$ crystal scintillators have never been recorded to have such great energy resolution (R, full-width half-maximum over peak position). Since phosphorescence and dose dependence of XRL intensity are both negligible in scintillation measurements, there was no discernible link between the scintillation light output and luminescence intensity of the samples. The fact that there is no relationship between luminescence intensity and scintillation pulse amplitude suggests that there is still room for advancement in the $ZnWO_4$ production technology and that the achieved scintillators' quality, particularly for samples made through double crystallization, is not perfect. More R&D is being done with the goal of creating larger-volume crystals for low counts tests.

4. HOW TO PROFIT FROM ANISOTROPIC SCINTILLATORS

As previously remarked, recoil nuclei caused by the examined DM candidates might be distinguished from the background by taking advantage of the anticipated fluctuation in their low energy distribution during the day. This is possible because of the anisotropic light response for heavy particles. As a result, the expected signal counting rate in the relevant energy window is time-dependent. With a multidetector setup, a matrix of, for example, 5 × 5 $ZnWO_4$ crystals with a total mass of 200 kg, 5 years of data collection, a software energy threshold of 2 keV, and a condensed framework described in [14],[1] the contemplated experiment can achieve a sensitivity for the cross section at levels of 10^{-5}–10^{-7} pb, depending on the DMp mass and the background level from 10^{-4} to 0.1 cpd/kg/keV (more details in [14]). The estimated counting rate versus the sidereal time and days of the year for a DMp-nucleus subject to elastic scattering with the multidetectors of $ZnWO_4$ anisotropic scintillators is shown in Figure 4. The model takes into account a DMp mass of 10 GeV and a 5×10^{-5} pb cross section on the nucleon (influenced by a spin-independent coupling constant and a fairly straightforward scaling law of the DM-nucleus elastic cross section; see [14] for all the model details).

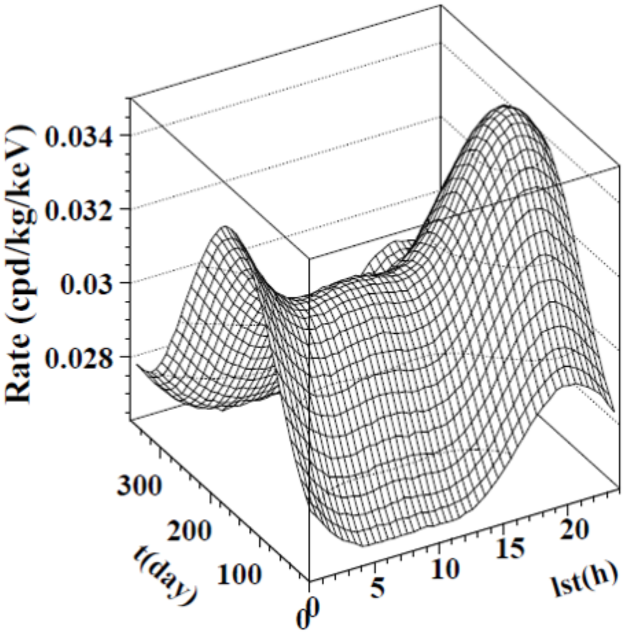

FIGURE 4: The estimated rate versus sidereal time and days of the year in case of a DMp-nucleus elastic scattering by means of 200 kg of a multidetector of 5 × 5 $ZnWO_4$ anisotropic scintillators. The model takes into account a DMp mass of 10 GeV, with a cross section on nucleon of 5×10^{-5} pb. In [14], every aspect of the framework under consideration is meticulously illustrated. The profile of the annual modulation amplitude for a fixed sidereal day is displayed on the plane denoted by the day axes and counting rate axes.

5. CONCLUSIONS

Summarizing, the directionality DM studies may yield additional proof of the existence of DM candidates capable of causing nuclear recoils in the galactic halo and/or provide supplementary data regarding the nature and type of interactions of DMp candidates using a wholly new and different methodology. In order to look at the directionality of DM candidates causing nuclear recoils, anisotropic $ZnWO_4$ detectors show promising features. $ZnWO_4$ crystal scintillators have under-

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[1] In [14], the streamlined model does not take into account the impact of current uncertainty on the values of each assumption and parameter as well as other potential alternatives.

gone substantial R&D in order to achieve very high performance levels. The first evidence of anisotropy for nuclear recoils in the $ZnWO_4$ crystal scintillator's response has been described in [17] in the energy range down to a few hundred keV at a 5.4σ level of confidence.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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