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Feasibility study of a $ZnWO_4$ scintillator for exploiting materials signature in cryogenic WIMP dark matter searches

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Abstract

The mass number dependence of the WIMP–nucleus scattering offers a method for identifying a true WIMP signal over a neutron background. In this Letter we present a study on using a combination of $ZnWO_4$ and $CaWO_4$ absorbers to exploit this materials signature for WIMP detection. Using monochromatic X-ray radiation we examined the temperature variation of the luminescence properties for both materials and showed that at low temperature (8 K) $ZnWO_4$ exhibits $\sim 10\%$ higher light yield than $CaWO_4$. Analysis of relevant optical properties indicates that $ZnWO_4$ is a suitable cryogenic scintillator. We show that already modest exposure in the region of ~ 5 kg yr should allow the detection of WIMP interaction for cross sections at the level of current experimental sensitivities. The combination of these two tungstates could form the basis of the first multi-target detector capable of WIMP identification through materials signature.

1. Introduction

Most modern experiments aiming to detect WIMP dark matter are employing some form of active discrimination between nuclear recoil (the signal) and electron recoil (backgrounds). One of these discrimination techniques, used by CRESST and also ROSEBUD, is event by event discrimination through measuring a combination of phonon and scintillation signals from cryogenic detectors operating at temperatures in the milli-kelvin range [1,2]. The simultaneous detection of phonons and scintillation in dark matter searches, and in particular the use of calcium tungstate ($CaWO_4$) was pioneered by CRESST. A range of commonly available scintillators were tested for their feasibility as scintillating cryogenic detectors [1]. $CaWO_4$, having favourable properties overall, was shown to exhibit excellent discrimination [3].

A high scintillation yield in the milli-kelvin temperature range is a key criterion in the choice of a scintillating absorber in dark matter searches. Other criteria

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involve surface properties, radio purity and phonon propagation properties. $CaWO_4$ appears to be a rather satisfactory choice, providing high light yield at low temperature, and thereby offering good sensitivity for the detection of WIMP–nucleon elastic scattering. The higher the scintillation yield, the lower is the energy threshold for which discrimination between electron and nuclear recoil is possible for a given confidence level. Lower energy threshold translates into less exposure (mass $\times$ time) needed to reach certain levels of cross sections for WIMP–nucleon scattering. The characterization of scintillation materials at very low temperature has not been the mainstream of scintillation studies so far and although many scintillators have been examined at or near room temperature, little information is available at temperatures below that of liquid nitrogen.

$CaWO_4$ is an excellent target material for cryogenic dark matter searches, offering excellent discrimination between nuclear and electron recoil. Nuclear recoils are produced by WIMP scattering, but also by neutron interaction. The various types of events could be distinguished by the dependence of the scintillation yield on the type of recoiling nucleus. It is thus beneficial to have targets with a variety of nuclei, and also targets that are similar with only one nucleus different. This should allow extracting a WIMP signal via the material signature of WIMPs [4]. $ZnWO_4$ is a very interesting material in this regard. It differs from $CaWO_4$ only by having Ca replaced with Zn and the mass number of Zn ($A = 65.41$) is close to that of germanium ($A = 72.64$), thereby making cross calibration with detectors based on germanium easier [5,6].

In this Letter we report on the results of a comparative examination of the luminescence light yield of $ZnWO_4$ and $CaWO_4$ scintillators at low temperature, and present computer simulations on the sensitivity levels for WIMP–nucleon cross sections that could be accessed via a material signature.

2. Comparative characterization of $CaWO_4$ and $ZnWO_4$ scintillators

2.1. Scintillator characteristics at room temperature

An initial assessment of the feasibility of zinc tungstate as scintillating absorber for dark matter searches can be obtained from a comparison of the room-temperature scintillation characteristics of $ZnWO_4$ and $CaWO_4$. These materials have been known for decades as efficient phosphors and scintillators and their scintillation properties have been studied repeatedly [7–11]. Inspection of the data presented in Table 1 shows that $ZnWO_4$ has greater density than $CaWO_4$, meaning that $ZnWO_4$ possesses 19.3% more tungsten nuclei per volume than $CaWO_4$. With the strongest contribution to a signal from WIMP–nucleon scattering expected to involve tungsten nuclei, $ZnWO_4$ is advantageous as having a high density of tungsten nuclei. A further advantage arises from the scintillation emission spectrum, which centres near 480 nm for $ZnWO_4$ and 420 nm for $CaWO_4$. Although the exact position of the peak emission is not critical for the detection of scintillation light with a cryogenic detector (being a spectrally non-selective bolometer), there is an advantage of having the peak intensity at longer wavelength. This results from the fact that the reflectivity of most materials reduces for shorter wavelength. A peak emission of 480 nm is well positioned for many reflectors. $ZnWO_4$ has a longer scintillation time constant than $CaWO_4$ and this is likely to be the case also at low temperature. With photo-multipliers as detectors, this could be a disadvantage; however, the flexibility in design offered by cryo-detectors should allow a perfect match of time constants between scintillator and photon detector [12].

Determining the scintillation yield of a material is crucial in assessing its suitability as a target material; however, there appears to be considerable spread among the experimental results presented by different

Table 1
Comparison of characteristics of the NaI-Tl, $CaWO_4$ and $ZnWO_4$ scintillators at 300 K

Properties	NaI-Tl	$CaWO_4$	$ZnWO_4$
Density, g/cm^3	3.67	6.06	7.87
Light yield[*]	100	16[a] [9]	29[a] [9]
		27[b] [10]	18[b] [10]
			14 [7]
			18 [8]
			28 [11]
Emission peak, nm	415	420	480
Decay time, μs	0.2	9	21
Refractive index	1.85	1.93	2.1

[*] Relative to NaI-Tl; [a] crystal; [b] powder.