ZnWO$_4$ anisotropic scintillator for Dark Matter investigation with the directionality technique

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Signatures for direct detection experiments

In direct detection experiments to provide a Dark Matter signal identification with respect to the background a (model independent) signature is needed

- Model independent annual modulation: annual variation of the interaction rate due to Earth motion around the Sun
  at present the only feasible one, sensitive to many DM candidates and scenarios
  (successfully exploited by DAMA)

- Model independent Diurnal modulation: due to the Earth revolution around its axis
  2\textsuperscript{nd} order effect

- Diurnal variation: daily variation of the interaction rate due to different Earth depth crossed by the Dark Matter particles
  only for high $\sigma$

- Directionality: correlation of Dark Matter impinging direction with Earth's galactic motion
  it holds only for DM particle inducing recoils
In the case of DM particles interacting with nuclei, the direction of the induced nuclear recoil is strongly correlated with that of the impinging DM particle. Therefore, the observation of an anisotropy in the distribution of nuclear recoil direction could give evidence for such candidates.
Directionality sensitive detectors: TPC

- Detection of the tracks’ directions
  ⇒ Low Pressure Time Projection Chamber might be suitable; in fact the range of recoiling nuclei is of the order of mm (while it is \( \sim \mu \) m in solid detectors)

In order to reach a significant sensitivity, a realistic TPC experiment needs e.g.:
  1. extreme operational stability
  2. high radiopurity
  3. large detector size
  4. great spatial resolution
  5. low energy threshold

DRIFT-IIId

Not yet competitive sensitivity

Background dominated by Radon Progeny
Recoils (decay of \(^{222}\text{Rn}\) daughter nuclei, present in the chamber)

NEWAGE
\( \mu\)-PIC (Micro Pixel Chamber) is a two dimensional position sensitive gaseous detector

- Internal radioactive BG restricts the sensitivities
- We are working on to reduce the backgrounds!

DM-TPC

- The “4---Shooter” 18L (6.6 gm)
  TPC 4xCCD, Sea-level@MIT
- moving to WIPP
- Cubic meter funded, design underway
Directionality sensitive detectors: anisotropic scintillators

- Anisotropic Scintillator:
  - **for heavy particles** the light output and the pulse shape depends on the particle impinging direction with respect to the crystal axes
  - **for γ/e** the light output and the pulse shape are isotropic

The variation of the response of an anisotropic scintillator during sidereal day can allow to point out the presence of a DM signal due to candidate inducing nuclear recoils.

- The use of anisotropic scintillators to study the directionality signature was proposed for the first time in refs. [P. Belli et al., Il Nuovo Cim. C 15 (1992) 475; R. Bernabei et al., EPJC28(2003)203], where the case of anthracene was analysed; some preliminary activities have been carried out [N.J.C. Spooner et al, IDM1997 Workshop; Y. Shimizu et al., NIMA496(2003)347]
ZnWO$_4$ crystal scintillators in DAMA project

- Low background ZnWO$_4$ crystal scintillators with large volume and good scintillation properties realized (in collaboration with INR-Kiev)

- Various detectors with mass 0.1-0.7 kg realized by exploiting different materials and techniques

- Detectors installed in a cavity (filled up with high-pure silicon oil) $\phi$ 47 x 59 mm in central part of a polystyrene light-guide 66 mm in diameter and 312 mm in length. The light-guides was faced by 2 low-background PMTs

- Main aim of the measurements was the study of the properties of ZnWO$_4$ and the search for 2$\beta$ processes in Zinc and Tungsten isotopes ($T_{1/2} \sim 10^{18} - 10^{21}$ yr)

<table>
<thead>
<tr>
<th>Crystal scintillator</th>
<th>Size (mm)</th>
<th>Mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZWO-1</td>
<td>20 x 19 x 40</td>
<td>117</td>
</tr>
<tr>
<td>ZWO-2</td>
<td>$\odot$44 x 55</td>
<td>699</td>
</tr>
<tr>
<td>ZWO-2a</td>
<td>$\odot$44 x 14</td>
<td>168</td>
</tr>
</tbody>
</table>
Advantages of the ZnWO$_4$ crystal

- Very good anisotropic features
- High level of radiopurity
- High light output, that is low energy threshold feasible
- High stability in the running conditions
- Sensitivity to small and large mass DM candidate particles
- Detectors with ~ kg masses

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm$^3$)</td>
<td>7.87</td>
</tr>
<tr>
<td>Melting point (°C)</td>
<td>1200</td>
</tr>
<tr>
<td>Structural type</td>
<td>Wolframite</td>
</tr>
<tr>
<td>Cleavage plane</td>
<td>Marked (010)</td>
</tr>
<tr>
<td>Hardness (Mohs)</td>
<td>4–4.5</td>
</tr>
<tr>
<td>Wavelength of emission maximum (nm)</td>
<td>480</td>
</tr>
<tr>
<td>Refractive index</td>
<td>2.1–2.2</td>
</tr>
<tr>
<td>Effective average decay time (µs)</td>
<td>24</td>
</tr>
</tbody>
</table>
Measurements with $\alpha$ particles have shown that the **light response** and the **pulse shape** of a ZnWO$_4$ depend on the impinging direction of $\alpha$ particles with respect to the crystal axes.

**$\alpha/\beta$ ratio**

![Graph showing $\alpha/\beta$ ratio as a function of energy of $\alpha$ particles.](image1)

*Such effects are absent in case of electron excitation.*

(010), (001) and (100) crystal planes correspond to dir. 1, 2 and 3.

**PS parameter**

![Graph showing PS parameter as a function of energy of $\alpha$ particles.](image2)

These anisotropic effects are ascribed to preferred directions of the excitons’ propagation in the crystal lattice affecting the dynamics of the scintillation mechanism.

**Similar effect is expected in the case of low energy nuclear recoils**

$\Rightarrow$ **Dedicated measurements are foreseen in the next weeks**

<table>
<thead>
<tr>
<th>Ion</th>
<th>Quenching factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>dir. 1</td>
</tr>
<tr>
<td>O</td>
<td>0.235</td>
</tr>
<tr>
<td>Zn</td>
<td>0.084</td>
</tr>
<tr>
<td>W</td>
<td>0.058</td>
</tr>
</tbody>
</table>

An energy threshold of 10 keV in an experiment not optimized for the low energy region

Light output and threshold of ZnWO$_4$ crystal scintillator

Improvements of the energy threshold by:

- coupling 2 PMTs in coincidence at single ph.e. level
- decreasing operational temperature
- crystal in silicone oil (light collection improvement $\sim 40\%$)
- using silicon photodiodes, APD, SiPM, etc.
- or with a combination of the previous points

Low-threshold feasible
The dependence of the pulse shapes on the type of irradiation in the ZnWO$_4$ scintillator allows one to discriminate $\beta(\gamma)$ events from those induced by $\alpha$ particles and to identify the $\alpha$ background.

Once provided a suitable separation also at very low energy, PSD could – in principle – gives a 2nd independent but not mandatory way to exploit the directionality approach.
Radiopurity of the ZnWO$_4$ crystal scintillator

The measured radioactive contamination of ZnWO$_4$ approaches that of specially developed low background NaI(Tl):

- $<2$ $\mu$Bq/kg for $^{228}$Th and $^{226}$Ra:
  - $\sim 0.5$ ppt for $^{232}$Th;
  - $\sim 0.2$ ppt for $^{238}$U;
  - $< 0.02$ mBq/kg for $^{40}$K;
  - total $\alpha$ activity of 0.18 mBq/kg

Developments is still ongoing: $\Rightarrow$ future ZnWO$_4$ crystals with higher radiopurity expected
Radiopurity of the ZnWO$_4$ crystal scintillator

Montecarlo calculation for the expected background at low energy considering the measured radiopurity of the developed detectors

- background contribution in the low energy region is $\approx 0.1$ counts/day/kg/keV
- the radiopurity of ZnWO$_4$ is very good, but still not sufficient. Our objective is to reduce by at least one order of magnitude the low energy counting rate due to the intrinsic crystal contamination
Improving radiopurity of ZnWO_4 crystal

• screening of zinc oxide to avoid cosmogenic $^{65}$Zn

• protocol for the purification of the initial zinc (vacuum distillation and filtering) and tungsten (electron beam and zone melting)

• low-thermal gradient Czochralski technique in a platinum crucible (with very good results in producing large size crystals with high radiopurity levels)

• Segregation of radioactive elements (U, Th, Ra, K) expected (very similar compound to CdWO_4) and under investigation; recrystallization could further improve radiopurity level of ZnWO_4

• Detectors cut and assembled just after the growth of the crystalline bulk in a glove-box in controlled atmosphere.

• Selection of tools and abrasives for cutting and polishing the crystals

• Etc.
ZnWO₄ – work in progress...

- Cryostat for low temperature measurement with scintillation detectors realized
- Test of the Cryostat in progress
- Measurements of anisotropy at low energy with neutrons source in preparation
- Lowering the energy threshold (new PMT with higher QE, SiPM, APD, SDD,...)
- Development of electronics
As a consequence of the \textit{light response anisotropy for heavy particles}, recoil nuclei induced by the considered DM candidates could be discriminated from the background thanks to the expected variation of their low energy distribution along the day.

The expected signal counting rate in the energy window \((E_1,E_2)\) is a function of the time \(t\) (\(v_d(t)\) the \textit{detector velocity in the galactic rest frame})

\[
R(E_1,E_2,t) = \int d^3\tilde{v} \int d\Omega_{\text{cm}} \frac{\rho_0 N_n}{m_{\text{DM}}} \left| v + v_d(t) \right| \frac{d\sigma_n}{d\Omega_{\text{cm}}} \frac{1}{2} \left[ \text{erf} \left( \frac{q_n (\Omega_{\text{out}}) E_n - E_1}{\sqrt{2}\Delta} \right) - \text{erf} \left( \frac{q_n (\Omega_{\text{out}}) E_n - E_2}{\sqrt{2}\Delta} \right) \right]
\]

\(R(E_1,E_2,t)\) is the \textit{signal rate in a given scenario}.

**NB:** Many quantities are model dependent and a model framework has to be fixed: in this example, for simplicity, a set of assumptions and of values have been fixed, without considering the effect of the existing uncertainties on each one of them and without considering other possible alternatives.
... the model framework considered here

- a simple spherical isothermal DM halo model with Maxwellian velocity distribution, 220 km/s local velocity, 0.3 GeV/cm³ local density ($\rho_0$) and 650 km/s escape velocity;
- DM with dominant spin-independent coupling and the following scaling law (DM-nucleus elastic cross section, $\sigma_n$, in terms of the DM elastic cross section on a nucleon, $\sigma_p$):

$$\sigma_n = \sigma_p \left( \frac{M_n^{\text{red}}}{M_p^{\text{red}}} \cdot A \right)^2 = \sigma_p \left( \frac{m_p + m_{\text{DM}}}{m_n + m_{\text{DM}}} \cdot \frac{m_n}{m_p} \right)^2$$

- a simple exponential form factor:

$$F_n^2(E_n) = e \left( \frac{E_n}{E_0} \right) = e \left( \frac{3(\hbar c)^2}{2m_n r_0^2} \right)$$

$$E_0 = \frac{3(\hbar c)^2}{2m_n r_0^2}$$

$$r_0 = 0.3 + 0.913m_n$$

### Quenching factor:

$$q_n(\Omega_{\text{out}}) = q_{n,x} \sin^2 \gamma \cos^2 \phi + q_{n,y} \sin^2 \gamma \sin^2 \phi + q_{n,z} \cos^2 \gamma$$

where $q_{n,i}$ is the quenching factor value for a given nucleus, $n$, with respect to the $i$-th axis of the anisotropic crystal and $\Omega_{\text{out}} = (\gamma, \phi)$ is the output direction of the nuclear recoil in the laboratory frame $q_{n,i}$ have been calculated following ref. [V.I. Tretyak, Astropart. Phys. 33 (2010) 40] considering the data of the anisotropy to $\alpha$ particles of the ZnWO₄ crystal

### Energy resolution:

$$\text{FWHM} = 2.4 \sqrt{E(keV)}$$
Example of expected signal rate in the given scenario

Signal rate in [2-3] keV energy range with $\xi \sigma_p = 5 \times 10^{-5} \text{ pb}$

- Maximum rate at 21 h sidereal time of LNGS, when the DM preferential arrival direction is near the zenith, that is near the crystal axis with the largest light output.

- Analogous results can be obtained also analysing the anisotropic behaviour of the pulse shape of scintillation events.

The signature is very distinctive and cannot be mimicked by background
Example of expected signal

Expected rate as a function of sideral time and days of the year

[2-3] keV $\sigma_p = 5 \times 10^{-5}$ pb

$m_{DM} = 10$ GeV

[6-7] keV $\sigma_p = 5 \times 10^{-5}$ pb

$m_{DM} = 100$ GeV

- Identical sets of crystals placed in the same set-up with different axis orientation will observe consistently different time evolution of the rate
- The diurnal effect will refer to the sidereal day and not to the solar day
Example of the reachable sensitivity calculated considering the above mentioned simplified model framework for an experiment with:

- 200 kg of ZnWO$_4$
- 5 years of data taking
- four possible time independent background levels in the low energy region:
  - $10^{-4}$ cpd/kg/keV
  - $10^{-3}$ cpd/kg/keV
  - $10^{-2}$ cpd/kg/keV
  - 0.1 cpd/kg/keV

The directionality approach can reach in the given scenario a sensitivity to the cross section at level of $10^{-5} - 10^{-7}$ pb, depending on the particle mass.

For comparison, there are also shown (green, red and blue) allowed regions obtained with a corollary analysis of the 9.3$\sigma$ C.L. DAMA model independent result in terms of scenarios for the DM candidates considered here.
Conclusions

- Anisotropic ZnWO$_4$ detectors are promising detectors to investigate the directionality for DM candidates inducing nuclear recoils.

- These detectors could permit to reach - in some given scenarios - sensitivity comparable to that of the DAMA/LIBRA positive model independent results.

- Such an experiment can obtain, with a completely different new approach, further evidence for the presence of some DM candidates in the galactic halo and provide complementary information on the nature and interaction type of the DM candidate.