New target materials for scintillating bolometers

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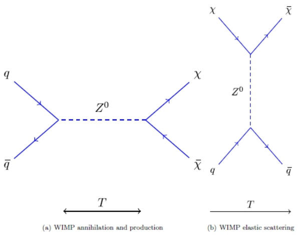
Application of scintillating bolometers

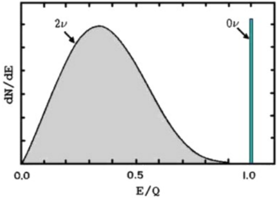
Scintillating bolometers offer:

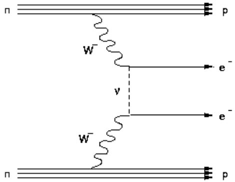
- detection of scattering events with very small recoil energies (keV)
- powerful background rejection
- rare event identification

Physical applications:

- rare radioactive decays
- Neutrinoless Double Beta Decay
- Direct Dark Matter detection

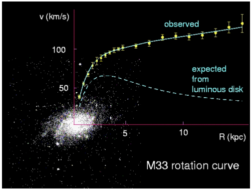


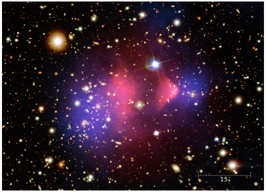


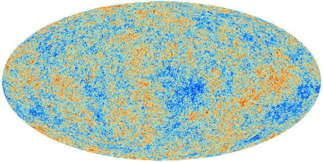


Dark Matter

- Hints for the existence of Dark Matter on all cosmic scales (rotation velocity of galaxies and clusters, Bulletcluster, CMB)
- Verification and characterisation of Dark Matter can be achieved by the direct detection
- A well motivated candidate is the Lightest Supersymmetric Particle (LSP) also called WIMP (weakly interacting massive particle) (mass 10-100 GeV, cross section $< 10^{-44} cm^2$)





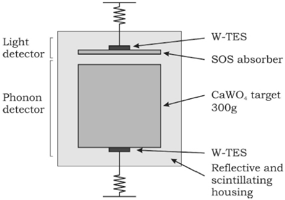


$=>$ assumption for the direct detection of Dark Matter:
elastic coherent WIMP-nucleus scattering

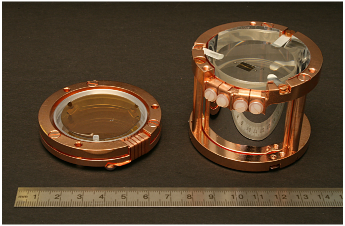
Scintillating bolometers: working principle

- Energy deposition in the absorbing scintillator crystal produces phonons (heat) and photons (light) => two channel readout
- Due to the small heat capacity ($\propto T^3$) even small energy depositions (< 10 keV) trigger a measureable temperature increase
- Light emission depends on the interacting parcticle (α, β, γ or neutron) => quenching factors

CRESST collaboration uses scintillating bolometers for the direct Dark Matter detection



scheme of the CRESST-II design

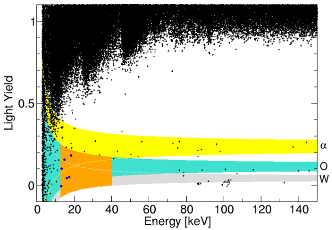


CRESST-II module with a $CaWO_4$ target

Scintillating bolometers: limiting factors

Limitations:

- phonon channel performance is superior to the light channel performance ($<$ 2-3% of the deposited energy is detected in the light channel)
- improvement of the light channel leads to narrower bands in the light yield scatterplotts $=>$ better event discrimination in the low energy region



Light yield scatterplot of last CRESST-II run

$$LY = \frac{\text{light signal}}{\text{phonon signal}}$$

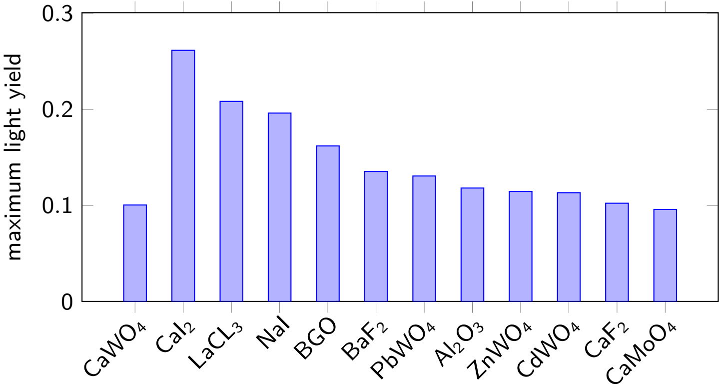
Improvements of the light channel:

- light detector efficiency
- absolute light yield of the target material (scintillation efficiency, refractive index, geometry...)

Light yield calculation for scintillating crystals

- formula for the calculation of the scintillation efficiency (semi-empirical model) at low temperatures [2][Rodnyi, P. A. et al, 1995][3][Mikailik, V. B. et al, 2010]:

$$\eta = \frac{E_{em}}{2.35 \cdot E_G} \left[1 + 0.158 \cdot 10^4 \cdot \left(\frac{1}{\epsilon_\infty} - \frac{1}{\epsilon_{stat}} \right) \cdot \frac{[\hbar\omega_{LO}]^{3/2}}{1.5 \cdot E_G} \right]^{-1} \cdot S \cdot Q$$



Performance estimates with Monte-Carlo simulations

Step 1: Influence of the light yield on the performance

- a recoil event with a target nucleon A with a given energy produces a Poisson distributed number of photons in the scintillator:

$$P_n(\lambda) = \frac{\lambda^n}{n!} \cdot exp(-\lambda) \text{ with } \lambda = absLY \cdot QF_A \cdot E_{rec}/E_{em} \quad (1)$$

- each number of photons produce a Gaussian distributed response of the light detector:

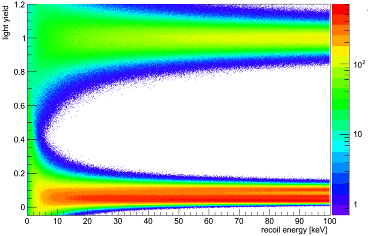
$$E_{det,L} = \frac{1}{\sqrt{2\Pi} \cdot \sigma_0} \cdot exp\left(-\frac{1}{2}\frac{E^2 - (n_A \cdot E_{em})^2}{\sigma_0^2}\right) \text{ and } LY_A = \frac{E_{det,L}}{E_{rec} \cdot \text{absLY}} \quad (2)$$

- light detector resolution: $6.0 \cdot 10^{-3}$ keV (the best value of CRESST-II), quenching factors are taken from [4][Huff, P., 2010], for the absolute light yield see above

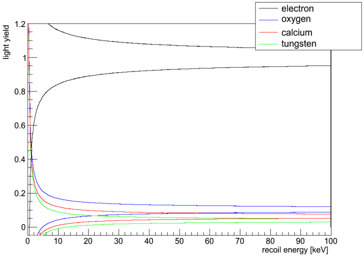
Step 2: Simulation of the dector response of a standard WIMP signal (M_W=60 GeV, $\sigma_W = 1 \cdot 10^{-44} cm^2$):

- expected number of WIMP-scatterings/events in the ROI is calculated individually for each nucleon
- for each event the (phonon) energy and the light yield is simulated

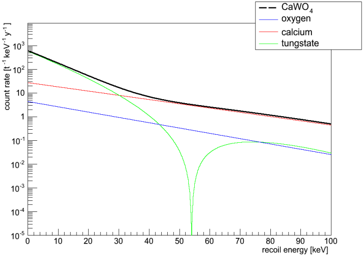
MC Simulation $CaWO_4$



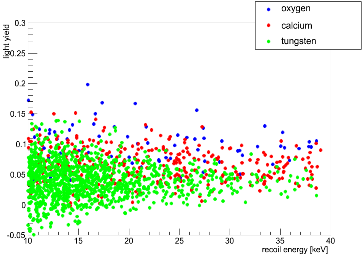
LY scatterplot for $CaWO_4$ with an uniform energy distribution



Recoil bands (80% C.L.)

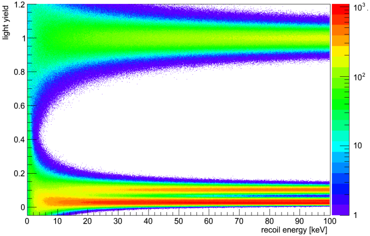


WIMP countrate for $CaWO_4$: 1488 events in ROI

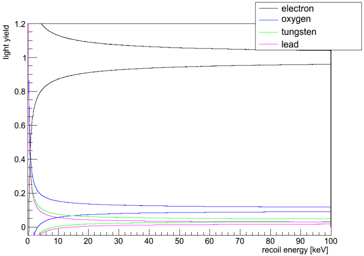


expected WIMP signature in the ROI

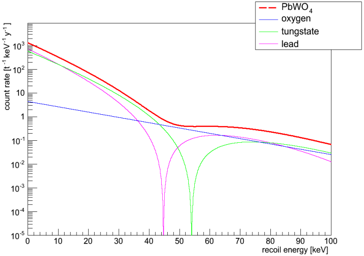
MC Simulation $PbWO_4$



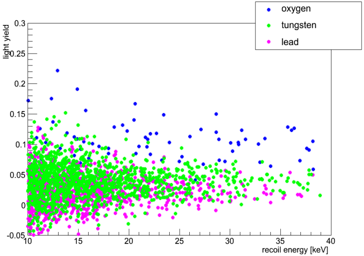
LY scatterplot for $PbWO_4$ with an uniform energy distribution



Recoil bands (80% C.L.)

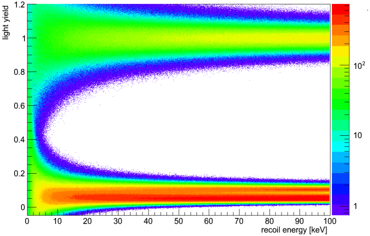


WIMP countrate for $PbWO_4$: 2137 events in RIO

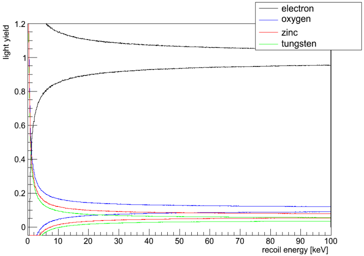


expected WIMP signature in the RIO

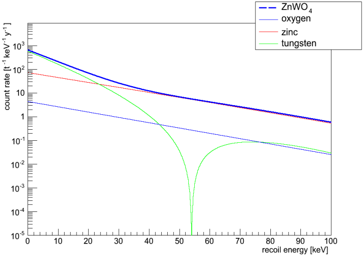
MC Simulation ZnWO$_4$



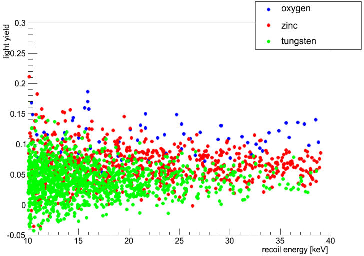
LY scatterplot for ZnWO$_4$ with a uniform energy distribution



Recoil bands (80% C.L.)

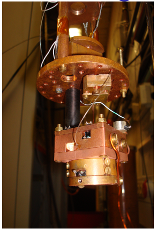


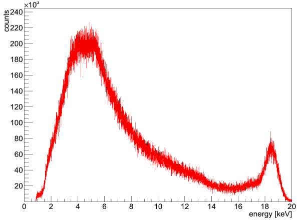
WIMP countrate for ZnWO$_4$: 1894 events in ROI



expected WIMP signature in the RIO

Measurement of the light yield at mK temperatures



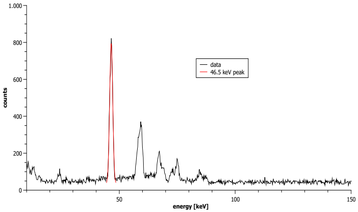


^{137}Cs spectra in $CaWO_4$

material	light yield
$CaWO_4$	0.0264 ± 0.0013
$PbWO_4$	0.0049 ± 0.0006

results of the low temperature light yield measurements

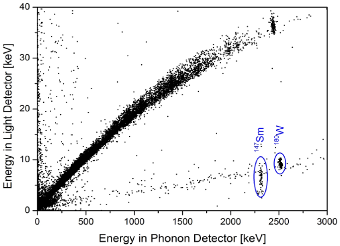
- Verification of ligth yield calculation of the investigated materials ($CaWO_4$ and $PbWO_4$)
- =>construction of detector for crystal samples (20mm x 5 mm)
- evaluation of the internal radioactivity of the $PbWO_4$ sample
  => ^{210}Pb contamination 1,2kBq/kg (LoAx Germanium spectroscopy)
- poor light yield compared to $CaWO_4$
- => further investigation is feasible if the crystal sample is cleaner (e.g. Roman lead)

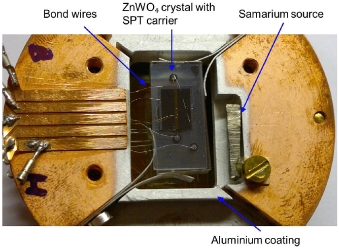


Gammaspectroscopy of $PbWO_4$

$ZnWO_4$ surface investigation

- one module with $ZnWO_4$ was tested in the last CRESST-II run
- low temperature light yield compatible with $CaWO_4$ [5][Kraus, H. et al, 2005][6][Bavykina, I. ,2009]
- radiopurity is expected to be better compared to $CaWO_4$
- unexpected detector feature: leakage of the ^{147}Sm α-line to low light signal events





- possible explanation of the phenomenom : surface contamination with ^{147}Sm and surface dependency of the light yield

→ measurements of $ZnWO_4$ samples with different surface treatments (diamond-polished, HCl,..) will start soon

Summary and outlook

- new target materials can improve the performance of scintillating bolometers by increasing the light yield and the statistics
- new target materials offer better statistics for new parameter space (e.g. low mass WIMPs < 10 GeV)
- new target materials offer new approaches to other fields of physics (e.g. neutrinoless double beta decay)

Thank you for your attention!

Bibliography

[1] Angloher, G. et. al., Springer-Verlag (2012), Results from 730 kg/days of the CRESST-II Dark Matter search, The European Physical Journal C, 72(4): 1-22, doi: 10.1140/epjc/s10052-012-1971-8

[2] Rodnyi, P. A., Dorenbos, P. and van Eijk, C. W. E. (1995), Energy Loss in Inorganic Scintillators., Phys. Status Solidi B, 187: 15-29., doi: 10.1002/pssb.2221870102

[3] Mikhailik, V. B. and Kraus, H. (2010), Performance of scintillation materials at cryogenic temperatures. Phys. Status Solidi B, 247: 1583Ű1599. doi: 10.1002/pssb.200945500

[4] Huff, P., PhD. (2010) The Detector Parameters Determining the Sensitivity of the CRESST-II Experiment

[5] H. Kraus and V.B. Mikhailik and Y. Ramachers and D. Day and K.B. Hutton and J. Telfer (2005) Feasibility study of a ZnWO4 scintillator for exploiting materials signature in cryogenic {WIMP} dark matter searches, Physics Letters B 1-2 ,610: 37 - 44,

[6] Bavykina, I., PhD. (2009), Investigation of ZnWO4 and CaMoO4 as Target Materials for the CRESST-II Dark Matter Search