Impact of Coherent Neutrino Nucleus Scattering on Direct Dark Matter Searches based on CaWO$_4$ Crystals

A. Gütlein,$^1$ G. Angloher,$^2$ A. Bento,$^3$ C. Bucci,$^4$ L. Canonica,$^4$ A. Erb,$^5,^6$ F. v. Feilitzsch,$^5$ N. Ferreiro Iachellini,$^2$ P. Gorla,$^4$ D. Hauff,$^2$ J. Jochum,$^7$ M. Kiefer,$^2$ H. Kluck,$^1$ H. Kraus,$^8$ J.-C. Lanfranchi,$^5$ J. Loebell,$^7$ A. Münster,$^5$ F. Petricia,$^2$ W. Potzel,$^5$ F. Pröbst,$^2$ F. Reindl,$^2$ S. Roth,$^5$ K. Rottler,$^7$ C. Sailer,$^7$ K. Schäffner,$^4$ J. Schieck,$^1$ S. Schöner,$^5$ W. Seidel,$^2$ M. v. Sivers,$^5$ L. Stodolsky,$^2$ C. Strandhagen,$^7$ R. Strauss,$^2$ A. Tanzke,$^2$ M. Uffinger,$^7$ A. Ulrich,$^7$ I. Usharov,$^7$ S. Wawoczny,$^5$ M. Willers,$^5$ M. Wüstreich,$^2$ and A. Zöller$^5$

$^1$Institut für Hochenergiephysik der Österreichischen Akademie der Wissenschaften, A-1050 Wien, Austria
$^2$Max-Planck-Institut für Physik, D-80805 München, Germany
$^3$Departamento de Física, Universidade de Coimbra, P3004 516 Coimbra, Portugal
$^4$INFN, Laboratori Nazionali del Gran Sasso, I-67010 Assergi, Italy
$^5$Physik-Department, Technische Universität München, D-85747 Garching, Germany
$^6$Walther-Meißner-Institut für Tieftemperaturforschung, D-85748 Garching, Germany
$^7$Eberhard-Karls-Universität Tübingen, D-72076 Tübingen, Germany
$^8$Department of Physics, University of Oxford, Oxford OX1 3RH, United Kingdom

Atmospheric and solar neutrinos scattering coherently off target nuclei could be a serious background source for the next generation of direct dark matter searches. We present our studies on the maximal sensitivity on the elastic spin-independent WIMP-nucleon cross section which can be achieved by a background-free experiment based on calcium tungstate as target material. An experiment achieves this maximal sensitivity when one neutrino event is expected for the experiment’s energy threshold and exposure. Thus, a first detection of coherent neutrino nucleus scattering (CNNS) could also be in reach of such an experiment, if neutron-like backgrounds are small enough ($\lesssim 0.1$ events for the respective exposures). Due to the small energies of solar neutrinos, calcium tungstate with its light nuclei oxygen and calcium seems to be well suited for a detection of CNNS. We show that for a counting experiment using only the integral above an energy threshold as well as a Bayesian analysis taking into account spectral shapes a detection of CNNS on a $3\sigma$ confidence level is possible for exposures between 50 and 300 kg-years.

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I. INTRODUCTION

The dynamics of galaxies and galaxy clusters [1,2] give strong hints for the existence of dark matter. The precise measurements of the temperature fluctuations of the cosmic microwave background are well described by a contribution of $\sim 27\%$ [3] of cold dark matter to the overall energy density of the universe. However, the nature of dark matter remains unclear. Direct dark matter searches [3,11] aim at a detection of Weakly Interacting Massive Particles (WIMPs) [1,2] scattering off nuclei.

WIMPs are expected to scatter mainly off nuclei while the majority of the background interacts with electrons. Most direct dark matter searches are able to discriminate between electron and nuclear recoils [5,9] using the simultaneous measurement of two different signals generated in the detector material for each particle interaction.

In this work we focus on low-temperature detectors based on calcium tungstate (CaWO$_4$) crystals as those currently operated in the CRESST-II experiment [12,13]. These scintillating crystals generate different amounts of scintillation light for different types of interaction allowing a discrimination between electron and nuclear recoils on an event-by-event basis via the simultaneous measurement of scintillation-light and heat signals generated by the interaction of an incident particle [12,13]. Therefore, a CRESST-II detector module consists of a CaWO$_4$-based low-temperature detector measuring the heat signal generated by the incident particle, and a separate low-temperature light detector based on a silicon-on-sapphire absorber measuring the scintillation light.

II. NEUTRINO BACKGROUND

Coherent neutrino nucleus scattering (CNNS) [14] is a neutral current process of the weak interaction where a neutrino scatters elastically off a target nucleus via the exchange of a virtual Z$^0$ boson. For small transferred momenta the wave length of the Z$^0$ is comparable to the diameter of the nucleus. Thus, the neutrino scatters coherently off all nucleons.

Neutrinos scattering coherently off nuclei in the detector mimic WIMP scatterings. Thus, atmospheric and solar neutrinos could be a serious background source. This

*corresponding author, achim.guettein@oeaw.ac.at
neutrino background and its limitation for the sensitivities of direct dark matter searches have been studied in great detail during the last years [15,20].

As can be seen in FIG. 1 the neutrino limits are 3 to 4 orders of magnitude below the current exclusion limits. However, the next generation of direct dark matter searches with larger target masses and better detector performances could reach sensitivities where neutrino backgrounds have to be taken into account. Thus, these experiments could also be able to observe coherent neutrino nucleus scattering (CNNS) for the first time.

| Material | 1 keV | 2 keV | 3 keV | 5 keV | 10 keV |
|----------|-------|-------|-------|-------|--------|
| Ge       | 42.66 | 10.86 | 2.18  | 3.06 \cdot 10^{-2} | 5.95 \cdot 10^{-3} |
| Xe       | 28.48 | 1.41  | 2.88 \cdot 10^{-2} | 8.92 \cdot 10^{-3} | 6.30 \cdot 10^{-3} |
| CaWO₄    | 17.33 | 5.40  | 3.49  | 1.62  | 0.32   |

TABLE I. Expected numbers of nuclear recoil events due to CNNS of atmospheric and solar neutrinos above different nuclear recoil-energy thresholds $E_{thr}$ for an exposure of 300 kg-years.

To estimate the sensitivity of different target materials we calculate the expected number of CNNS events above a certain nuclear recoil-energy threshold $E_{thr}$ for CaWO₄, Ge, and Xe (see TABLE I) for an exposure of 300 kg-years. The thresholds $E_{thr}$ in TABLE I are the nuclear recoil-energy thresholds where nuclear and electron recoils are well separated and, thus, only very few background events are expected above those thresholds. Because of the small energies of solar neutrinos the expected recoil energies are also very small. However, due to the light oxygen and calcium nuclei solar neutrinos are leading to higher recoil energies in CaWO₄ compared to Ge or Xe. Thus, with a threshold of $E_{thr} \lesssim 5$ keV an experiment based on CaWO₄ detectors would have the potential for a detection of CNNS events. For Ge and Xe the threshold has to be lower (3 keV and 2 keV, respectively).

In addition to a small energy threshold and a very good suppression of beta and gamma backgrounds, it is crucial for the detection of CNNS that no significant ($\lesssim 0.01$ events for the experiment’s exposures) backgrounds (e.g., neutrons) are observed in the nuclear recoil bands, i.e., the regions where nuclear recoils are expected.

The current CaWO₄-based detectors used in the CRESST-II experiment show a good performance leading to the best sensitivity for WIMP masses below $\sim 3$ GeV [5]. However, the suppression of beta and gamma backgrounds in the nuclear-recoil bands has to be improved for a potential detection of CNNS. Our studies show that with the following improvements on the already achieved detector performance a detection of CNNS could be in reach for the next generation of CaWO₄ experiments:

- Beta and gamma background reduced by a factor of 50 reaching $\lesssim 0.1$ keV$^{-1}$kg$^{-1}$day$^{-1}$
• Energy threshold and resolution of the light detector improved by a factor of 2

• Amount of detected scintillation light increased by a factor of 2

With the improvements in energy resolution and detected scintillation light the light-yield resolution is improved by a factor of 4. The light yield is defined as the ratio of the measured scintillation light and recoil energy. For gammas with energies of 122 keV the light yield is normalized to 1\(^{-1}\). The light yield is essential to discriminate between electron and nuclear recoil events. Thus, an improved light-yield resolution leads to an additional improvement of the background level in the nuclear recoil band.

![Energy spectra of beta and gamma background (red, dashed) and CNNS signal (blue, solid) in the nuclear recoil band.](image)

**FIG. 2.** (Color online) Energy spectra of beta and gamma background (red, dashed) as well as neutrino signal (blue, solid) in the nuclear recoil band of CaWO\(_4\) detectors with an improved performance compared to the current CRESST detectors\[5\]. For energies \(\gtrsim 3\) keV the expected neutrino signal is higher than the expected background level. This requires that other background sources (e.g. neutrons) can be neglected also for large exposures.

**A. Counting experiment**

One way to claim a signal detection is to reject the background-only hypothesis. In a simplified approach we only use the number of events above an energy threshold (counting experiment). Also the uncertainties of background and CNNS rates are neglected in this approach. The results of a more detailed analysis taking into account the different spectral shapes and uncertainties of signal and background can be found in section\[III B\].

For a counting experiment the background-only hypothesis is rejected if the observed number of events \(k_0\) is inconsistent with the Poisson distributed number of background events. This number \(k_0\) can be determined using:

\[
P_{cl} = P_{\lambda_{Bg}}(k < k_0) = \sum_{k=0}^{k_0-1} \frac{\lambda_{Bg}^k}{k!} e^{-\lambda_{Bg}}
\]

where \(P_{cl}\) is the chosen confidence level for the rejection of the background-only hypothesis and \(\lambda_{Bg}\) is the expected number of background events above an energy threshold \(E_{thr}\), i.e., the integral over the red spectrum in FIG 2. For a detection of CNNS at a 3\(\sigma\) confidence level the number \(k_0\) of observed events has to be large enough to reach a confidence level of \(P_{cl} \geq 99.9\%\).

The detection potential \(P_{det}\) is the probability that at least \(k_0\) events determined with equation (1) are observed for an expected number \(\lambda_{Bg}\) of background and \(\lambda_{Sig}\) signal events:

\[
P_{det} = P_{\lambda_{Bg}+\lambda_{Sig}}(k \geq k_0) = 1 - \sum_{k=0}^{k_0-1} \frac{(\lambda_{Bg} + \lambda_{Sig})^k}{k!} e^{-(\lambda_{Bg} + \lambda_{Sig})}
\]

The detection potential \(P_{det}\) for exposures of 50 (blue, dashed) and 300 kg-years (red, solid) is depicted in the top panel of FIG. 3 for different nuclear recoil-energy thresholds between 1 and 20 keV for a detection of CNNS at a confidence level of \(P_{cl} \geq 99.9\%\). The steps in both lines are due to the discrete nature of the Poisson distribution. The steps occur when the number of events \(k_0\) (shown in the bottom panel of FIG. 3), required to reject the background-only hypothesis, changes. The dotted vertical lines indicate some of these changes. For both exposures shown in FIG. 3 (50 and 300 kg-years) a detection of CNNS at a 3\(\sigma\) confidence level might be possible with probabilities \(P_{det}\) of \(\sim 16\%\) and \(\sim 54\%\), respectively.

Thus, the detection of coherent neutrino nucleus scattering could be in reach for the next generation of direct dark matter searches based on CaWO\(_4\) as target material, if it is possible to achieve the improved detector performance assumed for this work. In addition, due to the small number of events \((k_0 = 1)\) it is crucial that all backgrounds in the nuclear recoil band are well known and small enough \((\lesssim 0.01\) events\) in the energy range between 1 and 20 keV.
In this section we show the results of a more detailed study where we performed Bayesian fits of a background-only model as well as a model containing signal and background to simulated spectra.

For Bayesian fits the posterior probability density function (PDF) $P(\text{Model}|\text{Data})$, i.e., the (conditional) probability that a model with its parameters describes the measured data is maximized. For both models the posterior PDFs are given by Bayes’ theorem [18, 25]:

$$P(B, S|\text{Data}) = \frac{p(\text{Data}|B, S)p_0(B)p_0(S)}{P(Bg + Sig)}$$ (3)

$$P(B|\text{Data}) = \frac{p(\text{Data}|B, S = 0)p_0(B)}{P(Bg)}$$ (4)

$$P(Bg + Sig) = \int p(\text{Data}|B, S)p_0(B)p_0(S)dBdS$$

$$P(Bg) = \int p(\text{Data}|B, S = 0)p_0(B)dB$$

where $B$ and $S$ are the number of background and neutrino events, respectively, $p(\text{Data}|B, S)$ is the likelihood that a spectrum as the measured data occurs if the model is correct and $B$ and $S$ are the true event numbers, $p_0(B)$ and $p_0(S)$ are the prior probabilities for the number of background and neutrino events, respectively. The normalizations $P(Bg + Sig)$ and $P(Bg)$ are used for model comparison.

In a first step an energy spectrum is simulated using the spectra shown in FIG. 2 and assuming an energy threshold of $\sim 1$ keV. Both, a model containing neutrino signal and background as well as a background-only model are fitted to this simulated spectrum using equations (3) and (4). For the fits of both models we used a normal distribution with a width of 10% for the prior probability $p_0(B)$ to account for the uncertainty in the background rate. For the prior probability $p_0(S)$ a uniform distribution was used to account for the fact that CNNS has never been observed and, thus, any neutrino event number is equally likely (including no CNNS signal). By Bayesian model comparison the probability that the background-only hypothesis is true can be calculated:

$$P(Bg \text{ only}|\text{Data}) = \frac{\frac{1}{2}P(Bg)}{\frac{1}{2}P(Bg) + \frac{1}{2}P(Bg + Sig)}$$ (5)

where the factor $\frac{1}{2}$ is used for the prior probabilities of both models. The confidence level for a detection of CNNS is given by $1 - P(Bg \text{ only}|\text{Data})$.

To estimate the probability for a detection of CNNS at a confidence level of 99.9% (3σ effect) we repeated the procedure described above 4000 times for each exposure. The result of these studies is similar to the result of the simple approach discussed in section III. The probability for a detection of CNNS at a 99.9% confidence level is $\sim 60\%$ for an exposure of 300 kg-years and $\sim 12\%$ for an exposure of 50 kg-years, respectively. In addition, we simulated 4000 spectra without neutrino signal for both exposures. No false detection of CNNS occurred in these background-only spectra.

In principle one could expect that this method achieves a better sensitivity since it takes the different spectral shapes of background and neutrino signal into account. However, this improvement is compensated by the uncertainties on background and neutrino event-rate which are included in the fit via the prior probabilities $p_0(B)$ and $p_0(S)$, respectively.

IV. CONCLUSIONS

In this work we studied the impact of coherent neutrino nucleus scattering (CNNS) of atmospheric and solar neutrinos on direct dark matter searches, especially those based on CaWO$_4$. In the first part we calculated the maximum sensitivity on the elastic spin-independent WIMP-nucleon cross section which can be achieved with a background-free experiment based on CaWO$_4$ (see section II). We compared this sensitivity with current sensitivities as well as the maximum sensitivities of Ge and Xe (see FIG. 1). For the next generation of direct dark matter searches, CNNS could become a serious background source limiting the achievable sensitivities.

Due to the small energies of solar neutrinos and the light oxygen and calcium nuclei, CaWO$_4$ seems to be suitable for a detection of CNNS. Thus, we calculated the probability for a detection of CNNS for direct dark matter searches based on CaWO$_4$ as target material under the assumption of negligible neutron-like backgrounds. Our studies show that with an improved detector performance compared to the current performance of the
CRESST experiment a detection of CNNS might be in reach for exposures of 50 to 300 kg-years.

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