



Accurate Calibration of Nuclear Recoils at the 100 eV Scale Using Neutron Capture

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Received: 1 November 2021 / Accepted: 29 June 2022 / Published online: 5 September 2022
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Abstract

Searches for light dark matter (DM) and studies of coherent elastic neutrino-nucleus scattering (CEvNS) imply the detection of nuclear recoils in the 100 eV range. However, an absolute energy calibration in this regime is still missing. The CRAB project proposes a method based on nuclear recoils induced by the emission of an MeV gamma following thermal neutron capture. A detailed feasibility study has shown that this method yields distinct nuclear recoil calibration peaks at 112 eV and 160 eV above background for tungsten. In the first phase, the CRAB project foresees to perform a nuclear recoil calibration of cryogenic CaWO_4 detectors read-out by TES, similar to the detectors used in CRESST and NUCLEUS. The low-power TRIGA reactor in Vienna provides a clean beam of thermal neutrons well suited for such a measurement. Newly developed and compact sub-keV calibration sources based on x-ray fluorescence (XRF) provide an absolute energy calibration during operation at the research reactor as well as in the DM/CEvNS experiments. In the second phase, additional tagging of the photons produced in the de-excitation process will allow extending the calibration method to even lower energies and to a wider range of detector materials, such as Ge. Combined with the XRF source, CRAB may allow measuring energy quenching in the sub-keV regime.

Keywords Calibration techniques · Neutron capture · Sub-keV · Dark matter · CEvNS

1 Dark Matter Search and Neutrino Physics with Low-Threshold Cryogenic Detectors

Direct dark matter (DM) searches and studies of coherent elastic neutrino-nucleus scattering (CEvNS) offer a high potential to search for new physics. To understand the nature of Dark Matter, a large number of experiments based on different

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technologies are currently searching for the elastic scattering of DM particles. The probed mass range spans from several $100 \text{ MeV}/c^2$ to TeV/c^2 [1]. CEvNS offers the possibility for a precision measurement of the weak neutral current, and thus, allows searching e.g., for new neutrino-quark couplings [2]. Similarly to direct DM, many different experiments dedicated to studying CEvNS have been started in the past few years or are being planned.

The signature in direct DM and CEvNS experiments is a nuclear recoil induced by the elastic scattering of a DM particle or a neutrino on a nucleus. In both cases, the resulting differential recoil spectrum is featureless and decreases sharply toward higher energies. Thus, the number of detected events greatly depends on the achieved energy threshold. For DM searches, the detection threshold limits the sensitivity to low mass DM particles, whereas in the case of CEvNS, the neutrino energies which can be probed depends on the energy threshold.

Only recently, developments in cryogenic detectors have made nuclear recoil energies of a few tens of eV accessible and are being used in ongoing or future low mass DM and CEvNS experiments. Due to extremely low energy thresholds of $O(\leq 100 \text{ eV})$, cryogenic detectors are leading in the field of direct DM searches at masses below $\sim 1 \text{ GeV}/c^2$. While CEvNS of higher energy neutrinos (up to 53 MeV) has been observed [3, 4], the same scattering process of reactor neutrinos with energies below 8 MeV remains unobserved. Cryogenic detectors with thresholds of $O(< 100 \text{ eV})$ will allow studying CEvNS of reactor neutrinos of a few MeV for the first time.

A prerequisite to search for new physics in this new energy regime, is a thorough understanding of the detector response. Especially for low-threshold cryogenic detectors, this implies a major challenge due to the lack of electronic and nuclear recoil calibration sources at sub-keV energies. The response at higher energies is well understood: the energy dissipation follows a collision cascade in which secondary recoils and high-energy electrons are created. The former may create defects in the crystal structure, if the (secondary) recoil overcomes the lattice dislocation energy of $O(25 \text{ eV})$. Most of the dislocation energy will be dissipated into phonons again, however, typically $O(\text{few eV})$ will be stored in the final defect configuration and will be lost to the measurement. As we approach nuclear recoils of a few 100 eV , the hit nuclei stay in their lattice position, followed by a pure phononic excitation. Furthermore, as the threshold energy for displacement highly depends on the crystal lattice, such low energy nuclear recoils can be sensitive to the direction of the recoil. A broad spectrum of sub-keV nuclear calibration lines, in combination with electron recoils will allow to study the impact of energy loss by lattice defects.

In addition, measuring the quenching factor (QF), i.e., the fraction of energy loss dissipated to electrons, is of large interest. The Lindhard model [5] describes well the translation of the measured electron signal to the initial nuclear recoil at high energies. However, it deviates from measurements in the sub-keV range. Both, detectors with a pure ionization read-out such as semiconductor detectors, as well as cryogenic detectors exploring the Neganov–Trofimov–Luke (NTL) effect suffer from this limitation. Recently, there is a large interest in measuring the QF as it limits current low mass DM and CEvNS experiments. The CONUS collaboration e.g., measured the QF of germanium down to nuclear recoil energies of 0.4 keV [6].

However, it is important to conduct measurements at even lower energies. Especially, a possible cutoff in the energy dissipated to electrons needs to be investigated [7].

The CRAB (Calibrated Recoils for Accurate Bolometry) project proposes a new method for a direct and model independent calibration of nuclear recoils of O(100 eV). The calibration technique is described in full detail in Ref. [8].

2 A Precise Calibration of O(100 eV) Nuclear Recoils with CRAB

2.1 The Method

A nucleus which captures a thermal neutron (25 meV) creates a compound nucleus in an excited state close to the neutron separation energy, S_n . This energy is typically of the order of a few MeV and the de-excitation to the ground state occurs via the emission of γ -rays and conversion electrons. In most of the cases, this happens via a cascade. However, the nucleus may also de-excite directly to the ground state via a single- γ transition. In such a case, the nucleus experiences a nuclear recoil with a kinetic energy $T = \frac{E_\gamma^2}{2m_N}$. The high MeV γ -ray easily escapes the detection in a cm-size detector. Thus, for sufficiently small detectors, a nuclear recoil induced by the single- γ transition gives a mono-energetic calibration peak, homogeneously distributed in the detector volume.

Key parameters for suitable isotopes are a high natural abundance Y_{ab} , a large neutron capture cross section $\sigma_{n,\gamma}$, and a high branching ratio for the single- γ transition, I_γ^S . Table 1 summarizes the most promising isotopes for tungsten and germanium, both elements are widely used in low-threshold cryogenic experiments:

Table 1 Summary of the most promising isotopes of tungsten and germanium

Target nucleus (A)			Compound nucleus (A+1)		
Isotope	Y_{ab} (%)	$\sigma_{n,\gamma}$ (barn)	I_γ^S (%)	S_n (keV)	E_R (eV)
^{182}W	26.50	20.32	13.94	6191	112.5
^{183}W	14.31	9.87	5.83	7411	160.3
^{186}W	28.43	37.89	0.26	5467	85.8
^{70}Ge	20.53	3.05	1.95	7416	416.2
^{73}Ge	7.76	14.70	–	10,196	754.9
^{74}Ge	36.52	0.52	2.83	6506	303.2

Key properties of the target nuclei are a high natural abundance (Y_{ab}) and a large neutron capture cross section ($\sigma_{n,\gamma}$), as well as a high branching ratio for the single- γ transition (I_γ^S) of the compound target. The neutron separation energy (S_n) is the highest available γ energy, E_R denotes the observable nuclear recoil induced by a single- γ transition. The single γ -transition of ^{73}Ge has not been observed so far

the low mass DM experiment CRESST [9] and the future reactor neutrino CEvNS experiment NUCLEUS [10] use CaWO_4 crystals, while germanium is used e.g., by EDELWEISS [11] and SuperCDMS [12] to search for DM, or MINER [13] and Ricochet [14] aiming to study CEvNS.

2.2 Feasibility Study for Application on CaWO_4

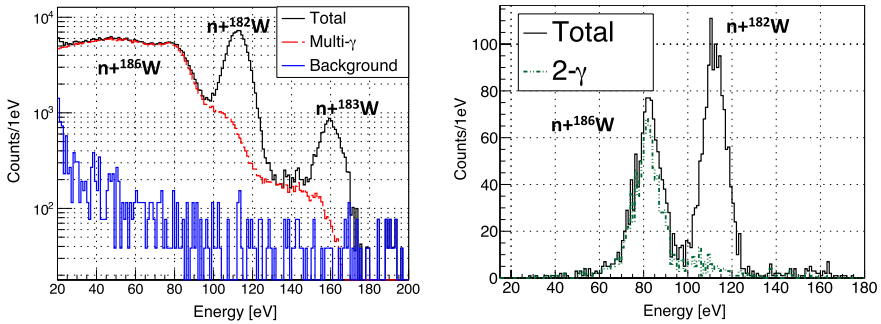
The de-excitation cascades have been predicted by the Monte Carlo (MC) simulation code FIFRELIN [15]. A full description is essential for the feasibility of the CRAB method, as the multi- γ cascade and conversion electrons provide a source of internal background. The low energy γ -rays from multi-cascades induce a continuum of nuclear recoils in the sub-keV region-of-interest (ROI), while conversion electrons and partial energy deposition of high energy γ -rays may deposit energy above. For rate and dead-time considerations, all energy depositions need to be taken into account.

The predicted spectra of γ -rays and conversion electrons are combined with a full GEANT4 MC simulation [16] for the propagation of the γ -rays, electrons and neutrons. A 0.76 g CaWO_4 target detector, as used by the NUCLEUS experiment [17], was simulated inside a dilution refrigerator and illuminated with a beam of thermal neutrons. An energy resolution of 5 eV (σ) was assumed. Figure 1a shows the simulated spectrum with two clear calibration peaks at 112 eV and 160 eV above the main background contributions. The calibration line at 86 eV is dominated by a continuous spectrum originating from recoils induced by multi- γ cascades.

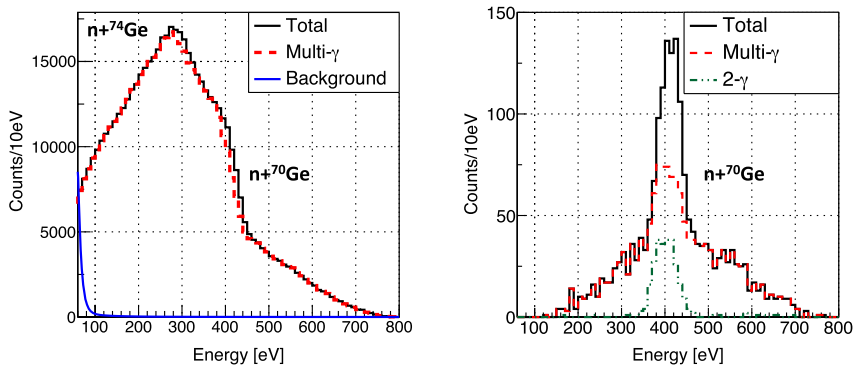
2.3 γ -Tagging

In order to suppress the large multi- γ background, the γ -rays associated to a certain S_n -level can be tagged. To investigate this method, two cylindrical BGO crystals ($\varnothing 3'' \times 3''$) have been added on both sides of the CaWO_4 crystal at a distance of 4 cm in the simulation. The former can be operated as cryogenic detectors at 20 mK, and feature a sufficiently high detection efficiency and energy resolution for the coincident tagging of the high energy γ -rays [18]. Figure 1a shows that a third calibration peak at 82.4 eV associated with the de-excitation of ^{187}W can be revealed by applying a coincidence cut of (5.47 ± 0.2) MeV in the BGO. As the branching ratio for the single- γ transition is relatively low (Table 1), the peak centered at 82.4 eV originates from the 2- γ transition of ^{187}W : a first γ -ray with an energy close to S_n is followed by a second γ carrying the remaining energy of about 150 keV toward the ground state. Depending on the relative direction of the two-emitted γ -rays, nuclear recoils between 75 and 85.6 eV are induced. Besides the de-excitation of ^{187}W , the applied coincidence selects nuclear recoil signals around 112.5 eV induced by the transition of ^{183}W where its single-photon (6.19 MeV) is registered in the (5.47 ± 0.2) MeV window of a BGO detector.

Similar to the tungsten case, the γ -tagging method can be used to overcome limitations given by the detector performance. Figure 1b shows the nuclear recoil spectrum induced in a germanium detector as used by the EDELWEISS experiment [11].



(a) Simulated nuclear recoil spectrum in a 0.76 g CaWO_4 crystal with an energy resolution of 5 eV (σ) exposed to a thermal neutron beam flux of 270 $\text{n}/\text{cm}^2/\text{s}$ during 3.4 days without (*left*) and with (*right*) γ -coincidences.



(b) Simulated nuclear recoil spectrum in a 33 g Ge crystal with an energy resolution of 20 eV (σ) exposed to a thermal neutron beam flux of 5 $\text{n}/\text{cm}^2/\text{s}$ during 7 days without (*left*) and with (*right*) γ -coincidences.

Fig. 1 *Left* Simulated nuclear recoil spectra for a CaWO_4 (**a**) and germanium (**b**) crystal. The *red* spectrum shows the internal background induced by multi γ -cascades, the expected background is shown in *blue*. The latter was taken from [14] and rescaled. *Right* The same simulation as shown on the left when requesting a coincidence in one of the two auxiliary γ -detectors (BGO). For CaWO_4 (Ge) a 0.2 MeV-wide coincidence window centered at 5.47 MeV (7.42 MeV) is chosen, corresponding to the S_n energy of ^{187}W (^{71}Ge). In the CaWO_4 case, this window is large enough to select single- γ transitions of ^{183}W in which the emitted γ -ray Compton scatters in a BGO detector. The *green* spectra show the contribution of nuclear recoils induced by the de-excitation to the ground state via the emission of two γ -rays instead of a single- γ transition. Figures adopted from [8] (Color figure online)

With a size of ($\varnothing 20 \text{ mm} \times 20 \text{ mm}$), the volume of the detector is significantly larger, leading to a poorer energy resolution of about 20 eV (σ) compared to the previously considered (5 mm)³ CaWO_4 detector. No calibration peak is visible. The 416 eV-nuclear recoils associated with the single γ -transition of ^{71}Ge are dominated by a background originating from multi- γ cascades. The tail toward 800 eV originates from the de-excitation of ^{73}Ge , which features a high multipolarity of the transition from the S_n to the ground state. Requiring a coincidence in the γ detectors, a calibration peak around 400 eV becomes visible.

The γ -tagging can be used to further enlarge the spectrum of calibration lines. Beyond tagging single- γ transitions centered at the S_n energy, this technique may allow to select numerous nuclear recoils of even lower energies, however, at a much reduced rate. In the case of 2- γ transition, the induced nuclear recoil is clearly defined by the emission angle of the two γ -rays. Thus, specific nuclear recoils can be selected by the angular arrangement of the γ detectors and by applying two narrow coincidence energy windows in the distinct detectors, their sum being centered at S_n .

2.4 CRAB at the TRIGA Reactor in Vienna

The slow response of the cryogenic detectors poses tight constraints on the count rate and, hence, on the incident thermal neutron flux. In a dedicated study, an optimal event rate of 10 Hz for a (5 mm)³ CaWO₄ cryogenic detector with a pulse decay time of 10 ms was determined. Given the previously described simulations, this corresponds to an incident thermal neutron flux of 270 n/cm²/s.

The 250 kW TRIGA-Mark II reactor in Vienna [19] can provide such a low neutron flux. With an initial flux of 10⁴ n/cm²/s, the desired neutron flux is achieved by Bragg diffraction from a monochromator crystal and a combination of beam optics. No further flux reduction is required. This is an important criterion for the choice of neutron source, since the attenuation of neutrons typically induces additional background by γ -rays and fast neutrons.

Background measurements combined with GEANT4 MC simulation yield that no significant background is expected in the ROI for CaWO₄. The neutron and γ backgrounds have been measured at the experimental site foreseen for the CRAB experiment. The γ background is largely suppressed due to the small size of the detectors. The thermal neutron flux is orders of magnitude below the intensity of the CRAB beam line, and fast neutrons from the reactor core are attenuated by the pool and concrete wall to a negligible level.

The CRAB experiment will proceed in two phases: A first proof of principle measurement with a (5 mm)³ CaWO₄ crystal is planned for 2023. This measurement will provide a first direct calibration of nuclear recoils in CaWO₄ of O(100 eV). Simultaneous calibrations based on electronic recoil will provide a cross-calibration of the recoils such that the results can be transferred to other experiments. Calibration sources based on X-ray fluorescence (XRF) with calibration lines of a few 100 eV are currently being developed, as well as an LED calibration system [20]. The latter calibration method is based on Poissonian photon statistics and can provide a calibration down to a few tens of eV. In a second phase, the experimental setup will be upgraded with detectors for the γ -tagging. In this phase, the spectrum of calibration lines will be enlarged and materials other than CaWO₄ can be studied.

3 Outlook for CRAB

The method we suggest provides a direct and model independent calibration of O(100 eV) nuclear recoils based on the emission of an MeV γ -ray following a neutron capture. A first validation of this method is planned with a CaWO_4 cryogenic detector in 2023 at the TRIGA reactor in Vienna. With expected calibration lines at 112 eV and 160 eV, this measurement will provide a precise calibration in the ROI (10–100 eV) of the NUCLEUS experiment [21]. Upgrading the CRAB experiment with additional detectors to tag the emitted γ -rays will bring the full potential of this method: the selection of a larger number of calibration lines and the application to other materials such as germanium.

A broad spectrum of nuclear calibration lines will enable to study the linearity of the detector response. In combination with sub-keV electron recoils provided by an XRF or LED calibration source [20] the impact of lattice defects can be studied. Furthermore, the selection of γ -rays with a specific angle with respect to the crystal lattice will allow studying potential directional dependencies. The second phase of CRAB provides a complementary approach to existing measurements of the QF in germanium with a simultaneous phonon and charge read-out.

The CRAB method will give insight into the phonon physics and the understanding of the detector response at unprecedentedly low energies. Recently it has received attention in the community and preliminary results with Si cryogenic detectors have been achieved [22]. The proposed experiment at the TRIGA-Mark-II reactor proposes a direct and accurate calibration of O(100 eV) nuclear recoils, tackling one of the major challenges toward finding and interpreting new physics in neutrino studies and light dark matter searches.

Acknowledgements This work has been supported through the DFG by the SFB1258 “Neutrinos and Dark Matter in Astro- and Particle Physics”.

Funding Open Access funding enabled and organized by Projekt DEAL.

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