Discrimination between Nuclear Recoils and Electron Recoils by Simultaneous Detection of Phonons and Scintillation Light

P. Meunier, M. Bravin, M. Bruckmayer, S. Giordano, M. Loidl, O. Meier, F. Pröbst, W. Seidel, M. Sisti, L. Stodolsky, S. Uchaikin, and L. Zerle.

Max Planck Institut für Physik, Föhringer Ring 6, München, Germany.

Abstract

We have developed a detector, consisting of a cryogenic calorimeter with a scintillating crystal as absorber, and a second calorimeter for the detection of the scintillation light, both operated at 12 mK. Using a CaWO$_4$ crystal with a mass of 6 g as scintillating absorber, we have achieved a discrimination of nuclear recoils against electron recoils with a suppression factor of 99.7% at energies above 15 keV. This novel method will be applied for background rejection in the CRESST (Cryogenic Rare Event Search with Superconducting Thermometers) experiment looking for dark matter Weakly Interacting Massive Particles (WIMPs).

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Direct dark matter WIMPs (Weakly Interacting Massive Particles) searches are looking for nuclear recoil events caused by WIMPs scattering off a nucleus in a detector. The kinetic energy of a recoiling nucleus due to a WIMP interaction is expected to be of order of a few tens of keV. Such recoils have a low ionization and scintillation efficiency and are therefore hard to detect in conventional detectors. In contrast, cryogenic calorimeters are fully sensitive to nuclear recoils and can achieve much lower energy thresholds, making them the most promising detectors for a dark matter search.

Since these dark matter events are expected to be very rare, such experiments have to be carefully shielded against cosmic radiation and ambient radioactivity. The sensitivity of
these experiments is finally determined by the residual background, dominated by $\beta$, $\alpha$ and $\gamma$ emissions from radioactive contaminations of the detectors and the surrounding materials. In contrast to WIMP interactions, this background deposits energy in the detector mostly by electron recoils, which are characterized by a higher ionization or scintillation efficiency than nuclear recoils. Thus the simultaneous measurement of ionization and phonons or scintillation light and phonons can be used to discriminate between electron and nuclear recoils, and can therefore suppress this background, leaving over nuclear recoil events caused by ambient neutrons and WIMPs. The use of a cryogenic calorimeter in conjunction with conventional ionization or scintillation measurement can provide high sensitivity together with excellent discrimination capability. The simultaneous measurement of ionization and phonons for a dark matter search has been developed and successfully implemented in the CDMS (Cryogenic Dark Matter Search) experiment\(^3\) and is also being used in the EDELWEISS (Experience pour DEtecter Las WImps En Site Souterrain) experiment\(^4\). In view of achieving background suppression in the CRESST (Cryogenic Rare Event Search with Superconducting Thermometers) experiment - which relies on dielectric absorbers \(^1\), \(^2\), we have characterized several scintillators at millikelvin temperatures. Since this kind of background rejection was proposed\(^5\), \(^6\), it had only been possible to discriminate between $\alpha$-particles and photons\(^7\), \(^8\). We report here simultaneous measurement of scintillation light and phonons and demonstrate a clear discrimination between electron and nuclear recoils down to 10 keV energy.

In order to obtain a good background suppression it is important to find dielectric crystals with good scintillation properties at low temperatures.

For measuring different scintillators, we prepared the scintillator holder in such a way that it was possible to remove and exchange the scintillating crystal without any change in the light detector and in the geometrical set-up. As light detector, we used a cryogenic calorimeter consisting of a sapphire substrate (10x20x0.5 mm\(^3\)) that was coated on one 10x20 mm\(^2\) surface with silicon to improve the light absorption and had a tungsten superconducting phase transition thermometer deposited on the opposite surface. This set-up was mounted in
a dilution refrigerator and cooled to about 12 mK, which is the operating temperature of the light detector. An $^{241}$Am source was mounted inside the cryostat, irradiating the scintillator with 5.5 MeV $\alpha$ particles and 60 keV photons. For energy calibration, the light detector was irradiated with a $^{55}$Fe source emitting 5.9 keV and 6.5 keV X-rays. The scintillators measured so far are BGO (Bi$_4$Ge$_3$O$_{12}$), BaF$_2$, PbWO$_4$ and CaWO$_4$. We have found that they all work sufficiently well at mK temperatures. Only the BGO crystal changed its properties after a few cooling cycles.

In table I the energies of the detected light for the measured scintillators are shown. These numbers are the detected energies and are not corrected for light collection efficiencies which vary for different scintillators because of their different refraction indices and light wavelengths. In BGO the detected light created by an $\alpha$ particle was a factor 2.2 smaller than for a photon of the same energy. For CaWO$_4$ this factor was 3.6.

Since the scintillation effect in tungstates is connected to the [WO$_4^{2-}$]-ion, presumably also other tungstates may work. Molybdates are other promising candidates for scintillation detectors at mK temperatures. We will test these materials in the near future.

Among the measured crystals, we chose CaWO$_4$ as a scintillator for the first simultaneous measurement of scintillation light and phonons.

Fig. 1 shows the set-up. It consists of two independent detectors: a 6g CaWO$_4$ scintillating crystal with a tungsten superconducting phase transition thermometer, and a second calorimeter placed next to it to detect the scintillation light. The scintillator has been surrounded by three aluminum mirrors in order to improve the photon collection efficiency. With this set-up an equivalent light energy of 480 eV has been measured for 60 keV $\gamma$-ray interactions in CaWO$_4$.

Both detectors were operated at about 12 mK. The CaWO$_4$ crystal was irradiated with 122 keV and 136 keV photons from a $^{57}$Co source and simultaneously with electrons from a $^{90}$Sr $\beta$-source. The two sources contributed about equally to the count rate. The photon lines were used for the energy calibration (in both detectors). The trigger is provided by the phonon detector.
The left plot in fig. 2 shows a scatter plot of the pulse height observed in the phonon detector versus the pulse height observed in the light detector. A clear correlation between the light and phonon signals is observed. The right hand plot shows an additional irradiation with neutrons from an americium-beryllium source. A second line can be seen due to neutron-induced nuclear recoils. It is to be observed that electron and nuclear recoils can be clearly distinguished down to a threshold of 10 keV.

The scatter plots in fig. 3 show the ratio of the pulse height in the light detector to the pulse height in the phonon detector versus the pulse height in the phonon detector. The lower band in the right plot is caused by nuclear recoils while the upper band with the ratio around 1 is caused by electron recoils. From the two ratios a quenching factor of 7.4 can be inferred. The quenching factor for an $\alpha$ particle interaction is different, is approximately half of it, but it still allows to discriminate $\alpha$ from neutron interactions.

The leakage of some electron recoils into the nuclear recoil line gives the electron recoil rejection according to the quality factor of ref. 9. A detailed evaluation together with the data without neutrons, shown in the left plot of fig. 3, yields a rejection factor of 98% in the energy range between 10 keV and 20 keV, 99.7% in the range between 15 keV and 25 keV and better than 99.9% above 20 keV. The energy spectrum measured with the phonon detector due to the irradiation with electrons and photons is shown in fig. 4a. Besides the lines at 122 keV and 136 keV there are two lines at 63 keV and 55 keV caused by the escape of $K_{\alpha}$ and $K_{\beta}$ tungsten X-rays, excited by the 122 keV line in the CaWO$_4$ crystal. The corresponding energy spectrum measured in the light detector is shown in figure 4b.

The residual background which can’t be rejected with this method at the present state of art consists of neutron events. Other events that can have the same signature of a WIMP event are nuclear recoils induced by an $\alpha$ decay taking place inside the detector very close to the surface so that the $\alpha$ particle can escape with an energy release in the crystal lower than a few tens of keV. Also the interaction of a nucleus emitted by the shield surface surrounding the detector as a consequence of an $\alpha$ decay taking place at the surface of this material can have the same signature of an WIMP event. This kind of background due to $\alpha$ emitter
surface contamination can be rejected completely by surrounding the CaWO$_4$ crystal with a passive shield made of the same scintillating material. In this way, whenever the recoil nuclei induced by the $\alpha$ decay excites the CaWO$_4$ crystal, the light detector can also detect the scintillation light of the $\alpha$ particle, and therefore the event can be rejected.

The simultaneous measurement of light and phonons has several advantages over the simultaneous measurement of phonons and charge. In the charge measurement electrical contacts always produce an unfortunate dead layer on the surface which causes surface events, especially electrons from outside, to leak into the nuclear recoil band. As our measurements with electrons clearly show, this problem does not exist in the light detection. The large quenching factor of the CaWO$_4$ gives a very effective separation of nuclear recoils from electron recoils. As opposed to charge measurement, light collection does not suffer from problems such as space charge build-up, field inhomogeneities or phonons produced by drifting the charges. Due to these advantages many of the effects, known from charge and phonon measurement to cause leakage of electron recoils into the nuclear recoil band, are absent. As a result the background suppression efficiency of the light-phonon detection is excellent and it works equally well for photon and electron backgrounds, thus avoiding particle dependent systematic uncertainties in the discrimination.

The opportunity to employ different scintillators with different target nuclei gives an unique handle for understanding and reducing backgrounds in dark matter searches. Even the neutron background, always considered to be the ultimate limitation for such experiments, could be investigated by varying the target nuclei.

In summary, a cryogenic particle detector which measures simultaneously the scintillation light and the thermal signal has been developed. Four different scintillating crystals have been tested as cryogenic detector absorbers, and they all showed to work adequately at low temperature. Using a 6 g scintillating CaWO$_4$ crystal, it has been demonstrated that this technique allows a discrimination between nuclear and electron recoils with a suppression factor of 98% in the energy range between 10keV and 20keV, 99.7% in the range between 15 keV and 25 keV and better than 99.9% above 20keV. Applying our present techniques
and optimizing the design we are very confident to produce detectors with a mass of a few hundred grams and similar performances.

This work was supported by the Max Planck Institute for Physics, and by the EC-Network Program ”Cryogenic Detectors”, Contract no.ERBFMRXCT980167.
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FIGURES

Fig. 1.  Schematic view of the arrangement used for the simultaneous light and phonon detection.

Fig. 2.  Pulse height in the light detector versus pulse height in the phonon detector. The scatter plot on the left side has been measured with an electron and a photon source, while a neutron source was added to measure the right plot.

Fig. 3.  Ratio of the pulse height in the light detector to the pulse height in the phonon detector versus pulse height in the phonon detector for irradiation with photons and electrons (left), and with photons, electrons and neutrons (right). Electron recoils are in the upper band while nuclear recoils are in the lower band.

Fig. 4.  a): The energy spectrum measured with the phonon detector; the detector has been irradiated with a $^{90}$Sr $\beta$ source and a $^{57}$Co $\gamma$ source and neutron source. b): The measured energy spectrum with the light detector; the energy scale applies for the heat measurement.
Table I. Energies of the detected light for the measured scintillators at a working temperature of 12 mK.

| Crystal | Detected Light Energy (keV) for 5.5 MeV $\alpha$ | Detected Light Energy (eV) for 60 keV $\gamma$ |
|---------|-----------------------------------------------|-----------------------------------------------|
| CaWO$_4$ | 5.2                                           | 210                                           |
| BGO     | 8.4                                           | 200                                           |
| PbWO$_4$ | 1.9                                           | -                                             |
| BaF$_2$ | 2.1                                           | -                                             |
