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Recent results with a 62 g Ge cryogenic dark matter detector

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Abstract

We report on recent results with a 62 g Ge cryogenic detector that combines simultaneous ionization and phonon measurements to allow rejection of radioactive background in a dark matter experiment. This detector has FWHM baseline resolutions of 500 eV in phonons and 1200 eV in ionization. A simplified charge collection scheme has been employed to improve the efficiency of the background rejection. Based on the success of this detector we are currently building six 165 g detectors as part of the CDMS experiment.

1. Introduction

There are several requirements for a detector used to search for weakly interacting massive particle (WIMP) dark matter: a mass of a kg or more, energy sensitivity of a keV or better, and background rejection capability [1]. We have developed a cryogenic detector which simultaneously measures the amount of ionization and the thermal energy produced by particle interactions in a semiconductor crystal [2]. Current WIMP searches are limited by background photons and betas, both of which cause recoils of electrons. WIMPs, by contrast, scatter elastically with nuclei. In Ge nuclear recoils are less ionizing than electron recoils, thus this simultaneous measurement distinguishes the two types of interactions.

Here we discuss a new detector with improved resolution in the thermal measurement and a simpler charge collection scheme than the detector reported at LTD5 [3]. Use of these detectors as part of the cryogenic dark matter search (CDMS) experiment is discussed separately in these proceedings [4].

2. Experimental setup

Our detector consists of a 62.3 g disk of ultra pure ($n_a - n_d \approx 6 \times 10^{11}\ \mathrm{cm}^{-3}$) Ge, 36.4 mm in diameter and 12.3 mm thick with rounded edges. The thermal energy is measured with two neutron transmutation doped (NTD) Ge thermistors which are attached with a eutectic bonding technique. One is $2.9 \times 3.0 \times 1.2\ \mathrm{mm}^3$ and the other is $1.6 \times 1.6 \times 0.3\ \mathrm{mm}^3$. The two faces of the crystal have degenerately-doped contacts that serve as electrodes for measurement of ionization created in the bulk of the detector. The detector is operated at temperatures near 20 mK in a dilution refrigerator.

Our amplifiers have separate "front-end" JFETs housed in the cryostat about 40 cm from the detector and operated at ≈140 K to minimize electronics noise. An AC biasing scheme with a lock-in amplifier is used to avoid microphonics and $1/f$ noise in the phonon measurement. We have recently replaced a commercial lock-in (PAR 124A) with home-built AC bias and demodulator circuits which have significantly lower noise.

3. Recent progress on the thermal measurement

The thermistors on our most recent detector represent a significant improvement from those on previous devices. The resistance of NTD Ge is governed by variable range hopping conduction, which depends very sensitively on temperature. Below about 30 mK the resistance decreases strongly with increasing electrical measurement power, and we observe an additional few millisecond time constant in the thermistor. We interpret these as caused by electron–phonon decoupling [5].

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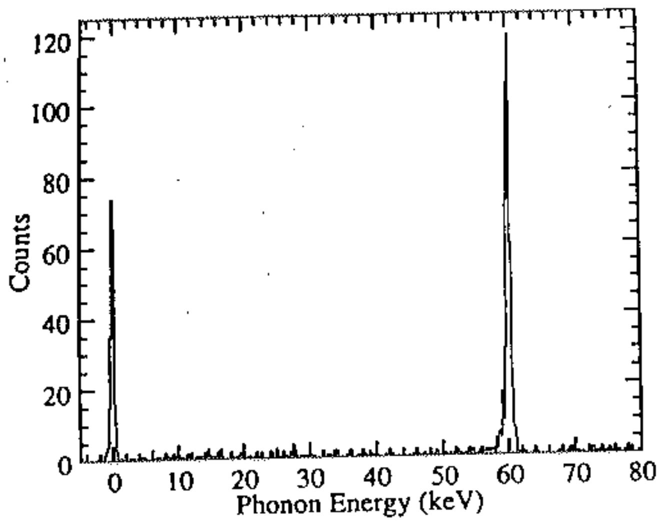

Fig. 1. The thermal measurement of 60 keV photons from a ^{241}Am source. The baseline peak is obtained by a template fit to noise-triggers, thus it is a measure of the electronics noise.

This hot electron effect is crucial to optimizing the sensors. Stronger electron–phonon coupling allows larger bias voltages and hence larger pulses. The coupling is proportional to the size of a thermistor [6], but larger thermistors have larger heat capacities, which reduces their sensitivity. Detailed calculations bear out what is perhaps intuitive: the optimum thermistor is one for which the electron and the bulk Ge heat capacities are roughly equal. The thermistor resistance is as large as possible without causing either too much microphonic noise pick-up or too long an electrical time constant.

The larger thermistor on our detector is nearly optimal by these criteria, while the smaller one is similar to that on previous detectors and serves as a test of the model. We find that pulses in the larger sensor are about 2.5 times those in the smaller sensor, and both pulse heights are predicted to within 30% by the model. The fall time of the pulses is roughly 20–30 ms.

This increased pulse height and noise reduction in our electronics have improved the resolution of our phonon measurement, as shown in Fig. 1. The FWHM resolution on the baseline is 495±35 eV, and at 60 keV is 700±35 eV. While the baseline noise was consistently this low, the resolution at 60 keV was often as high as 1200 eV, an effect that may be due to lack of temperature regulation of our cryostat. The baseline and 60 keV resolutions in ionization are 1200±50 and 1600±50 eV.

4. Discrimination of recoils of electrons and nuclei

In Fig. 2 we show a test of the background rejection power of our detector obtained by exposing it to both photons, which represent the background, and neutrons, which scatter elastically with nuclei just as WIMPs should.

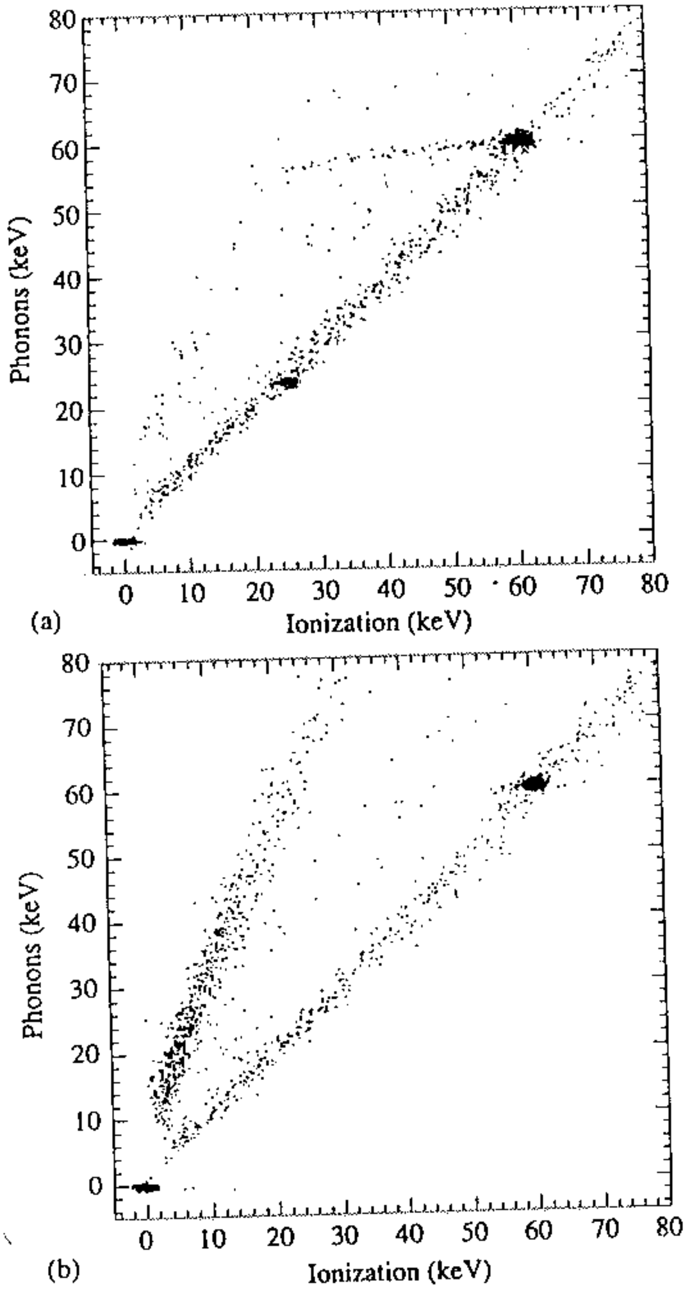

Fig. 2. Scatter plots of the phonon and ionization measurements with the detector exposed to (a) 60 keV photons and background radiation and (b) the same photons as (a) plus neutrons and photons from ^{252}Cf. Both measurements are normalized to equivalent electron recoil energy: the 60 keV photon appears at this energy in both measurements.

The neutrons are clearly distinguishable from photons in Fig. 2b.

There are a number of events with incomplete charge collection that do not lie along either the photon or neutron distributions, and which limit the background rejection efficiency. In Fig. 3 we plot the ratio of phonon and ionization equivalent electron energies for total recoil energies from 10–30 keV. Clearly the discrimination is reasonably good, even at very low energies. It also appears that there are a significantly number of neutrons present in the "photon" data set, so we can estimate only a lower

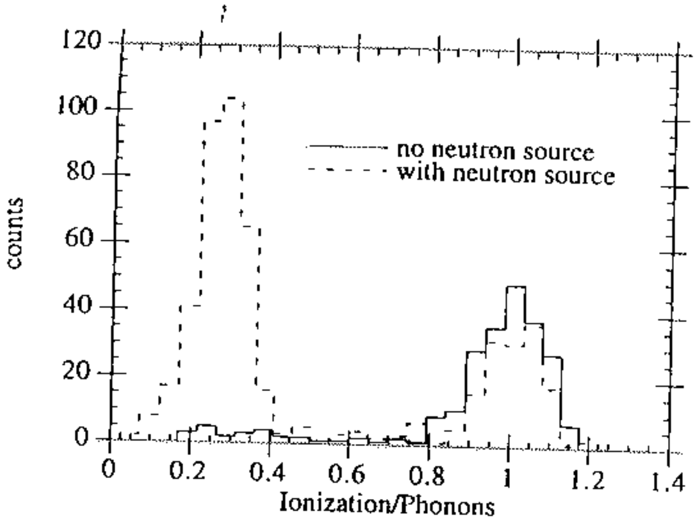

Fig. 3. The data of Fig. 2 replotted as the ratio of ionization to phonon energies. Photons are the peak at a ratio of 1 because both measurements are normalized to electron equivalent energy.

limit to the rejection efficiency. If we pessimistically assume there are no neutrons in the photon data set, then for Fig. 3 we obtain 93±2%.

In our first detector, incomplete charge collection was a problem for events occurring near the large surface around the edge that was neither metalized nor implanted [2]. We believe static charges built up on this surface, canceling the applied electric field. This problem is minimized in the current detector by the rounded edges which allow the two electrodes to wrap around, leaving only a 0.5 mm wide gap between them.

Another issue is events that occur a few tens of microns underneath the implanted contacts on the detector, presumably because of back-diffusion of charges into the contacts. Particles which have short mean free paths in Ge will be more likely to land in this "dead layer" than more penetrating particles. Photons of 20, 60 and 1000 keV have penetration lengths in Ge of roughly 0.05, 0.09 and 33 mm, respectively, while the few-MeV neutrons we measure have penetration lengths of a few cm. We have not studied the energy spectra of the photons and neutrons incident on our detector in detail, but in Fig. 2 and 3 it appears that the photons have a low charge collection tail while the neutrons do not. This implies that the dominant problem in this data is relatively low energy photons interacting in the dead layer.

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