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Measurement of Ionization and Phonon Production by Nuclear Recoils in a 60 g Crystal of Germanium at 25 mK

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We report on the first measurement of the absolute phonon energy and the amount of ionization produced by the recoil of nuclei and electrons in a 60 g germanium crystal at a temperature of ≈ 25 mK. We find good agreement between our results and previous measurements of ionization yield from nuclear recoils in germanium. Our device achieves 10:1 discrimination between neutrons and photons in the few keV energy range, demonstrating the feasibility of this technique for large reductions of background in searches for direct interactions of weakly interacting massive particle dark matter.

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In experiments such as a search for direct interactions of hypothetical weakly interacting massive particle (WIMP) dark matter or the direct measurement of coherent neutrino scattering, a small event rate of nuclear recoils in the energy range of $\approx 1-30$ keV must somehow be recognized and measured in the presence of a high background rate of recoiling electrons from photons and charged particles [1]. Because nuclear recoils are less efficient at producing ionization than are recoiling electrons, it has long been recognized that the two classes of events could be distinguished by simultaneously measuring the amount of ionization and the amount of phonon energy produced by interactions in a semiconductor at temperatures well below 1 K [2].

We have constructed a 58.4 g germanium device which performs this simultaneous measurement at a temperature of ≈ 25 mK. The basic operating principles of this device have been described elsewhere [3]. Here we present the first direct measurement of the absolute phonon energy and the amount of ionization produced by both nuclear recoils from neutrons and electron recoils from Compton scattered photons at low energies. Our results agree well with measurements made by Chasman [4] in the 1960's with conventional germanium ionization detectors and with kinematically determined nuclear recoil energies. Finally, we demonstrate discrimination between electronic and nuclear recoils at energies as low as a few keV, making this technique very attractive for a search for WIMP dark matter. Spooner *et al.* [5] have reported discrimination between neutrons and photons using the same technique with a 0.25 g silicon device, but at energies greater than about 50 keV.

The detector consists of a disk (4 cm diam and 1 cm thick) of ultrapure p-type germanium, onto which several neutron-transmutation-doped germanium phonon sensors have been bonded. The ionization from events is collected by means of a 0.3 to 0.5 V bias applied between identical implanted p^+ Ohmic contacts on both faces of the disk. The detector is operated at a temperature of ≈ 25 mK in a dilution refrigerator. The front end of the electronics chain is a junction field-effect transistor mounted in the cryostat about 40 cm from the detector. An ac biasing technique is used to avoid $1/f$ noise, microphonics, and 60 Hz pickup for our slow (≈ 1 msec rise time, ≈ 40 msec fall time) phonon signals. Triggering is performed on the faster (≈ 1 μsec rise time) ionization signal. The time traces for both signals are digitized and fitted on-line to templates constructed by carefully averaging many events. This fit in the time domain is equivalent to the optimal filter because the noise is flat at the signal frequencies. A mild cut on the "chi-square" of the fit rejects pile up and electronically saturated events.

In Fig. 1(a) we show the simultaneous measurement of phonons and ionization from 59.5 keV photons from a ^{241}Am source. The source was mounted about 1 cm from one face of the detector, and collimated to give a rate of ~ 1 Hz on a spot of ≈ 200 μm diameter. A small piece of aluminum 1 mm thick was used to stop low-energy x rays and α particles. The signals have been scaled so that the energies are defined in terms of equivalent energy for

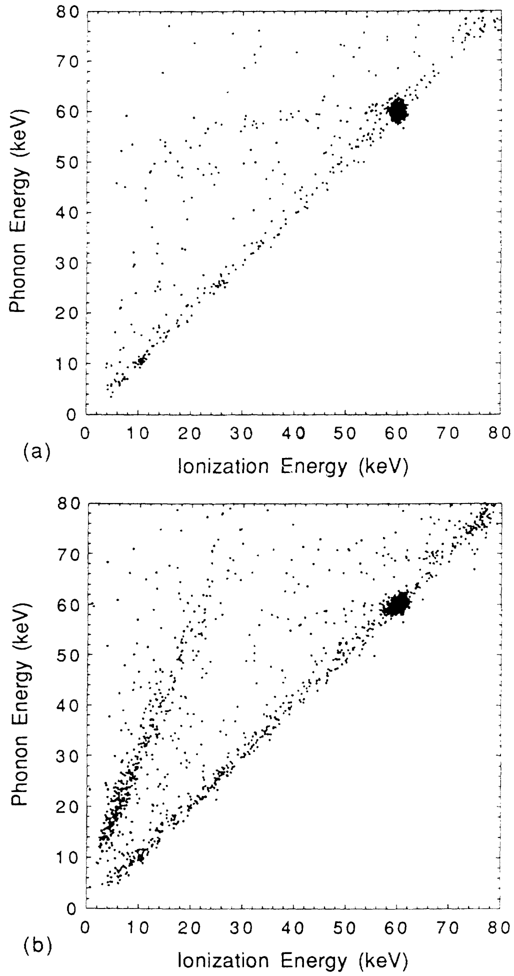

FIG. 1. Phonon and ionization equivalent energies measured for (a) 59.5 eV photons and Compton scatters of background photons. (b) The same measurement as (a) with the addition of neutrons and photons from a ^{252}Cf source.

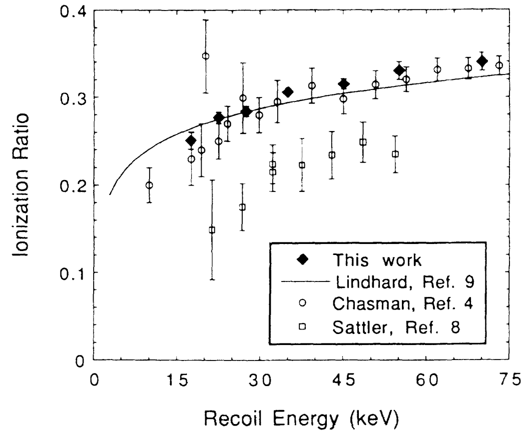

FIG. 2. The ratio of photon equivalent ionization energy to recoil energy for nuclear recoils, given as a function of recoil energy. Also shown are measurements from Refs. [4] and [8], and the calculation of Lindhard, with his parameter k set to 0.15. Error bars on our data points are statistical only; systematic errors are discussed in the text.

photons: The photon peak is at 59.5 keV in both the ionization and phonon measurements. In this convention photon and charged particle events lie along the line of equal phonon and ionization energies (for these interactions the partitioning into phonons and ionization is approximately independent of the incident energy.) A number of events can in fact be seen along this line. From measurements with a NaI counter, we ascribe most of these background events to Compton scattered 1.45 MeV γ rays from ^{40}K which is present in the walls of the room. The rms resolution of the 59.5 keV peak is typically 1 keV in phonons and 0.7 keV in ionization.

Figure 1(b) shows the response of the detector to neutrons and photons from a 50 μCi source of ^{252}Cf, in addition to photons from the ^{241}Am source. This Cf isotope spontaneously fissions, giving a broad spectrum of neutrons with mean energy near 2 MeV and a higher rate broad spectrum of photons of comparable energy. With all other conditions the same as for Fig. 1(a), we placed it without collimation outside our cryostat and beneath 28 cm of Pb to give similar rates of photons and neutrons throughout the detector. The neutrons are clearly distinguished in Fig. 1(b) as a second line with a greater slope, i.e., less ionization per unit phonon energy, than the photons. Their energy spectrum roughly agrees with a very simple Monte Carlo estimate. (Note that a 1 MeV neutron can deposit at most 53 keV in germanium.)

The fractions of the total recoil energy that appear as ionization and as phonons can be obtained from the data as follows. Energetic electrons and holes created in the initial interaction eventually relax to the band edges via phonon emission. These N charge pairs carry $NE_{\rm gap}$ of the original recoil energy E_R, where $E_{\rm gap}$ is the band-gap energy. The remaining energy appears as phonons, except in the case of nuclear recoils, which may lose a small fraction of their energy to the formation of crystal defects. As the charge carriers are collected they emit the energy they acquire from the drift field as phonons. In separate tests [6] we have concluded that when the electrons reach the implanted regions in this (p^+-p-p^+) device, they relax to the Fermi level and release their band-gap energy as phonons. The measured phonon energy, then, is $E=fE_R+eNV$, where f describes any energy lost to defects ($f=1$ for no loss), e is the magnitude of the electron's charge, and V is the charge collection potential ($=0.5$ V for this data set). In Ref. [6] we describe the absolute calibration of both the phonon energy E and the charge signal N. The "apparent" recoil energy fE_R is simply the total phonon energy minus the drift heat term. The equivalent ionization energy is N times 3.0 eV, the amount of energy per charge pair for photon interactions in germanium at low temperatures [7].

In Fig. 2 we plot the ratio of the photon equivalent ionization energy to the total recoil energy for nuclear recoils as a function of the recoil energy, along with measurements by Chasman [4] and Sattler [8] and the calculation of Lindhard [9]. The data have been binned by recoil energy, and we have made the tacit assumption that $f=1$. The error bars indicate statistical uncertainty only. To first order, errors in the charge calibration scale out of the ratio, but there is a small effect arising from the subtraction of the drift heat term. We estimate this error to be less than 2%. The statistical uncertainty on the recoil energy is also very small, but errors in the calibration may amount to several percent.

This is the first low-energy measurement of the ionization yield of a recoiling nucleus by a direct measurement of phonon energy. Previous measurements with conventional ionization detectors have used a monoenergetic neutron beam and either kinematics or the decay of known nuclear excited states to determine the energy of the recoiling germanium nuclei. In principle, this older method determines the relationship between recoil energy and ionization production. However, the amount of phonon energy generated and thus the amount of energy lost to defects is not determined. In our method the charge and phonon relationship is measured, but the energy lost to defects, and hence the full recoil energy, is not. The good agreement between our result and that of Chasman indicates that this energy loss is small.

Finally, we note that in Fig. 1(b) we can discriminate neutrons and photons at energies as low as the 2 keV equivalent ionization energy trigger threshold. The level of this discrimination, however, is currently limited by events, apparent in Figs. 1(a) and 1(b), which lie in the region of lower ionization efficiency than the photon line. There are two distinct populations of these events, both of which we attribute to incomplete charge collection. The first is due to 59.5 keV photons which land in a "dead layer" a few tens of microns thick beneath the implanted contact region. The other population limits the discrimination ratio to about 10:1 and is associated with the background photons which are (presumably) uniformly distributed in the detector. We believe that these events suffer from incomplete charge collection near the perimeter of the detector disk, presumably due to build up of charges on the surface of the germanium. This issue can be resolved by tests with collimated sources in various locations, and a guard ring or field shaping structure should solve the problem if our explanation is correct. If the rejection ratio can be improved by a factor of only 10, then five such detectors operating in a state-of-the-art low radioactive background environment for one year would be sensitive enough to detect neutralino dark matter predicted by several models [10].

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[1] M. W. Goodman and E. Witten, Phys. Rev. D **31**, 3059 (1985); J. R. Primack, D. Seckel, and B. Sadoulet, Annu. Rev. Nucl. Part. Sci. **38**, 751 (1988); P. F. Smith and J. D. Lewin, Phys. Rep. **187**, 203 (1990).

[2] For an early discussion of this idea, see B. Sadoulet, in *Proceedings of the Thirteenth Texas Symposium on Relativistic Astrophysics, Chicago, 1986*, edited by M. L. Ulmer (World Scientific, Singapore, 1987), p. 260, and references therein.

[3] A. Cummings *et al.*, IEEE Trans. Nucl. Sci. **38**, 226 (1991); T. Shutt *et al.*, this issue, Phys. Rev. Lett. **69**, 3531 (1992).

[4] C. Chasman, K. W. Jones, H. W. Kraner, and W. Brandt, Phys. Rev. Lett. **21**, 11430 (1968), and references therein. For comparison, two recent measurements using conventional silicon ionization counters are G. Gerbier *et al.*, Phys. Rev. D **42**, 3211 (1990); B. L. Dougherty, Phys. Rev. A **45**, 2104 (1992).

[5] N. J. C. Spooner, A. Bewick, G. J. Homer, P. F. Smith, and J. D. Lewin, Phys. Lett. B **273**, 333 (1991).

[6] Shutt *et al.* (Ref. [3]).

[7] C. A. Klein, IEEE Trans. Nucl. Sci. **15**, 214 (1968).

[8] A. R. Sattler, F. L. Vook, and J. M. Palms, Phys. Rev. **143**, 588 (1966).

[9] J. Lindhard, V. Nielsen, M. Scharff, and P. V. Thomsen, Mat. Fys. Medd. K. Dan. Vidensk. Selsk. **33**, 10 (1963).

[10] K. Griest (private communication).