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Phonon - Mediated Particle Detection : An Overview

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We review the current status of various programs developing phonon-mediated particle detectors for primary applications in particle and astrophysics. We begin with a brief summary and description of the general techniques employed by several of these groups. Experimental results on the detection of thermal phonons (e.g. using calorimeters) and athermal / ballistic phonons (e.g. using transition edge sensors or tunnel junctions) will be presented. Finally, we describe the design and operation of novel "hybrid" devices, and present results obtained with a cryogenic germanium hybrid detector which senses both phonons and ionization.

1. INTRODUCTION

The intent of this article is to provide the reader with an overview of phonon - mediated particle detection techniques, and to summarize the current state of research in the field. As shown in Table 1, primary motivations for developing cryogenic phonon detectors include searching for the hypothetical dark matter in the Universe, looking for neutrinoless ββ-decay, measuring coherent nuclear scattering, performing a nuclear reactor neutrino oscillation experiment, and eventually building a solar neutrino observatory. Additional applications are found, for example, in condensed matter and solid state physics (e.g. to study phonon dynamics), and nuclear and atomic physics (e.g. as high resolution x- and gamma ray detectors). In some designs, these detectors can be used to distinguish between nuclear and electronic recoils in solids. As we shall see below, this discrimination capability provides much of the background suppression needed for a proposed dark matter experiment. Detailed information about specific cryogenic detectors and experimental approaches can be found in references [1] and [2]. In addition, for a summary of most recent results obtained using large calorimeters and superconducting granule detectors, the reader is referred to a separate article in these proceedings by W. Seidel [3].

2. DETECTOR OVERVIEW

The intrinsic sensitivity of a particle detector is ultimately limited by the characteristic energy of the detected quanta. Not only does this energy scale set the limit on detector threshold, but it also ultimately determines detector resolution (more quanta, better statistics!). It is largely for this reason that over the past several decades we have witnessed the evolution from gas proportional chambers (E ~ 20 eV), to scintillation detectors (E ~ 5 eV), to conventional semiconductor ionization detectors (E ~ 1 eV), and now to cryogenic detectors based on superconductivity (E ~ 1 meV) and phonons (E ~ 1 μeV @ 10 mK).

As a simple example, consider the "best" semiconductor diode devices of ~ 1 kg scale (i.e. of a mass comparable to what is needed for a dark matter or neutrino experiment). The energy resolution and threshold of two such (Ge) ionization devices are $\Delta E_{FWHM} \approx 2$ keV (at 10.4 keV), $E_{min} \approx 3.0$ keV [4]; and $\Delta E_{FWHM} \approx 2.5$ keV (at 1.3 MeV), $E_{min} \approx$ 12 keV [5]. For an *electronic* scattering event, the fraction (f_e) of recoil energy going into producing e^- / hole pairs is (@ 77 K) :

$$f_e \sim \Delta / E \sim 0.7 \text{ eV} / 3.0 \text{ eV} \sim 0.25,$$

where Δ is the semiconductor "gap" energy and E is the energy per e^- / hole pair. The fraction of the energy going into *phonons* is then :

$$f_\emptyset \approx 1 - f_e \sim 0.75.$$

We see that more event energy appears as phonons! In experiments using conventional ionization

Table 1. Partial list of detector development groups and their primary application goals.

Detector Type	Institution	Primary Motivation
Superconducting Grains		
Drukier,et. al.	Interferometrics, Inc.	dark matter, ßß decay
Gonzalez-Mestres,et. al.	Annecy	dark matter, solar ν
Stodolsky,et. al.	MPI, Munich	coh. nucl. scatt.
Waysand,et. al.	Univ. Paris	solar ν
Tunnel Junctions		
Booth,*et. al.*	Oxford University	solar ν
Kraus,*et. al.*	TUM, Garching	x-ray detection
Zehnder,*et. al.*	PSI	ν, particle detection
Bolometers and Superconducting Films		
Cabrera,*et. al.*	Stanford Univ.	ν, coh. nucl. scatt
Cooper,*et. al.*	MPI, Munich	dark matter
Coron,*et. al.*	IAS - CNRS	dark matter
Fiorini,*et. al.*	Univ. of Milan	ßß decay, ν
McCammon, Moseley,*et. al.*	Univ. of Wisconsin, GSFC	x- and gamma rays
Sadoulet,*et. al.*	CfPA, UCB	dark matter
Hybrid and Other Techniques		
Fiorini,*et. al.*	Univ. Milan	ßß decay, ν
Lanou, Maris, Seidel, *et. al.*	Brown Univ.	dark matter
Sadoulet,*et. al.*	CfPA, UCB	dark matter
Spooner, Smith *et. al.*	Imperial College, London	dark matter
Umlauf, *et. al.*	Walter Meissner Inst.	dark matter

detectors, this phonon energy is lost. In addition, because the characteristic energy of the e^- / hole pairs (~ eV) is approximately three orders of magnitude larger than that of the phonons (~ meV), the intrinsic energy resolution would improve dramatically if one could collect the phonons (more on this later). For the case of *nuclear* scattering events, the fraction of recoil energy appearing as phonons is even greater; on the order of 90 % [6]. Moreover, this partitioning into ionization and phonons is energy dependent below ≈ 10 MeV deposited energy, favoring an even larger relative phonon production at recoil energies below ≈ 10 keV. This is the energy range of primary interest for a neutrino or dark matter experiment.

The potential applications for cryogenic phonon detectors prompted several groups from around the world to begin development of such devices. A few groups, such as that of B. Sadoulet at The Center for Particle Astrophysics (CfPA) at UCB, are now working on cryogenic *hybrid* detectors. In the Berkeley hybrid design, a high-purity Ge crystal is used to simultaneously sense the phonons *and* ionization produced by a scattering event. The collection of both a phonon and charge signal allows for discrimination between nuclear and electronic recoils, which is a powerful background supression technique. The group of E. Fiorini in Milan has constructed and tested a different type of hybrid device; one which is sensitive to phonons and *scintillation.* The group is interested in using such a scintillating bolometer in a double ß - decay experiment. This simultaneous detection scheme can distinguish between alpha particles (i.e. background) and betas (or gammas). Preliminary tests of a 2.1 gram CaF_2 prototype detector are encouraging [7].

Table 2. Simple comparison of a few types of phonon sensors

Sensor Type	*Advantages*	*Disadvantages*
Implanted Si or NTD Ge Thermistors	Easy fabrication, strong and reproducible dependence of resistence on temperature	Limited athermal phonon collection, must couple to target, ~ small area coverage
Superconducting Strips	Easy fabrication, quite sensitive to athermal phonons, ~ large area coverage	Requires well-regulated operating temperature, TES non-linear *
Tunnel Junctions	Couple well to nonthermal phonons, linear, excellent ΔE and Δx demonstrated	Fabrication difficult, small area coverage **
Superconducting Granules	Low energy threshold possible	Complex systems, avalanche effects
Paramagnetic Crystals	Sensors compatible with large absorber masses	Slow devices, ~ early stages of detector development

(*) Exception :*Quantum efficient* transition edge sensors would be linear in the far field regime
(**) Development of tunnel junction arrays (for larger sensing areas) is in progress.

3. PHONON DETECTION : THE BASICS

There are two basic approaches to phonon detection. In one case, the signal of interest is the initial phonon wavefront propagating from the interaction region, and in the other case, the signal consists primarily of phonons which have thermalized in the detector. Typically, a given type of sensor is optimized for detecting either athermal *or* thermal phonons,however in many cases the sensorintrinsically couple to both components with finite efficiency. A brief summary of the characteristics of several types of phonon sensors is shown in Table 2.

3.1. Thermal Phonon Detectors

We limit our discussion here to thermal detectors of macroscopic size; this unfortunately excludes the high resolution micro-calorimeters of McCammon and Mosely. For a summary of their impressive results, the reader is directed to Ref. 8.

In macroscopic devices, the detection of thermal phonons is often realized using small (~ mm^2) doped semiconductor thermistors which are appropriately attached to a "target" substrate. As we have seen, a scattering event in the target crystal (e.g. Ge or Si) produces phonons (and ionization). The deposited energy (E) is given simply by :

$$E = C\,\Delta T,$$

where C is the heat capacity and ΔT is the measured temperature rise of the crystal. According to the Debye Law, the heat capacity of an insulator at low T is :

$$C \sim (M / A)\,(T / T_D)^3,$$

where M is the sample mass, A is the atomic weight of the crystal, T is the temperature, and T_D is the "Debye temperature". For germanium, $T_D = 374$ K, and for silicon, $T_D = 645$ K. Thus, at cryogenic temperatures, the heat capacity for these devices becomes quite small (of order nJ / K at 20 mK). A small energy deposition in the target crystal therefore produces a detectable temperature rise, which gets sensed by the thermistor. Energy fluctuations in the detector limit the intrinsic detector resolution and threshold; these fluctuations have an rms amplitude given by :

$$<(E - < E >)^2> = k_b T^2 C (T),$$

where k_b is Boltzman's constant. J. Mather has shown [9] that under optimal operating conditions, the minimum detectable energy of a calorimeter is :

$$\Delta E_{th} = ß (k_b T^2 C(T))^{1/2} \sim (M^{1/2}) (T^{5/2}) (T_D^{-3/2}),$$

where ß is a constant of order 1. For example, a 1 kg Ge bolometer at an operating temperature of 20 mK would have $\Delta E_{th} \approx 100$ eV.

3.2. Athermal Phonon Detectors

The most efficient techniques for directly sensing athermal phonons typically involve the use of superconductors. Often, these sensors are in the form of superconducting tunnel junctions, transition-edge sensors, or superconducting thermistors. Quasiparticle trapping techniques based on superconductors have been used to improve detector energy and spatial resolutions [10], and to increase the sensitivity of bolometric detectors to athermal phonons [11]. The athermal phonons produced in a particle interaction carry important information about the event energy and location. It has even been suggested that by using appropriately designed phonon sensors, a determination of the incident particle directionality might also be possible. (Such a device would take advantage of subtle differences in the dynamical properties of fast transverse (FT), slow transverse (ST) and longitudinal (L) acoustic phonons.)

The initial spectral distribution of acoustic phonons produced by a scattering event contains a significant high frequency component (e.g. $\nu \sim 5$ - 10 THz in Silicon). This distribution results within the first ≈ 10 psec from the decay into phonons of electrically excited states, the decay of electron-hole pairs to the band edge, and the decay of primary optical phonons to high frequency acoustic phonons. At this point, the phonon dynamics are dominated by anharmonic decay, the rate of which is proportional to ν^5. The decay branches of interest are LA $\rightarrow$ TA + TA, and LA $\rightarrow$ LA + TA, with approximately equal partitioning of energy between the two daughter phonons (LA = Longitudinal Acoustic phonon and TA = Transverse Acoustic phonon). In silicon, the phonon decay time (averaged over modes) is of order $\tau_A \approx 25$ µsec (1 THz/ $\nu)^5$. As the phonon energies approach a few THz, anharmonic decay becomes less important and isotope / mass defect phonon scattering dominates the phonon dynamics. Isotope scattering, which is (to first order) isotropic, allows mixing between the phonon modes. In silicon, the characteristic isotope scattering time is of order $\tau_I \approx 0.4$ µsec (1 THz / $\nu)^4$.

In cold and sufficiently pure crystals (i.e. in crystals where thermally generated phonons are negligible and isotope scattering is minimal), athermal phonons can propagate ballistically for several cm. In addition, in anisotropic crystals such as Si, Ge, CaF_2 and GaAs, phonon focussing effects can occur [12], with the net result that significant phonon energy is directed onto a relatively small area of the crystal surface [Fig 1].

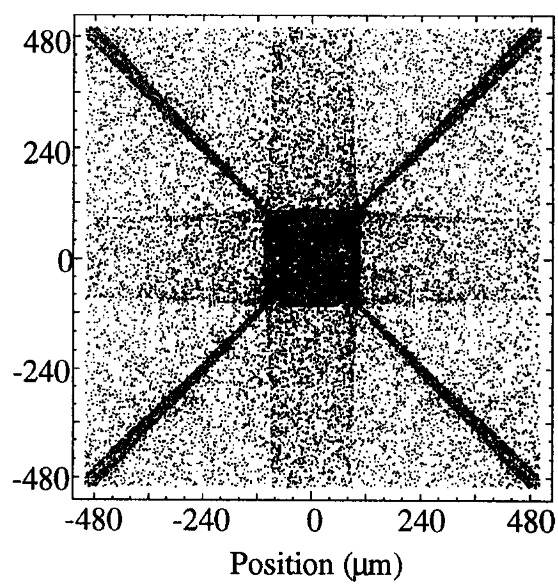

Figure 1. Calculated ballistic phonon energy density incident on the (100) surface of Si for a point source loacted at a depth of 1 mm.

Detection of the athermal phonons striking a detector surface is often realized using superconducting tunnel junctions [13]. A tunnel junctions (TJ) consists of two (sputtered or evaporated) thin films of superconducting metal (e.g. Al, Sn or Nb) separated by an even thinner layer (few tens of Å) of oxide. The TJ's are cooled to a temperature where thermal generation of phonons is negligible (i.e. $T \leq 0.1\ T_c$; $T_c \approx 1.3$ K for Al and $T_c \approx 3.7$ K for Sn). Phonons which reach the detector surface and strike the TJ break Cooper pairs in the superconducing film(s), producing quasiparticles (QP). In a good TJ sensor, a large fraction of these QP's quantum-mechanically tunnel through the thin oxide barrier and produce a signal. After much hard work, several groups have developed processes to fabricate TJ particle detectors / phonon sensors. H. Kraus, *et. al.*, at The Technical University of Munich in Garching used Al junctions in combination with superconducting Sn and Pb films to detect the ~ 6 keV K_α and K_β x-rays from an ^{55}Fe source with 60 eV (FWHM) resolution. These beautiful results can be found in Ref [2]. A most impressive effort by the group of N. Booth at Oxford has resulted in the realization of series-arrays of TJ's on semiconducting and superconducting crystals [2,14]. These arrays provide relativly large sensing areas (~ mm^2) while, in principle, not compromising on the energy and spatial resolution characteristic of single junctions. Continued work on the development and optimization of these sensor arrays is underway.

In the following two sections, we take a more in-depth look at two specific cryogenic detector programs, one at Stanford and the other at the Center for Particle Astrophysics, UC Berkeley. The Stanford devices (Si Crystal Acoustic Detectors) are optimized for collection of athermal and quasi-diffusive phonons, and the Berkeley technique is based on the simultaneous detection of ionization and (primarily) thermal phonons in Ge.

4. SILICON CRYSTAL ACOUSTIC DETECTORS (SiCADS)

The group of B. Cabrera at Stanford University is developing a new class of elementary particle detectors (SiCADs) capable of sensing weakly interacting particles such as neutrinos [15]. Straightforward photolithographic techniques are used to deposit meander patterns of thin superconducting films (e.g. Al, Ti and W) on the (100) surface(s) of single crystal, high-purity Si wafer substrates. These meander patterns, or "transition edge sensors" (TES), typically contain 400 parallel lines (400 Å thick, 2 µm wide on 5 µm pitch), and have an active area of 2 mm x 4 mm. Substrate thicknesses up to 1 mm have been routinely used. The devices are operated at a temperature $0.90\ T_c \leq T \leq 0.98\ T_c$ (i.e. at the "edge" of the superconducting - to - normal transition), and are current biased at a level where self-heating effects are negligible (~ 100 nA). Titanium TE devices have been characterized extensively, and have been used in coincidence experiments to detect x- and gamma rays, alpha particles and neutrons spanning an energy range of a few keV to 10 MeV. The Ti devices have also been used to study ballistic phonon proagation and phonon focussing effects in (100) Si [16].

A transition edge device directly senses the athermal (and quasi-diffusive) phonons produced by a scattering event in the bulk Si substrate. These "fast" phonons provide energy, timing and spatial information about an event. Assuming the BCS theory of superconductivity, the energy sensitivity of a TES (per unit area of film) near T_c is given by :

$$E_\sigma \approx 5.0\ N(0)\ \Delta_0^2\ d\ (1 - T/T_c),$$

where $\Delta_0 \approx 1.76\ kT_c$ is the gap, d is the film thickness, and N(0) is the density of states at the Fermi surface in the normal metal. It is clear from the above formula that, in general, one can increase the energy sensitivity of TES devices (and simultaneously decrease the energy threshold) by using superconductors of lower T_c (smaller Δ_0). One can also improve the sensitivity by going to narrower lines, since then less energy is required to from a normal region across the full width of a line. Although more sophisticated fabrication techniques must be used to fabricate narrow line patterns, the operating temperature of finished devices is unaffected; i.e. Ti patterns can still be operated in a simple ^{3}He refrigerator. (Tungsten devices always require the use of a more complicated dilution refrigerator, regardless of the linewidths.)

In Fig 2 we show the critical surface energy density for 400 Å thick Al, Ti and W sensors as a function of operating temperature. The two curves shown for tungsten correspond to a $T_c \approx 15$ mK (the T_c observed in pure samples of bulk W), and $T_c \approx 90$ mK (a value more typical of W thin films). A technique for reproducibly growing "low T_c" thin films of tungsten has recently been developed at Stanford; currently, these films have $T_c \sim 60$ mK and extremely narrow transition widths ($\Delta T_c \approx 0.4$ mK), and provide an sensor energy sensitivity $E_\sigma \approx 6$ meV / μm^2. For comparison, the TiTES currently have $E_\sigma \approx 500$ meV / μm^2.

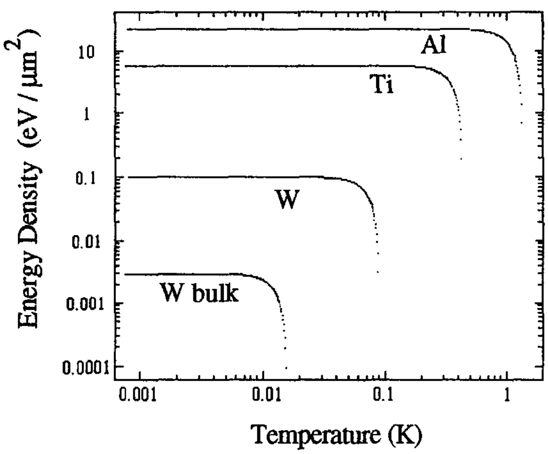

Figure 2. Calculated critical surface energy density for 40 nm thick transition edge sensors.

In SiCADs, the athermal phonons of interest have energies of order ≈ 5 meV ($\nu \approx 1.2$ THz), so a Ti TE device with 2 μm wide lines currently requires ~ 400 phonons to drive a "pixel" normal. (A pixel of film, which is the smallest unit of area that adds to a signal, is a square with sides egual to the film linewidth.) The character of the detector would be dramatically different if the energy from a single phonon were sufficient to drive a pixel normal. At that point, the SiCAD would become a *quantum efficient* , thresholdless detector; essentially every athermal phonon striking the surface would drive a commensurate length of TES line normal (although it may not be seen in the noise). The Stanford group is currently focussing on the development of such quantum efficient devices. If fabricated using 400 Å thick titanium films, quantum efficiency could be achieved with linewidths of ≈ 0.1 μm. This is technologically feasible, and patterns with 0.25 μm wide lines have already been tested [17].

For the tungsten TES, a sufficiently small critical energy density has already been demonstrated [18]. Quantum efficient operation has not been realized, however, because electron-dominated thermal conductivity along the W lines cools the quantum-induced normal regions faster than the natural integration time of the sensor. (Thermal conduction down the lines occurs on a timescale of $\approx$ 0.1 μsec; thermal relaxation to the substrate takes $\approx$ 100 μsec.) Similar energy diluting effects occur with Ti line TES, however there the effects are weaker. (For Ti, the ratio of the thermal conductivity along lines to the thermal relaxation to the substrate is only $\approx$ 25). One solution to this problem of energy transport (i.e. loss) down the lines is to construct TES with alternating "high gap" and "low gap" superconducting regions. In such a scheme, energy deposited in the sensing film gets "trapped" in the low gap regions, thereby minimizing the energy-diluting effects, and maintaining pixels above threshold long enough to contribute to the signal. The trapping efficiency is related, in part, to the ratio of the superconducting transition temperatures involved. Perhaps the most interesting design of a hybrid TES is then one which alternates regions of "alpha phase" tungsten ($T_c \sim 60$ mK) and "beta phase" tungsten ($T_c \leq 4$ K). Although construction of SiCADs with alpha-beta tungsten phonon sensors involves a creative and challenging combination of thin film fabrication techniques, preliminary work on these devices is very encouraging. One version of Al / Ti sensors has already been tested, and the fabrication of both Al / W_α and W_α / W_β "quasiparticle - trap - assisted" transition edge sensors is now underway. Continued work on the development of large area, athermal phonon sensors is bringing the Stanford team even closer to their goal of having a ~ 1 kg SiCAD with an energy threshold of ~ 1 keV and an energy sensitivity of ~ 100 eV.

5. A 60g Ge IONIZATION / PHONON DETECTOR

The Direct Detection Group of B. Sadoulet at the Center for Particle Astrophysics (CfPA) at UC Berkeley has constructed and characterized a cryogenic detector that simultaneously senses both the phonons *and* ionization produced by a scattering event. Such a simultaneous detection scheme could provide the significant background supression capability necessary to perform a search for the hypothetical dark matter of the Universe. Recall that for electronic scattering events in Ge nearly 3/4 of the recoil energy appears as phonons, whereas for nuclear recoils, phonons provide as much as 90 % or more of the signal energy. In addition, whereas the crossection for many types of weakly interacting massive particles (WIMPs) scattering off nuclei is orders of magnitude greater than for WIMPs scattering off electrons, most "background" sources (e.g. photons and betas) interact only with the electrons.

The Berkeley detector consists of a 58.4 g single-crystal disk (Ø = 3.8 cm, 0.96 cm thick) of ultra pure Ge ($N_A - N_D \approx 2 \times 10^{11}$ cm^{-3}), and is operated at ~ 25 mK. The ionization signal is collected by applying a small voltage across boron - implanted contacts on opposite faces of the disk ([B] ≈ 3 x 10^{14} cm^{-2}, 4000 Å thick). Full charge collection is achieved with applied voltages above ≈ 0.2 V, and typical operating voltages are of order 0.5 V. Larger applied voltages result in excessive thermal energy, which overwhelms the phonon signal produced by the initial interaction. The phonons are sensed using NTD Ge thermistors (1.4 x 1.4 x 0.33 mm), which are attached to one face of the Ge disk using either a thin layer of silver epoxy, or a Au - Ge eutectic bond. The response of the NTD thermistors is given by (at low temperature and electric field):

$$R(T) = R_O \exp(T_O / T)^{1/2},$$

where R_O and T_O are set by the thermistor dopant concentration. Although the NTD thermistors are intrinsically sensitive to athermal phonons, most (i.e. ≈ 90 %) of the detected phonon signal comes from thermal phonons. This is primarily due to the small surface area of the thermistors (i.e. poor surface area coverage on the large Ge substrate), and to the relatively low athermal phonon transparency of the eutectic (and especially glued) interfaces. Both the phonon and ionization channels are read out using cold silicon JFETs coupled to room temperature electronics (see Fig 3). A more complete description of the 60 gram detector can be found in Ref. 19.

Irradiation of the detector using a colimated ^{241}Am source resulted in the pulse height vs. pulse height distribution shown in Fig 3b. The energy scales are normalized so that 59.5 keV gamma rays from the source appear at 59.5 keV in both channels. The data were obtained by triggering on the charge channel and recording the simultaneous ionization and phonon signals. Random triggers were taken to provide an estimate of the baseline fluctuations and the total noise of the system ($\Delta E_{baseline} \leq 1.6$ keV FWHM in both channels). Also shown in Fig. 3 are projections along the energy axes for both the phonon (Fig 3a) and ionization (Fig 3c) channels. In the phonon channel, peaks corresponding to the 60, 18 and 14 keV gamma and x-rays of the source are clearly seen, with a FWHM resolution of 1.9 keV at 60 keV. The ionization spectrum shown has a FWHM resolution of 1.7 keV at 60 keV, however a FWHM resolution of 1.1 keV (at 60 keV) has also been observed with this device. The 18 and 14 keV x-rays are not well resolved in the charge channel. This is attributed to inefficient charge collection at the ionization contacts, perhaps due to the presence of a dead layer there. The contact problem was studied (in part) using a small (~ 0.5 gram) Ge device with p+ and n+ contacts. The results were encouraging: the ionization pulse height spectra had clearly resolved peaks down to the 2 keV trigger threshold.

The nuclear / electronic recoil discrimination capability of the 60 gram Ge detector was evaluated by irradiating the device with a ^{252}Cf neutron source (positioned outside the cryostat, and shielded with Pb to reduce the number of source - gamma rays striking the detector). An ^{241}Am source was mounted inside the cryostat for energy calibration purposes. The results of the ^{252}Cf experiment are shown in Fig 4, where, once again, the plotted pulse heights are normalized to incident photon energy. These data were obtained using a 2 keV equivalent ionization energy trigger threshold. Two lines are clearly identified. The first, appearing on the

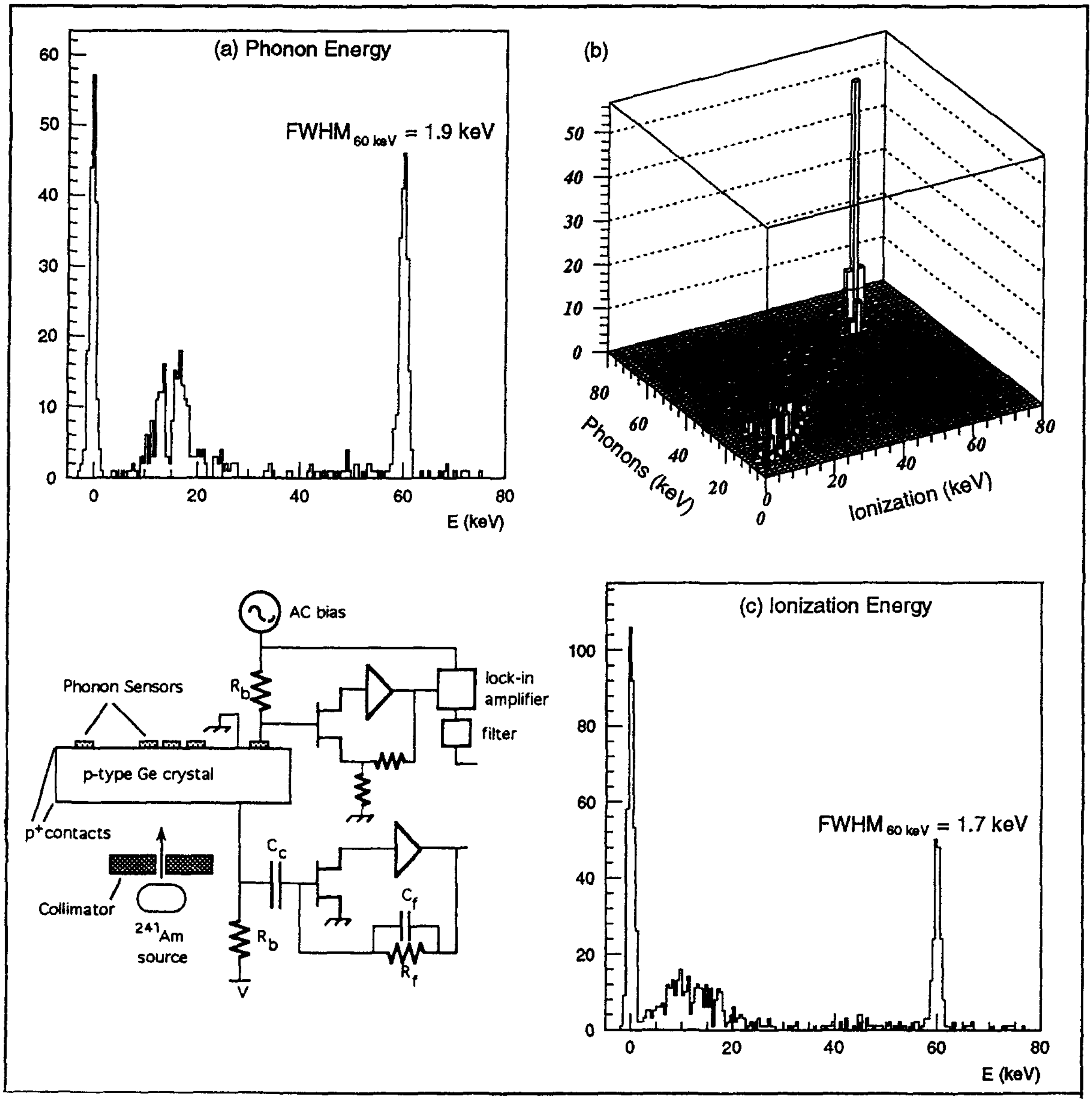

Figure 3. (a) Projection along energy axis for phonon signals plotted in Fig 3b. (b) Three-dimensional pulse height vs. pulse height distribution for simultaneously detected signals in the phonon and ionization channels. (c) Projection along energy axis for ionization signals plotted in Fig 3b. (d) Schematic diagram of 60 g Ge detector and electronics used for these measurements.

diagonal, corresponds to electronic recoils, and is marked by a spot corresponding to 60 keV gamma rays from the calibration source. The second line, with a steeper slope than the first, corresponds to neutrons. There are a number of events at low ionization which lie on neither line. These events are attributed to background photons which strike the perimeter of the detector [20]. Improved contacts and the use of guard ring structures should remedy this pulse height deficit in the charge channel.

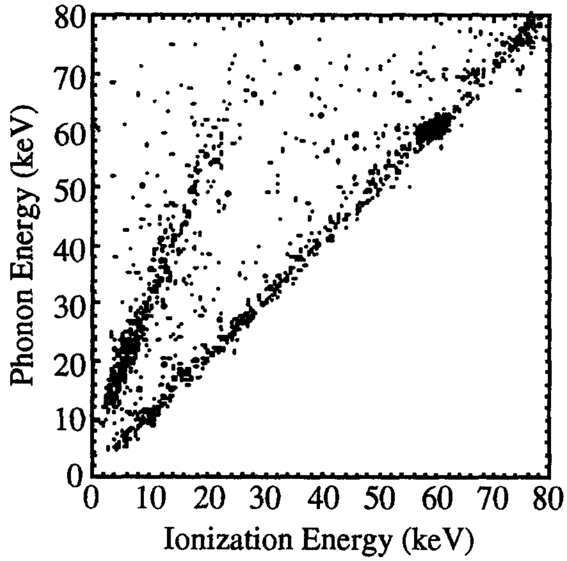

Figure 4. Phonon energy vs. ionization energy deposited in a 60 g Ge detector operated at ≈ 25 mK. The line with larger (smaller) slope corresponds to nuclear (electronic) recoils. Axes are normalized to incident photon energy. See text for details.

The 60 gram detector is a prototype of a larger device (~ 1 kg scale) intended for use in a pilot dark matter search experiment. With the 60 g detector, the Berkeley group has demonstrated a nuclear / electronic discrimination capability of > 90 % at recoil energies between 5 and 45 keV (see Fig 4). This rejection efficiency was obtained with little optimization of operating conditions. A more sophisticated triggering scheme, coupled with the use of improved ionization contacts, should provide closer to 100 % efficient nuclear / electronic discrimination at recoil energies as low as ≈ 1 keV.

6. A PILOT DARK MATTER SEARCH EXPERIMENT

Preparation for a pilot dark matter search experiment is underway at the Center for Particle Astrophysics. This is a collaborative effort of groups from UCB, Stanford Univ., UCSB and LBL. Neutrons are the dominant background of concern for this experiment, because they best mimic the signals that would be produced by WIMP dark matter candidates. The experiment will be housed in a newly-constructed, low radioactivity background facility on the Stanford campus. The facility is situated ≈ 20 m.w.e. (meters water equivalent) underground. At this depth, the raw muon rate is at an acceptable (albeit not ideal!) level, and the production of secondary neutrons from the hadronic component of cosmic rays is small (< 0.01/kg/day). Additional background neutrons come from fission products produced by nearby radioactive materials (mostly U in the ground). And finally, cosmic ray - induced distintigrations in nearby materials are expected to contribute ~ 10 n/kg/day. The use of appropriate shields (active and passive) inside and outside the experimental cryostat should result in a three-orders-of-magnitude reduction in background rate seen at the detector.

A dilution refrigerator of novel design will be used to cool the detectors to ~ 10 mK. One very attractive feature of this fridge is its removeable "experimental pail", which will house the detectors and their associated front-end electronics. As scheduled, the first detector to be run will consist of a large (i.e. 500 gram) natural, high-purity Ge device instrumented to detect both phonons and ionization. Subsequent runs will involve operation of Si and / or later-generation Ge devices, including, for example, isotopically enriched detectors of ^{73}Ge (sensitive to spin-dependent interactions) and ^{76}Ge.

The overall timescale for this ambitious dark matter search is the following : Stanford Underground Facility (completed), dilution refrigerator (being tested @ UCB), experimental pail (finalizing design and beginning construction @ LBL), data acquisition and electronics (under development at UCSB), shielding (testing in progress at Stanford), detector development (ongoing at UCB and Stanford). Cooldown of the first generation detector is planned for the Spring of 1993.

7. SUMMARY

We have witnessed rapid progress in the development of cryogenic phonon detectors over the past few years. Extensive charcterization and optimization of various phonon sensors (doped thermistors, superconducting transition edge sensors, tunnel junctions, etc.) has led to a more complete understanding of the full devices. Several groups (see also Ref 3) are now approaching the desired goal of having ~ 1 kg scale detectors with an energy threshold of ~ 1 keV and a (FWHM) energy resolution of ~100 eV at 1 keV. New sensing techniques continue to be explored, often with hopes of increasing detector sensitivity to athermal phonons. The Stanford team is taking this to an extreme in developing "quantum-efficient" devices, which would be capable of sensing individual nonthermal phonons in silicon. Finally, with the realization of hybrid devices, (e.g. the ionization / phonon detector developed at UCB), cryogenic phonon detectors will soon be used to address fundamental questions in particle astrophysics, such as those related to neutrino oscillations and the nature of dark matter in the Universe.

8. ACKNOWLEDGEMENTS

It has been a pleasure to report on the fine work of several groups in the cryogenic detector community; I regret not having space to discuss more of the results in detail, and I apologize for any errors or misrepresentations inadvertently included in this text. I am particularily grateful to B. Cabrera and B. Sadoulet for many useful discussions. I thank T. Shutt for providing plots of the data he obtained at UC Berkeley. Financial support was provided by a UC President's Fellowship and The Center for Particle Astrophysics at UC Berkeley.

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