Prototype Direction-Sensitive Solid-State Detector for Dark Matter

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A prototype weakly interacting massive particle (WIMP) detector system is described. The detection efficiency is much larger when the incident neutral particle flux is perpendicular to the detector plane than when it is parallel to the plane. A greatly scaled-up system based on this device would therefore be sensitive to the diurnal rotation of the "WIMP wind" produced by the solar system's rapid motion through the galactic halo. Experimental results are reported which exhibit the detection efficiency anisotropy when neutrons were used to simulate the interactions of WIMPS. [S0031-9007(96)00412-7]

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A large fraction of the mass, which dynamical measurements indicate must exist in the Universe, remains unobserved [1]. The question of the existence of this "missing" mass, its nature, and its relationship to elementary particle physics theories, is an important problem which is being investigated by many research groups [2].

One attractive hypothesis about the missing matter is that it consists of massive, stable, weakly interacting neutral particles as yet undiscovered in particle physics experiments [3]. Such particles exist in popular supersymmetric theories of the elementary particle spectrum [4]. Unless the particles interact exclusively through the gravitational interaction, they may be detected as they transfer energy and momentum to atoms of a detector medium through elastic scattering.

The expected interaction rates are extremely low [5]. Arduous efforts have permitted a few groups to achieve low enough backgrounds to exclude portions of the allowed WIMP parameter space [6,7,8,9]. However, most of the favorite particle physics candidate particles are predicted to interact at rates several orders of magnitude lower than current experimental limits. Increases in experimental sensitivity and lower backgrounds are being actively pursued [2].

In addition to working to reduce the background event rate, workers in the field have also been searching for ways to reject background events on the basis of some measured event characteristic(s) [10,11]. The event sample after rejection of background is enriched in WIMP recoils but still contains background events, for example due to neutron interactions, which pass the event selection criterion. Unambiguously isolating a WIMP signal from the data will be difficult.

Spergel [12] and Freese and Drukier [13] pointed out that there are definite kinematical signatures which distinguish WIMP signals as a group from time-invariant backgrounds. The signatures include a small annual variation in the total interaction rate and a large directional anisotropy of the recoil atoms, which rotates in the lab with the Earth's diurnal motion.

The strong anisotropy is due to the fact that the solar system orbital speed is comparable to the typical speed of WIMPs in the halo. Thus the WIMP velocity distribution relative to an Earthbound laboratory is strongly peaked in a direction opposite to the Earth's motion. This is reflected in the directional distribution of recoil atoms. Furthermore as the Earth rotates on its axis the asymmetry axis rotates in the laboratory at the sidereal rate, giving an unambiguous extraterrestrial signature for any signal detected in this way. Synchronous detection which is phase locked to the sidereal rate would permit the detection limit of a directionally sensitive system to continue to improve as $1/\sqrt{t}$ and to reach levels below the average background rate. In this work we describe the first real-time, solid-state detector system which has demonstrated sensitivity to the direction of recoiling low energy atoms and which could be scaled up into a WIMP detection system.

Description of the detector prototype.—The prototype detector system in these tests consisted of two 6×6 mm double-side-polished, high resistivity Si chips 270 μm thick, each carrying a microfabricated GeAu thermistor on one face. The thermistors respond bolometrically to the temperature change of the entire 6×6 mm chip caused by the absorbed energy [14]. The GeAu thermistors were developed in this laboratory and have been described elsewhere [14,15]. A recoil atom or other product of radiation interactions in the surface layers of one detector can exit that detector after depositing part of its energy, move through the vacuum to the second detector, and deposit the balance of its energy in the second detector. Events of this kind produce a coincidence event signature. Nonpenetrating events can be selected in these detectors on the basis of pulse shape since events in which appreciable energy is deposited in or near the GeAu (outer) face have been found to show a fast rise time

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and a fast-decaying initial "spike" component in the pulse shape. This selection was important in the present work to isolate a recoil-atom signal because of the intense radiation background from the strong sources used here.

Energetic Si recoils from ~1 MeV neutrons have ranges in silicon of thousands of angstroms, leading to a measurable coincidence rate for accessible neutron fluxes. Even so, the present 270 μm thick silicon substrates present a very large fraction of inactive mass for the coincidence detection. This need not be the case in future versions of the devices (see below). Our Monte Carlo simulations predict a strong dependence of the coincidence event rate upon the angle between neutron direction and detector plane, even for scattering processes which are isotropic in the center of mass, and even when transverse and longitudinal straggling are taken into account.

The two chips were suspended from nylon monofilament fibers with their bare Si sides facing each other, 12.7 mm apart (see Fig. 1), in the evacuated cold stage of a closed-system, sorbtion-pumped ^{3}He cryostat with base temperature of 0.26 K. Current bias of 160 nA was applied to each thermistor. The voltage signals due to temperature changes following radiation absorption were amplified by source followers based on Sony 3SK-164 GaAs-FET's mounted on the 1.5 K cold plate, and subsequently further amplified by room temperature electronics. Signals were displayed on a digital oscilloscope which was linked via GPIB to a personal computer, where data were recorded on disk for later analysis. The coincidence resolving time of this system was about 1 μs, due to a combination of the slow room-temperature electronics and the sampling time of the digital oscilloscope. This is much too slow to distinguish "forward" from "backward" events, so the 0°:90° asymmetry was measured instead.

Experimental data was taken with the detector system alternately exposed to a 2.6 mCi ^{137}Cs gamma-ray source and a 5 Ci (alpha activity) PuBe neutron source. The sources were placed alternately at positions where the vector from source to detector was parallel and perpendicular to the plane of the detectors.

The analysis began with fitting pulse shapes and amplitudes to functions derived from consideration of the equivalent circuit of the amplification chain. Nonpenetrating, two-detector coincidence events due to silicon atom recoils from elastic scattering were sought. Representative pulses from penetrating and nonpenetrating events are shown in Fig. 2. A nonpenetrating coincidence event is shown in Fig. 3.

Table I shows the numbers of coincidence evens registered in the two detectors during 28 hours of stable running with the neutron source. Data from two independent experiments using different room-temperature electronics have been combined. The two datasets represented nearly equal counting times and gave consistent results. Trigger thresholds for the two detectors were about 40 and

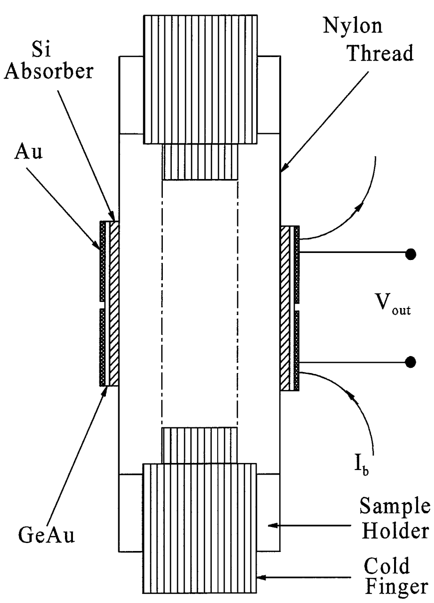

FIG. 1. Schematic cross section of a detector mounting, viewed from the 90° source position. The planes of the detectors are perpendicular to the page, with the thermistor sides facing outward. The sample holder has a hole giving a clear path in vacuum from one detector to the other.

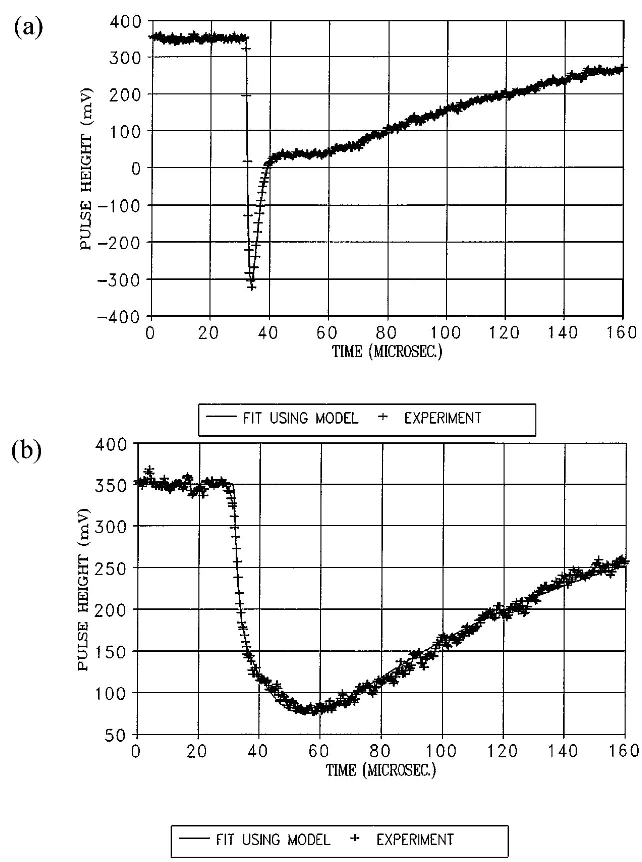

FIG. 2. (a) Characteristic pulse from particle penetrating GeAu thermistor and depositing energy directly in the thermistor itself. (b) Characteristic pulse from nonpenetrating particle.

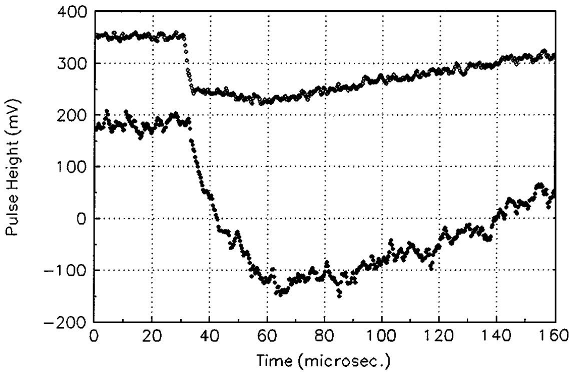

FIG. 3. Coincidence pulse pair from nonpenetrating particle.

80 KeV. One dataset was run triggering on a signal in either detector and seeking coincidences in software; the second dataset used faster room temperature electronics and a hardware coincidence trigger. A total of ten nonpenetrating coincidence events were seen in the perpendicular orientation and one in the parallel arrangement. Similar exposures with the ^{137}Cs source showed no nonpenetrating coincidence events in either orientation. This is expected, since Compton coincidences which do not penetrate one or the other detector are exceedingly rare.

A Monte Carlo calculation was performed for comparison with the experimental results. The simulation included Compton interactions of the γ rays produced by the PuBe source, as well as (n,n), (n,p), and (n,α) interactions with cross sections taken from Ref. [16]. The neutron spectrum of our 30-year-old PuBe source needed for the Monte Carlo calculation was measured with activation foils and was found to be strongly depleted in neutrons above 4 MeV, compared to the standard spectrum of a fresh PuBe mixture [17]. This correction to the spectrum has the effect of suppressing (n,p) and (n,α) reactions. The foil activation measurements were confirmed by our nonobservation of the large number of high energy, nonpenetrating (n,p) and (n,α) coincidences which would be produced by the fresh PuBe spectrum. We calculate that such a change of the spectrum could arise as the Be powder immediately adjacent to the Pu grains in the source is transmutated by (α,n) reactions into inert ^{12}C. Subsequent α's must transverse this inert material before interacting, which lowers the average α energy participating in (α,n) reactions and modifies the neutron spectrum.

TABLE I. Experimental results and Monte Carlo calculation or coincidence events between two thermistor detectors described in the text, exposed to PuBe neutron flux. Neutron flux is normal to detector plane in "Normal" configuration and parallel to detector plane in "Parallel" configuration.

	Configuration:	
	Normal	Parallel
Experiment:	10 ± 2	1 ± 1
Monte Carlo:	14 ± 2	1 ± 1

The expected numbers of events from the Monte Carlo calculation are also shown in Table I. The observed coincidence rate and parallel/perpendicular anisotropy is consistent with that expected for Si recoils from neutron elastic scattering.

WIMP detection method.—A Monte Carlo simulation of the recoil atom directional distribution following elastic scattering from WIMPs was also performed. The calculation was made for Si recoils in a Si lattice, using a Boltzmann distribution of WIMP velocities with a *rms* value 261 km/sec, cut off at 640 km/sec, with the Sun moving at 220 km/sec.

Transverse and longitudinal straggling of the recoil atoms' stopping distributions were included in the simulation, using average values calculated with TRIM [18]. The rate of coincidence events depositing at least 2 KeV of energy (a sensitivity we have achieved with the present GeAu devices at dilution refrigerator temperatures [14]) in each of two detectors was simulated for various orientations of the detector plane to the Earth's motion through the dark matter halo. The calculated 0°:90° and 0°:180° ratios were 3.3:1 and 8.5:1, respectively, with a weak dependence on WIMP mass in the range 30–300 GeV/c^2. The effective target thickness was found to be about 125 Å (0.83 milligram Si) per wafer face. To measure the 0°,180° ratio would require a system with improved time resolution and/or increased wafer spacing, or another scheme such as desensitizing alternate wafer faces with a high-mass superconducting coating.

Suppose that we have a direction-sensitive detector with mass M, background rate B events/kg day and a time average WIMP signal rate S events/kg day, with the forward rate being $[2A/(A+1)]S$ and the backward rate $2S/(A+1)$. The forward to backward signal ratio is thus A. It can be shown that a null result from counting for t days would place a 2.3σ statistical upper limit on S given by

$$S < 2.3\,\frac{A+1}{A-1}\sqrt{2B/tM}\,. \qquad (1)$$

To estimate the size of a WIMP detection system, consider first a discovery scenario in which WIMP dark matter exists and interacts at an average rate of 5 events/kg day. In a detector with asymmetry $A = 8.5$ and a counting time of 1000 days total, obtaining 10 events would require 2 g of active material, or 1060 wafers 8 inches in diameter and instrumented on both sides. Using Eq. (1), this observation would be statistically robust for background rates less than 3.7 events/kg day. This is a much higher background level than the ~ 0.01 neutron interactions/kg day expected inside local shielding in a suitable underground site [19,20], in spite of the large ratio of dead to live material in a 2 μm thick wafer. A null result in this detector array would set a limit somewhat better than 5 events/kg day, after a more detailed statistical analysis.

Wafers 2 μm thick are commercially available. These would also reduce the inactive mass of the detector and give the advantage that β particles from radioactivity would deposit mean energies well below threshold and penetrate multiple detectors, further improving the rejection of the remaining background. Fabrication processes [21] are also available to produce 1 μm thick, free-standing membranes of SiN, giving the possibility of an even thinner detector which would also have nuclear spin.

It is seen that a large detector system based on the method described here would be capable of excluding WIMPs to the level of interesting viable particle physics candidate particles, or *definitively identifying any positive signal.*

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