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Energy Deposition of Energetic Silicon Atoms Within a Silicon Lattice

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The energy dependence of the ionization produced in silicon by recoiling silicon atoms was measured in the 4–54-keV energy interval. It is found that the fraction of the recoil energy that is dissipated as ionization follows an $E^{1/2}$ dependence which agrees well with the predictions of the theory of Lindhard *et al.* [Mat. Fys. Medd. **33**, 10 (1963)].

I. INTRODUCTION

The detection of particles considered as nonbaryonic "dark matter" candidates has recently received much attention. The nature of this "nonluminous matter," which constitutes at least 90% of the mass of the universe, has been considered one of the most important questions confronting modern physics and astronomy.[1] In a recent review article, Primack, Seckel, and Sadoulet[1] review various methods proposed to detect these particles.

In some of these proposed experiments a gas or solid crystalline detector is used to directly sense the recoil energy deposited when an incident particle elastically scatters off a nucleus in the detector. After the primary collision the struck atom is usually not ionized and only a fraction of its energy is transferred to ionization in further collisions with other atoms in the medium. The remainder energy is thermally dissipated in the crystal. A discussion about the phonon flux detection is given by Martoff, Cabrera, and Neuhauser.[2]

The fraction of the recoil energy transferred to ionization by energetic silicon atoms within a silicon lattice has been measured by Sattler[3] in the energy range from 21.2 keV to 3.14 MeV. The results are consistent with predictions of the theory of Lindhard *et al.*[4] indicating that the resulting pulse height in an ionization detector of a slow nucleus is much smaller than that of an electron of the same kinetic energy.

In this paper we present data which extend Sattler's result[3] down to recoil energies in the 4–54-keV energy range. The experimental situation for germanium as well as silicon crystals has been recently reviewed by Sadoulet *et al.*[5]

II. EXPERIMENTAL SETUP

A. General method

Monoenergetic neutrons in the 1–4-MeV energy range were elastically scattered from a cooled surface barrier silicon detector. Signals from a neutron detector located at either $\theta_L=35.6°$ or $\theta_L=20.0°$ were used to gate the ionization response of the Si detector. The minimum Si atom recoil energy measured was 4 keV that corresponds to an incident neutron energy of 1 MeV elastically scattered at $\theta_L=20.0°$. To overlap with Sattler's data,[3] we measured recoil energies up to 54 keV, which corresponds to 4-MeV neutrons elastically scattered at 35.6°. Data points also were measured at 2- and 3-MeV incident neutron energies and $\theta_L=20.0°$ and 35.6°.

The linearity of the ionization response of the Si detector was checked with a precision pulser. The absolute energy values were checked with ^{55}Fe, ^{57}Co, and ^{241}Am sources.

At a given scattering angle the recoil energy was calculated including the finite geometry of the system. The energy deposited in the silicon lattice was obtained by the location of the coincidence "recoil peak" in the calibrated Si detector energy spectra. In the next few paragraphs we present a brief description of the experimental setup. For more details, see Ref. 6.

B. Monoenergetic neutrons and neutron detector

The measurements were performed using the Ohio University Tandem Van de Graaff facility. A proton beam, subnanosecond pulsed and bunched at a 5-MHz repetition rate and average beam current of 2 μA, was incident upon a 3-cm-long gas cell filled with tritium at 1.5 atm producing monoenergetic neutrons via the $T(p,n)^3$He reaction. Neutrons emitted at 0° were selected by placing a tapered collimator in the 0.75-m-thick shield wall[7] consisting of concrete, lead, borated paraffin, and brass, which separated the neutron source from the scattering chamber. The Si detector located at the center of an evacuated chamber was 1.1 m from the neutron source and fully intersected the neutron beam.

A port in the scattering chamber located at $\theta=40°$ allowed the observation of scattered neutrons from the Si target at $\theta_L=35.6°$ through a thin (1.0-mm) stainless-steel window that minimized neutron absorption. At $\theta_L = 20.0°$ there was no such window and the scattered neutrons had to traverse the full 5.0-mm-thick steel chamber wall. The exit port at zero degrees consisted of a 1.0-mm-thick stainless steel window at the end of a 30-cm-long Al tube, and helped limit the number of stray neutrons scattered back into the neutron detector.

The neutron detector consisted of a cylindrical liquid scintillation cell, 10 cm thick by 10 cm in diameter, light coupled to a 12.5-cm-diam RCA-4522 photomultiplier tube (the scintillator material used was NE123). A massive water tank lined with lead was used to shield the detector and was collimated so as to primarily accept only those neutrons which scattered from the Si sample. The neutron detector was placed at 1.36 m from the Si target. Pulse-shape discrimination was used to veto against detected γ-ray events. A lower electronic threshold corresponding to 0.2-MeV neutrons was used throughout the experiment. A neutron time-of-flight spectrum obtained with 4-MeV neutrons and at $\theta_L = 35.6°$ is shown in Fig. 1.

C. The silicon solid-state detector

A 5.7-g Si surface barrier silicon detector 0.5 cm thick and 2.5 cm in diameter was fabricated for this experiment by J. Walton at Lawrence Berkeley Laboratory.[8] To reduce the electronic noise of the detector, it was thermally attached to a cold finger that was filled with liquid nitrogen. An ORTEC 142A preamplifier was mounted inside the scattering chamber and as close as possible to the Si detector. The field-effect transistor[9] (FET) that constituted the first amplification stage of the preamplifier was heat sunk to the cold finger through a metal braid. Lowest temperatures achieved were 77 K for the detector and 100 K for the FET. The scattering chamber had a thin neutron entrance window and achieved a vacuum better than 10^{-6} Torr when the cold finger was filled with liquid nitrogen.

To ensure that the bias applied to the totally depleted Si detector was strong enough to collect all the charge resulting from the recoil particles, coincidence spectra of silicon recoil atoms and scattered 4-MeV neutrons at 35.6° were measured as a function of detector bias. The pulse height of these silicon recoil atoms remained essentially constant for field strengths of 0.24, 1.0, and 2.0×10^3 V/cm. The majority of our data was obtained using field strengths of 0.24 and 1.0×10^3 V/cm. The range of 350-keV Si recoil atoms in Si (Ref. 10) is approximately 0.5 μm. The orientation of the detector relative to the incident neutrons was not considered. Sattler[3] indicated that the orientation had no significant effect on the shape of the spectrum produced by recoiling atoms.

D. Electronics and procedure

Signals from the cooled FET ORTEC 142A preamplifier were fed into a Tennelec TC244 amplifier. Coincidence events between this detector and scattered neutron time-of-flight events observed in a 200-nsec time range were fed into the OU-8000 microcomputer[11] which was used as the main data acquisition system. The liquid scintillator NE213 is sensitive to both γ rays and neutrons; these events were separated by using a standard pulse-shape discrimination (PSD) circuit. Single events requiring only a neutron time-of-flight signature or a PSD signature were recorded in separate analog-to-digital converters (ADC's). The data were histogrammed on line and also stored in an event-by-event mode. This allowed later detailed analysis with varied coincidence requirements. In Fig. 2 we present two spectra. The top represents the on-line histogram spectrum while the bottom represents the replayed spectrum obtained with the

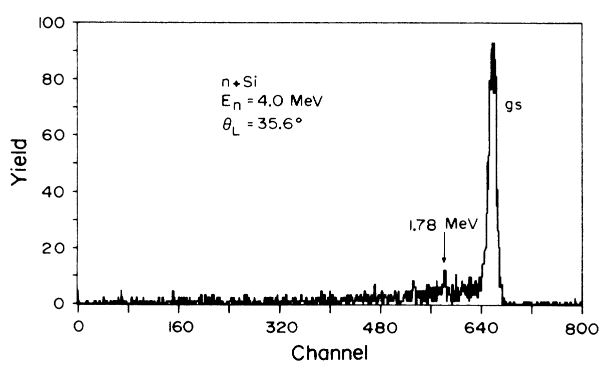

FIG. 1. Neutron time-of-flight spectrum for a 1.36-m flight path obtained with 4-MeV neutrons at $\theta_L = 35.6°$ in coincidence with Si recoiling atoms. Elastic and inelastic scattered neutron peaks are indicated.

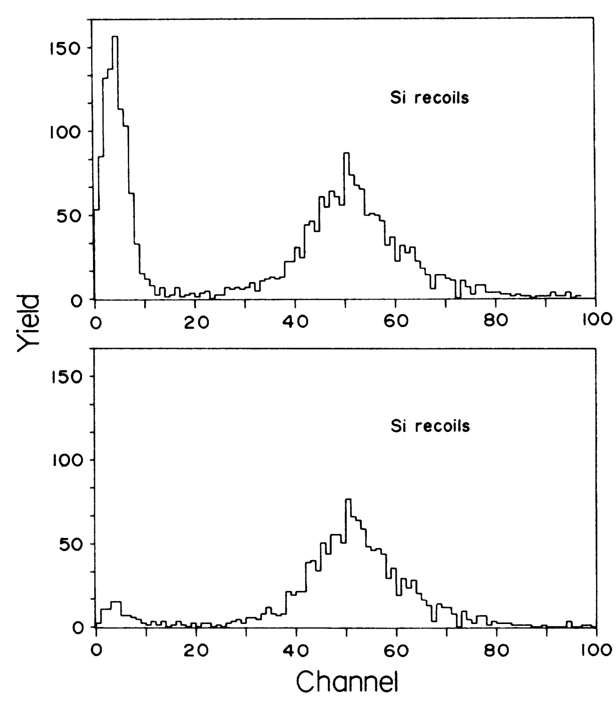

FIG. 2. Top: On-line energy spectrum of recoiling Si atoms. Bottom: Replayed energy spectrum of recoiling Si atoms with the requirement to be in coincidence only with elastically scattered neutrons.

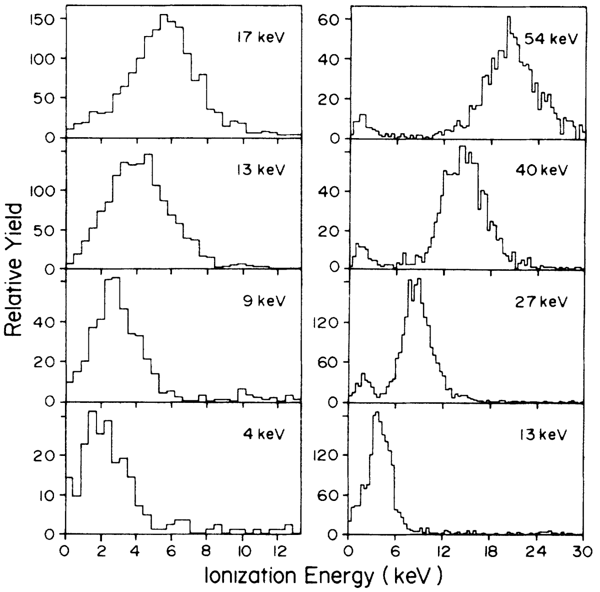

FIG. 3. Energy spectra for Si recoil events of the indicated energies, in coincidence with elastically scattered neutrons at $\theta_L = 35.6°$ (right column) and at $\theta_L = 20°$ (left column).

requirement of coincidence with the elastically scattered neutron time-of-flight peak. The drastic reduction in low Si pulse-height background is clearly visible. Unfortunately boiling of the liquid N_2 in the cold finger produced a microphonic noise near 6 KHz which initially severely limited the resolution and thus our ability to observe particularly low energy recoils. However, the pulse produced by a recoiling atom has a decay constant of a few μsec and the microphonic noise pulses have decay constants of tens of μsec. As a result we were able to implement an on-line background subtraction scheme in software. Every time a good pulse was produced, a signal produced 8 μsec later was subtracted. This method allowed us to extend our measurements down to the 4-keV

TABLE I. Silicon atom recoil energy, observed energy, and calculated fraction of energy observed as ionization.

Si atom recoil energy (keV)±0.5[a]	Observed Si atom recoil energy (keV)	Fraction of energy observed as ionization (%)
53.7	24.2±0.9	45±1.7
40.2	16.7±0.6	42±1.6
26.8	9.7±0.4	36±1.6
17.4	5.1±0.2	30±1.5
13.4	4.0±0.2	31±1.9
13.0	3.5±0.1	27±1.3
8.7	2.1±0.1	23±1.7
4.3	$1.3^{+0.1}_{-0.5}$	32^{+6}_{-14}

[a]Estimated uncertainty based on results of a Monte Carlo simulation program.

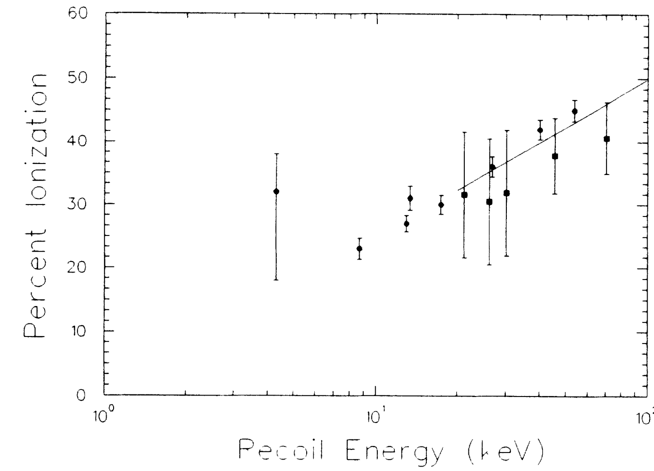

FIG. 4. Fraction of Si atom recoil energy released as ionization energy as a function of Si recoil energy. The solid line represents the prediction by Lindhard, as quoted by Sattler (Ref. 3). The square data points are from Ref. 3; the solid circles are the present data.

Si atoms' recoil energy.

Photon sources, ^{55}Fe, ^{241}Am, and a ^{57}Co conversion electron source, were individually mounted within the vacuum chamber and were used to obtain an absolute energy calibration of the system. A precision pulser was used to check and obtain the linearity of the system in the 1–500-keV energy range. Periodic checks on the stability of the system were done by routinely taking ^{241}Am photon spectra during the experiment, which was done without perturbing the vacuum or cryostat system. No variation was detected in the peak locations of the photon sources.

III. RESULTS

In Fig. 3 we present coincidence spectra obtained at $\theta_L = 20.0°$ and 35.6°, respectively, and with incident neu-

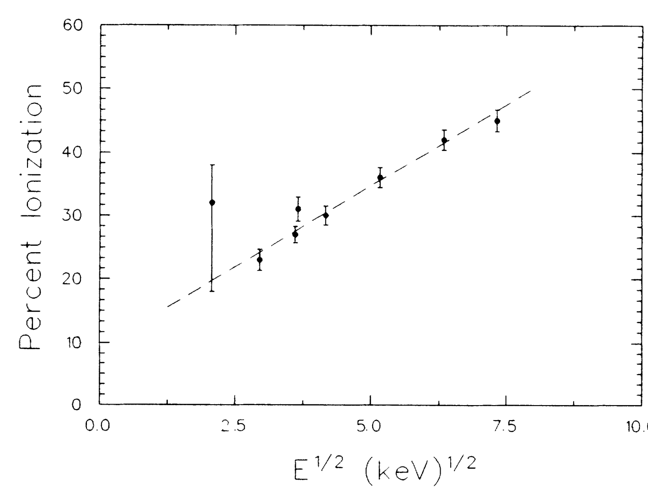

FIG. 5. Fraction of Si atom recoil energy released as ionization energy as a function of Si recoil energy, where the abscissa is proportional to the square root of the recoil energy. The dashed line represents such an energy variation.

tron energies of 4.0, 3.0, 2.0, and 1.0 MeV. In Table I we present the values of the Si atoms' recoil energy, the measured recoil energy, and the fraction of the energy observed as ionization. These data, denoted by solid circles, are also presented graphically in Fig. 4 together with some data points of Ref. 3, denoted by solid squares.

Sattler, in the discussion of his data,[3] gives a detailed description of the theory developed by Lindhard *et al.*[4] which we do not reproduce here. He also lists the predictions of Lindhard[3,4] for the fraction of ionization energies versus Si atoms' recoil energy in the range 20 keV to 3.14 MeV. Those predictions are plotted as a solid line in Fig. 4, which are in good agreement with the present data. Lindhard *et al.*[4] predict that the fraction of energy going into ionization has an approximate $E^{1/2}$ dependence at low energy. We present our data and a dotted line representing this $E^{1/2}$ dependence in Fig. 5. The observed agreement seems to indicate the correctness of Lindhard's assumption down to 4-keV recoiling Si atoms.

Since the fraction of the recoiling energy released as ionization decreases with decreasing recoil energy, the energy lost to atomic processes increases accordingly, making the acoustic detection of this low-energy radiation much more suitable in this energy domain (Ref. 12).

IV. CONCLUSIONS

We have measured the energy released as ionization energy by recoiling Si atoms in a silicon lattice in the energy range 4–54 keV. In the energy above 21.2 keV the present data overlap well with previous measurements by Sattler.[3] The theory of Lindhard *et al.*[4] seems to reproduce quite well the fraction of the total energy of the recoiling silicon atom that is deposited as ionization energy, which in this low-energy domain has an approximate $E^{1/2}$ energy dependence.

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