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Measurements of ionization produced in silicon crystals by low-energy silicon atoms

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We measured the ionization and the fluctuations in ionization produced in a Si(Li) detector by silicon atoms at five particular kinetic energies ranging from about 4 to 109 keV. The method is simple and precise, yet untried until now, and provides excellent calibration points for silicon. Our results are in good agreement with the predictions of Lindhard *et al.* [Mat. Fys. Medd. **33**, 10 (1963)].

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INTRODUCTION

Spectroscopic detectors for neutrinos and various hypothetical weakly interacting dark-matter candidates may be made that sense the coherent, elastic scattering of such particles with nuclei [1]. Several existing and proposed techniques are being pursued using crystalline silicon or germanium as both a target and detector medium. The advantages of these materials include purity (to reduce radioactive backgrounds) and relatively low atomic mass or substantial atomic number (to raise recoil energies or enhance cross sections) [2]. In addition, detectors fabricated from such crystals can be made sensitive to ionization or heat, or even to the prompt phonon signal produced by low-energy recoiling atoms [2,3].

Slow atoms engender less ionization than do photoelectrons of similar energies. Relative ionization efficiencies for germanium in germanium were measured by Chasman, Jones, and Ristinen [4] and Sattler, Vook, and Palms [5] and, for silicon in silicon, by Sattler [6], Zecher *et al.* [7], and Gerbier *et al.* [8]. Their results are generally consistent with the predictions of Lindhard *et al.* [9], but there is significant disagreement, with respect to experimental errors, between the more recent measurements.

In this Brief Report we present ionization measurements for silicon atoms stopping in a lithium-drifted silicon detector [Si(Li)]. Our method is simple, but novel in this context, and provides a set of fixed calibration points in an interesting energy region. As in the previous experiments, slow atoms were knocked out of the silicon lattice via neutron scattering. Instead of constraining the neutron velocities, however, we exposed our detector to broad-energy neutrons produced upon proton-beam bombardment of thick lithium targets. Furthermore, no auxiliary apparatuses were used to determine the scattering angles. To confine the kinematics, we exploited four strong resonances in the neutron-Si elastic-scattering cross section, which engendered recoiling atoms of definite (maximum) energies and led to well-resolved modulations (edges) in the ionization spectra. An additional edge was provided by narrow-energy neutrons produced just over the $^7\mathrm{Li}(p,n)^7\mathrm{Be}$ threshold. The range of recoil energies sampled spans that covered by the more recent, previous experiments. Our results are precise enough to permit a close comparison with the predictions of Lindhard *et al.*

EXPERIMENT

Our measurements were made using the 3-MeV Van de Graaff accelerator at Lockheed's Applied Physics Research Laboratory in Palo Alto, California. Unpulsed beams of protons were sent into ~1-mm-thick pure lithium targets, the latter mounted on a 1-mm-thick stainless-steel beam-line end cap. No collimation or shielding was used, minimizing the "contaminant" flux of neutrons that backscattered from laboratory-room surfaces and nearby objects.

The Si(Li) surface-barrier detector [10] was 10 mm in diameter and 5 mm thick, positioned ~30 cm from our lithium target, coaxial with the proton beam. It was operated near liquid-nitrogen temperature and totally depleted with an applied bias of 1000 V (easily enough to ensure full charge collection). The microphonics-suppressed cryostat was supplied commercially.

Charge collected in the detector passed through a low-noise preamplifier, into an EGG 572 main amplifier and finally into a remotely controlled Tracor Northern 7200, 4096-channel analyzer. Thresholds were set above ~0.4 keV to avoid recording electronics noise. Frequent calibrations were performed using ^{55}Fe and ^{241}Am x-ray sources. Linearity, gain, and resolution [260-eV full width at half maximum (FWHM) at 6 keV] all remained stable to within 0.1%.

The accelerator was calibrated by noting an onset of neutrons at the $^7\mathrm{Li}(p,n)^7\mathrm{Be}$ forward-production threshold of 1881 keV. Beam currents were held low enough (<1 μA) to keep Si(Li) event rates below 4000 sec^{-1}, ensuring that pulse-height resolutions were unimpaired by pileup. Spectra with sufficient statistics were generated in under 30 min.

Our method exploits the known elastic-scattering resonances in silicon at neutron energies of 56, 189, 566, and 815 keV. Since the accelerated protons slowed (to a stop) within our lithium targets, neutrons of all energies were produced, up to a maximum set by the beam energy. In turn, neutrons of any particular energy T scattering in our Si(Li) detector at any angle could provide recoiling atoms of all energies up to approximately $T/7.5$. Therefore, "edges" appeared in the ionization spectra corresponding to recoils from neutrons at the resonance energies. However, scatterings from even higher-energy neutrons also contributed to our spectra in the regions of interest. To reduce this "background," data were taken for proton beams of 1895, 2100, 2330, and 2650 keV, enough to produce neutrons of maximum energies only moderately above the resonances. (See Fig. 1 for a list of these maxima.)

For one measurement, beam energies were set just over the ^{7}Li$(p,n)^7$Be forward-production threshold to obtain neutrons of more narrowly defined energies close to 30 keV. Neutrons striking our Si(Li) detector had first to pass undeflected through the steel end cap of our beam line. Because of the existence of a strong scattering resonance in iron at 28 keV, average neutron energies were raised slightly, and energy spreads were further reduced.

RESULTS

Our raw data are shown in Fig. 1. Beside neutron-Si scattering "signals," the spectra include underlying Compton continua due to ^{7}Li$(p,p\gamma)^7$Li γ rays coming off our lithium targets. These 478-keV γ rays were by far the dominant background; there was little evidence of any other source. The shape of these continua could be measured by taking data at beam energies below the neutron-production threshold. Representative backgrounds are shown fitted to the raw spectra taken at 2330 keV and just over 1881 keV.

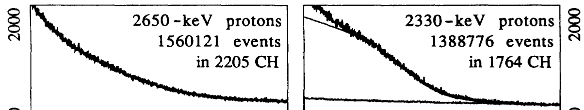

Fig.	max. neutron energy (keV)	scatt. (res.) energy (keV)	Si recoil energy (keV)
(a)	943	815	109.1
(b)	605	566	75.7
(c)	350	189	25.3
(d)	77	56	7.50
(e)	~35	31	4.15

FIG. 1. Raw ionization data are shown above differentiated spectra. Abscissa energy scales were determined from x-ray calibrations. Ordinate scales are in units of counts per channel. Event totals are given only for data in the ranges shown. "Differentiation scales" are explained in the text. Representative Compton backgrounds are shown underlying the 2330- and 1881^+-keV spectra, with an additional, simulated n-Si scattering signal fitted to the former. The inset lists maximum energies of production for ^{7}Li$(p,n)^7$Be neutrons, the scattering energies sampled (mostly at resonances), and the corresponding silicon recoil energies.

The edges indicative of scattering at particular energies are not always readily apparent or easy to interpret. By differentiating, they are remade into more clearly resolved peaks. Our simple differentiation "filter" takes the observed counts N in channels $(k-n-1,\ k+n)$ and returns $\Delta N(k)/n \equiv [\sum_{k+1}^{k+n} N(i) - \sum_{k-n-1}^{k} N(i)]/n$. If the scale n is at most comparable to the range over which spectral features appear, little filter distortion occurs. This transformation averages over statistical fluctuations, n channels at a time; but its stepwise discontinuities produce some raggedness when spectra are very noisy. Nevertheless, it cannot create peaks where there are none, and its output is almost indistinguishable from more sophisticated, smoothly varying (e.g., Gaussian) filters.

Differentiation scales were chosen to reveal the peaks, yet preserve some visible measure of statistical fluctuations. The scales shown in Fig. 1 are about as big as the number of channels it takes for the peaks to appear. However, peak shapes change very little even when differentiation scales are altered by a factor of 2.

We assume there are no unforeseen, rapid modulations which underly the peaks, i.e., that backgrounds vary smoothly. (Indeed, there are no suggestions of narrow features such as stray x-ray peaks appearing in our raw data; but even if there were, our differentiation filter would deemphasize them.) Estimates of peak locations and widths may then be made, estimates which are fairly insensitive to reasonable variations in the shapes of these backgrounds. Our results are presented in Table I and Fig. 2.

The indicated recoil-energy uncertainties reflect, in part, disagreements between past experiments as to the exact locations of the resonances. Furthermore, the peak at 33.3 keV (due to 566-keV neutrons) is augmented by the existence of a narrow D-wave resonance at 531 keV, which is only ~4% as voluminous. Therefore, a weighted average recoil energy is quoted. Finally, our uncertainty in the recoil energy of 4.15 keV is estimated after accounting for the predicted neutron-energy distribution near the production threshold and the loss in neutron flux due to scattering within our steel end cap.

The prominance at 55 keV is not very strong, and its shape is influenced by the nearby, high-side tail of the 33.3-keV peak. These aspects reflect, in large part, the relative heights and widths of the corresponding scattering resonances. Nevertheless, definite spectral inflections indicate the presence of a ~55-keV prominance, and we may locate its center and width to within large errors.

"Lindhard shifts" are offsets that must be added to our observed peak locations before ionization efficiencies are calculated. They reflect the nonlinearity of the predictions of Lindhard *et al.* for ionization (E) with respect to recoil energy (K). If this relationship is approximated as $E = aK^{1+b}$, then the offset is $\delta E \approx 3b\sigma^2/(1+b)E$, where σ is the width of our peak. Since $b \approx 0.2$, we have $\delta E \approx \sigma^2/2E$. (An additional 0.94-keV adjustment for

TABLE I. Summary of results. Ionizations and widths are given with respect to equivalent x-ray energy scales. Uncertainties are 1σ estimates. Lindhard shifts are calculated adjustments to observed ionizations, due to the nonlinearity of the ionization efficiency. Widths are FWHM estimates, except for 25.3-keV recoils, which is HWHM. The last column contains ratios of excess fluctuations (1σ) to recoil energies.

Si recoil energy (keV)	Observed ionization (keV)	Lindhard shift (keV)	Ionization efficiency (%)	Observed width (keV)	Expected width (keV)	Excess fluct. (%)
109.1±0.7	55.5±2	0.55	51.4±2	16±3	3.5±0.4	6.1±1.2
75.7±0.4	33.3±0.4	0.31+0.94	45.6±0.5	9.6±1.0	1.1±0.3	5.3±0.6
25.3±0.3	8.90±0.1	0.074	35.5±0.6	1.30±0.04	0.75±0.1	3.6±0.3
7.50±0.03	2.01±0.02	0.012	26.9±0.4	0.55±0.07	0.24±0.01	2.8±0.4
4.15±0.15	0.93±0.02	0.008	22.5±0.5	0.32±0.06	0.236±0.005	2.2±0.9

75.7-keV recoils is required since scattering is P wave within the 566-keV resonance.)

"Observed widths" are all full width at half maximum estimates, except for the 8.90-keV peak, for which the low-side half width at half maximum (HWHM) is quoted. Small reductions of order 1% were made to correct for oversmoothing caused by differentiation on scales larger than peak widths. "Expected width" calculations take into account our electronics noise (99-eV rms) and the scattering-resonance widths. These latter are transformed into ionization-equivalent terms after multiplying by $E/7.5K$. "Excess fluctuations" denote ratios of the by-quadrature residuals of observed and expected widths to the silicon recoil energies. (We obtain 1σ fluctuations after dividing these ratios by appropriate factors depending on whether full or half widths are considered.)

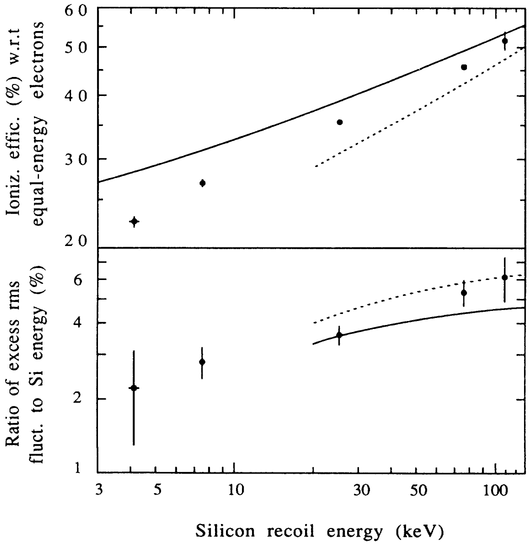

FIG. 2. Ionization efficiencies are measured relative to equal-energy electron depositions (i.e., as from Compton scattering). Excess fluctuations are 1σ (rms). The solid and dashed curves trace predictions by Lindhard *et al.* within their approximations D and E, respectively. Because of increasing uncertainties in these predictions at lower energies, the curves do not extend below certain minima.

As in our measurements of peak locations, the quoted uncertainties reflect our (liberal) assessments of the ranges of possible background shapes.

Other systematic effects that have been considered include the multiple scattering of individual neutrons within our Si(Li) detector, which occurs of order 1% of the time. Such events augment the atomic recoil-energy distribution to include a piece which extends a bit beyond the expected maximum. Since this is equivalent to an underlying "background" which varies smoothly, the differentiated spectrum is just as precisely interpreted. Our method is robust.

In Fig. 1(b) a simulated scattering signal is shown fitted to data taken at 2330 keV. To model this signal, we calculated the thick-target ^{7}Li$(p,n)^7$Be neutron flux for energies from about 300 to 605 keV. The P-wave angular dependence of scattering within the 566-keV resonance was accounted for, as was the influence of the nearby D-wave resonance. Our own ionization and fluctuation results were used to scale and smear the calculated spectrum. This *a posteriori* simulation, together with the fitted Compton background, reproduces our data quite well in the edge region. The poor fit below ~25 keV is likely due to an unaccounted-for flux of lower-energy neutrons that backscattered from laboratory objects. The presence of such neutrons would not affect our interpretations of this edge.

Finally, data were taken at many beam energies different from the ones mentioned. Scattering peaks reappeared atop different backgrounds, but at the same locations and with similar widths.

DISCUSSION

To extend the range of recoil energies investigated, data were taken for proton beams of ~1891 keV and with our Si(Li) detector at 30° with respect to the beam line. This is similar to what was done at 1881 keV, except that neutrons produced at the 30° threshold would have had energies near 22 keV. While a neutron-production onset was confirmed, there was no well-resolved scattering peak in the resulting differentiated ionization spectrum. This may have been due to the combined effects of a lower production cross section at 30°, the spectral proximity of events attributable to electronics noise, and the lack of intervening materials (such as our steel end cap) whose component elements possess convenient scattering resonances which help narrow the neutron-energy distribution.

An attempt will not be made here to explain any disagreement between the present results and others of comparable precision [7,8]. However, our data do not support quite as steep a dependence of the ionization efficiency on recoil energy as may be suggested by these other measurements.

Both our ionization efficiency and fluctuation results are in general agreement with trends in the calculations of Lindhard *et al.* over the entire range of energies sampled [11]. However, the predictions within approximation D consistently overestimate our measured efficiencies and (although not as significantly) underestimate the observed fluctuations. (Approximations D and E are identical except that the latter includes an assumption of small energy transfers in secondary silicon-silicon collisions.) This gap would narrow if the rate of energy loss through ionization is less than that assumed in the calculations. However, since Lindhard *et al.* overestimated the nonionizing stopping power [12], we may suspect that approximation E is more accurate.

In conclusion, at five particular energies from about 4 to 109 keV, we have measured ionization efficiencies and fluctuations for recoiling silicon atoms stopping in a Si(Li) detector. Although our experimental method is simple, it lacks general applicability; for example, there are no convenient neutron-scattering resonances in germanium with which to perform similar measurements in this low-energy region. Nevertheless, for the important case of silicon, a significant range of recoil energies were sampled, and the data were unambiguously and precisely interpreted. Our results compare well with the predictions of Lindhard *et al.* and indicate which of their approximations provide a more accurate energy-loss theory.

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