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Average Triton Energy Deposited in Silicon per Electron-Hole Pair Produced

JOHN J. SMITHRICK AND IRA T. MYERS
Lewis Research Center, National Aeronautics and Space Administration, Cleveland, Ohio 44135

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The average triton energy required to produce an electron-hole pair in silicon was measured. The measured value was 3.64±0.04 eV. This is the first published measurement of this quantity. Precision charge calibration of the amplifier system, plus a special experimental method for correcting for dead-layer losses in the detector, was used to improve the accuracy of the result.

I. INTRODUCTION

IN order to calculate the energy deposited in a neutron spectrometer where tritons and α's are the recoil particles, the energy deposited in silicon per electron-hole pair produced must be known. Several measurements have been published for α particles, electrons, and heavy charged particles,[1–9] but none have been reported for tritons. The available theoretical work[10] is not definitive enough to distinguish between particle types.

This paper describes a precise experimental measurement of ϵ_T (energy deposited in silicon per electron-hole pair for tritons). Errors due to pulse calibration are minimized by a careful charge calibration technique; errors due to dead-layer effects are minimized by a special technique using recoil α particles.

The results of this work are compared with reported measurements of α particles, electrons, and nitrogen ions to ascertain the possibility of a trend in energy deposition per electron-hole pair with particle mass.

II. DEAD-LAYER CORRECTION

In order to measure the triton energy deposited in a material per electron-hole pair produced (ϵ_T), it is necessary to know both the energy lost in the solid and the charge produced, since ϵ_T is the ratio of these two quantities. In the present work, the tritons from the $\mathrm{Li}^6(n,\alpha)\mathrm{T}$ reaction[11] were used as a source of tritons of known energy, and the charge q_T produced per triton in the silicon was measured with a calibrated amplifier–pulse-height-analyzer system. The lithium-6 was part of a semiconductor sandwich-type neutron spectrometer[12] which functioned as a detector of the tritons and α-particles produced in the reaction (see Fig. 1). The energy given to the triton plus the energy given to the α particle is equal to the neutron energy plus the known Q of the reaction. In these measurements, thermal neutrons were used; hence, the energy E_T given to the triton plus the energy E_α given to the α particle was the Q of the reaction.

The triton energy ϵ_T per electron-hole pair is given by

$$\epsilon_T=\frac{e}{q_T}\left[E_T-\left(\frac{dE}{dx}\right)_{T,\mathrm{Au}}\bar{X}_{\mathrm{Au}}-\left(\frac{dE}{dx}\right)_{T,\mathrm{LiF}}\bar{X}_{\mathrm{LiF}}\right], \quad (1)$$

where e is the charge on the electron, q_T is the charge produced in the detector by a triton, and E_T is the triton energy. The quantities $(dE/dx)_{T,\mathrm{Au}}\bar{X}_{\mathrm{Au}}$ and $(dE/dx)_{T,\mathrm{LiF}}\bar{X}_{\mathrm{LiF}}$ are the dead-layer energy losses in the gold and lithium fluoride layers, respectively. The thicknesses $\bar{X}_{\mathrm{Au}}$ and $\bar{X}_{\mathrm{LiF}}$ must be averaged over all angles for the triton. However, since α particles are emitted in the same number and with the same angular distribution as the tritons, the measured energy loss of the α particle in the dead layer may be used to correct for the triton energy loss. The α-particle energy loss in the dead layers is given by $E_\alpha-q_\alpha\epsilon_\alpha/e$, where E_α is the critical α-particle energy, q_α is the measured α-particle charge as deposited in the detector, and ϵ_α is the α energy per electron-hole pair in silicon as known from the literature. (See Table I.) In compiling Table I, some of the earlier, lower accuracy work[6,7] has not been included.

TABLE I. Average α-particle energy deposited in silicon per electron-hole pair produced.

Reference	ϵ_α [eV/(electron-hole pair)]
1	3.62±0.04
	3.65±0.02
2	3.61±0.01
3	3.61±0.01
4	3.58±0.015
5	3.625±0.02
Average	3.62±0.02 (95% confidence)
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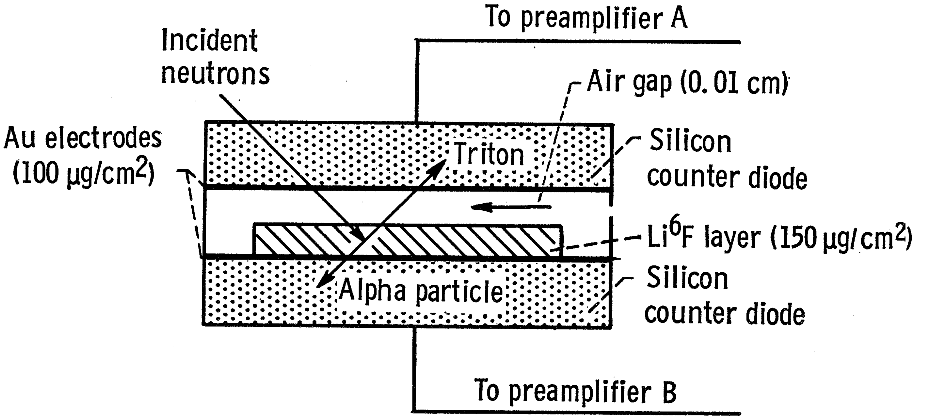

FIG. 1. Neutron spectrometer detector.

The relation between the average energy lost in the dead layers by a triton and by an α particle is

$$\left(\frac{dE}{dx}\right)_{\mathrm{T,Au}}\bar{X}_{\mathrm{Au}}+\left(\frac{dE}{dx}\right)_{\mathrm{T,LiF}}\bar{X}_{\mathrm{LiF}}=\frac{1}{K}\left(E_{\alpha}-\frac{q_{\alpha}\epsilon_{\alpha}}{e}\right), \qquad (2)$$

where K is the average value of the ratio of the stopping power of α particles to the stopping power of tritons. The differences of triton and α energy and the fact that two dead-layer materials are involved are handled by a simple averaging technique. As will be seen in the error analysis given later, the error in the value of ϵ_{T} contributed by the dead-layer correction is small.

III. APPARATUS

A schematic diagram of the lithium-6 spectrometer detector is shown in Fig. 1. Neutrons incident upon the assembly interact in the Li^{6}F layer giving rise to tritons and α particles according to the Li$^6(n,\alpha)$T reaction. The tritons and α particles are detected in the two silicon semiconductor counters. The silicon counter pulses are ultimately recorded by a pulse-height analyzer. The amplitude of these counter pulses has a one-to-one correspondence to the triton and the α-particle energy. The source of thermal neutrons was a 0.5-Ci plutonium-beryllium source surrounded by paraffin.

A block diagram of the spectrometer-detector electronic system, used both to measure ϵ_{T} and for the charge calibration of the amplifier–pulse-height-analyzer system, is shown in Fig. 2. This system consisted of a precision mercury-wetted relay pulse generator, two charge amplifiers, a coincidence unit, and an 800-channel pulse-height analyzer. The coincidence unit receives its signals from the two charge amplifiers and delivers a gate signal to the analyzer if the two signals from the charge amplifier are in time coincidence within

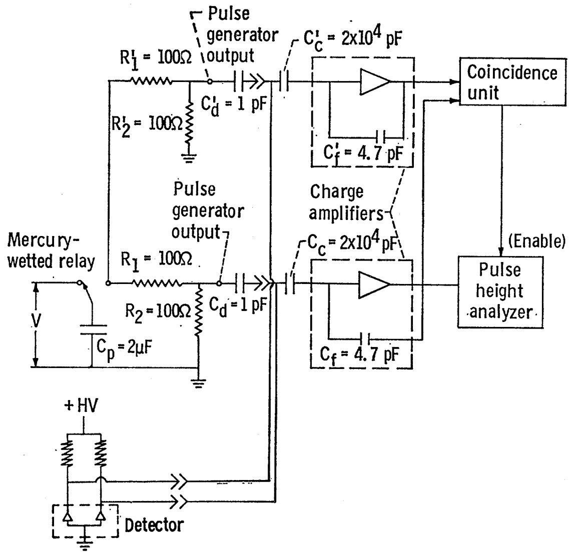

FIG. 2. System used to measure ϵ_{T} and for charge calibration.

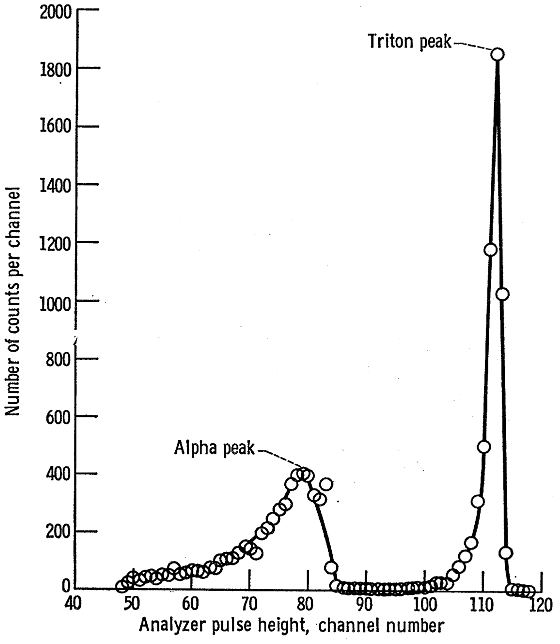

FIG. 3. Typical experimental pulse-height distribution.

about 6 μsec. The gate signal enables the analyzer to accept the signals supplied to it from one of the charge amplifiers. The purpose of using a coincidence unit is to minimize the number of electronic noise pulses counted by the pulse-height analyzer.

The spectrometer system was used with and without a cadmium cover on the spectrometer detector, and the difference in readings was used to calculate q_T and q_α. The use of a cadmium difference eliminated the effect of the small number of fast neutrons present. The cadmium difference readings were used as weighting factors to calculate the average analyzer pulse height of the triton and the α particle. A typical experimental pulse-height-distribution curve for tritons and α particles is presented in Fig. 3. The charge corresponding to the average pulse height of the triton and α particles was then obtained from a pulse-height-analyzer calibration curve.

The accuracy to which the charge deposited by the triton can be measured depends on the accuracy of the amplifier–pulse-height-analyzer system calibration. The calibration of this system was performed with a mercury-wetted relay pulse generator driving a 1-pF capacitor, which was used as a charge generator (Fig. 2). A detailed description of this calibration method and its accuracy is presented in Ref. 13. In this reference the effects of cable capacitance, cable reflections, and system response time on the accuracy of the precision calibration of the charge amplifier–pulse-height-analyzer system used in this work are presented. The calibration accuracy was about 0.4%.

FIG. 4. Typical curve $\epsilon_{T,m}$ as a function of $1/\sqrt{(V_d+V_b)}$ detector, 46; diode 343; channel B, room temperature.

IV. RESULTS AND DISCUSSION OF ERRORS

TABLE II. Values of ϵ_T for various silicon spectrometer detector diodes.

Detector	Diode	Channel	ϵ_T [eV/(electron-hole pair)]
46	343	B	3.65
46	343	A	3.63
46	355	A	3.62
48	345	A	3.63
48	359	A	3.64
48	359	A	3.64
Average			3.64±0.04

The value of ϵ_T as measured (denoted by $\epsilon_{T,m}$) depends upon the bias V_d applied to the detector. This dependence is due to the variation of the junction capacitance with applied bias, which causes a change in the capacitance loading of the amplifier input circuit. A typical curve of $\epsilon_{T,m}$ as a function of $(V_d+V_b)^{-1/2}$ is presented in Fig. 4, where V_b is the detector barrier potential of about 0.6 V. The plot of $\epsilon_{T,m}$ against $(V_d+V_b)^{-1/2}$ gives a straight line since the detector capacitance has the voltage dependence of an abrupt p-n junction. The $\epsilon_{T,m}$ values extrapolated to a zero value of $(V_d+V_b)^{-1/2}$, which is equivalent to zero detector capacitance, is independent of the applied bias. Extrapolated values ϵ_T of $\epsilon_{T,m}$ for various detector diodes are presented in Table II. All these values agree within the experiment error.

The total error in ϵ_T was taken as the rms error of the systematic and the statistical errors in ϵ_T. The systematic error is due to the uncertainty in the parameters involved in ϵ_T. The statistical error in ϵ_T was computed, based on a 95% confidence level, from the standard deviations of the ϵ_T values presented in Table II. The total rms error in ϵ_T is 1.0% and is based on the data presented in Table III, which consist of a list of parameters, their percentage errors, and their rms contribution to the total error in ϵ_T. The data in this table indicate that the systematic error contributes more than the statistical error to the total rms error in ϵ_T, and also that K is the primary contributor to the systematic error. The total error on ϵ_T is larger than, but comparable to, the errors on best later values of ϵ_α.

TABLE III. rms contributions to error in ϵ_T.

Source of error	Error in parameter (%)	rms contribution to error in ϵ_T (%)
K	23.0	0.6
E_T	0.5	0.5
q_T	0.4	0.4
ϵ_α	0.6	0.08
q_α	0.4	0.06
E_α	0.5	0.08
Statistical	···	0.34
total rms error		1.0

TABLE IV. ϵ in silicon for different charged particles.

Type of particle	Average energy deposited per electron-hole pair produced [eV/(electron-hole pair)]	Reference
Electrons	3.79±0.01	3
	3.67±0.02	5
Tritons	3.64±0.04	This paper
α's	3.62±0.02	Table I of this paper
Nitrogen atoms	3.50±0.07	7

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V. CONCLUDING REMARKS

Based on the information in Tables II and III, the average value of ϵ_T is 3.64±0.04 eV per electron-hole pair in silicon. A search of the literature revealed no other value of ϵ_T. Literature values of ϵ for α particles, electrons, and nitrogen atoms are summarized in Table IV. A first examination of the table seems to indicate a decrease in ϵ with increasing mass of the bombarding particle. This conclusion must be tempered by the comparatively large difference between values of ϵ for electrons, reflecting a large uncertainty in the accuracy of the measured values. Also, Halbert and Blankenship's value[7] for ϵ for nitrogen atoms is given as being equal within 1% to the value of ϵ for α particles, which they determined to be 3.50±0.05 eV per electron-hole pair. If the best value of ϵ_α of 3.62 is taken to be correct, then the Ref. 7 value for ϵ for nitrogen atoms may be in error.

Because of the uncertainties indicated, it is not possible to confirm a trend in energy deposition with particle mass. Further, based on a best value of ϵ_α of 3.62 and the value of ϵ_T derived herein, it may be concluded that ϵ_T and ϵ_α are equal, within experimental error.

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Mössbauer Measurements of Tin-Antimony Solid Solutions*

S. L. Ruby, H. Montgomery,† and C. W. Kimball‡
Argonne National Laboratory, Argonne, Illinois 60439

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The isomer shifts for both Sb^{121} and Sn^{119} nuclei have been measured in primary solid solutions of the Sb+Sn system. The experimental results show that the variation of isomer shift with concentration is much weaker than that from one insulating compound to another. This indicates that an increase in the number of electrons per atom hardly changes the number of 5*s* electrons.

The isomer shift has been measured for Sb^{121} and Sn^{119} nuclei in both tin-rich and antimony-rich Sb+Sn alloys over the complete range of solid solubility. Such measurements show how alloying influences the number and character of the valence electrons of both solvent and solute ions. From these results, one may then draw inferences about the electronic structure of primary solid solutions of polyvalent metals.

Alloys of composition 0, 2, 4, and 6% antimony in tin and 0, 2.5, 5.0, 7.5, and 10% tin in antimony were examined. (All compositions are given in atomic percent.) In the measurements of the Sn^{119} resonance, both $CaSnO_3$ and Mg_2Sn were used as source matrices. The antimony measurements were performed with Sb^{121} in a $CaSnO_3$ matrix. For the results reported here, source and absorber were held at 80°K. Measurements were also made with the absorber at 200°K. The composition dependence of the shift at this higher temperature was the same (within experimental error) as that measured at the lower temperature, so only the measurements at 80°K are reported here. A broadened singlet was observed for both Sn^{119} (width ~1.6 mm/sec) and Sb^{121} (width ~2.8 mm/sec) for all alloys. In order to establish that our samples were indeed single-phase alloys, two methods were used. First, metallographic observation at 300 *X* after a standard Nital etch showed no second-phase precipitate. Second, x-ray analysis was used to confirm the β-Sn(*A*5) and antimony (*A*7) structures.

The results for the experimental isomeric shifts are given in Table I. To compare with earlier work, it is convenient to refer these measurements to α tin and InSb, respectively, rather than to the $CaSnO_3$ sources used. This is done by adding −1.78 and 8.62 mm/sec to the experimental values. Previous measurements on the Sn+Sb system[1] have been attempted with Sn^{119}; there is indication that the material used was often of two phases.

Table I. Isomer shifts and electronic charge densities.

	Experimental shifts[a]		Charge densities	
Sb (%)	Sn (mm/sec)	Sb (mm/sec)	Sn	Sb/1.3
0	2.528±0.003	(−11.27±0.04)[b]	19.180±0.02	17.58±0.05
2	2.539	−11.29±0.08	19.255	17.59±0.40
4	2.541	−11.14±0.02	19.267	17.41±0.15
6	2.547	−11.08±0.06	19.306	17.38±0.06
90	2.650±0.005	−11.58±0.02	19.990±0.03	17.90±0.03
92.5	2.649	−11.581	19.983	17.93
95	2.660	−11.602	20.057	17.98
97.5	2.660	−11.678	20.057	18.02
100		11.690		17.02

[a] Measured relative to $CaSnO_3$.

[b] This point is found from a measurement of the shift between InSb and a source of β tin containing Sn^{121*} that decays to Sb.

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* Based on work performed under the auspices of the U. S. Atomic Energy Commission.

† Visiting scientist, Metallurgy Division. Permanent address: The University of Edinburgh, Edinburgh, Scotland.

‡ Visiting scientist, Metallurgy Division. Permanent address: Northern Illinois University, DeKalb, Ill.

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