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PHOTON AND ELECTRON RESPONSE OF SILICON DIODE NEUTRON DETECTORS*

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ABSTRACT

The photon response of silicon diode neutron detectors is analyzed theoretically and measured in the 15 to 25 MeV region. The main mechanism for producing a response in the diode is shown to be the displacement of silicon atoms by scattering of electrons. If the photon source is an electron accelerator target, the response is mostly due to electrons originating in the target with a smaller contribution from electrons produced in the diode by photons generated at small angles to the beam.

INTRODUCTION

In recent years there has been a trend toward the use of higher energy electron accelerators as x-ray and electron sources for radiotherapy. There are now several commercial electron linacs available in the range of 18-35 MeV. Betatrons up to 45 MeV are available and have been used for many years in the energy range above 15 MeV. For most elements the photoneutron threshold is somewhere in the 6-18 MeV range, so there is an inevitable production of neutrons also. Since the neutrons are relatively unaffected by the photon collimation and shielding, they constitute a component of leakage radiation which contributes to the whole-body dose of the patient. Measurements of the neutron radiation fields around medical accelerators have been reported frequently. (See for example Wilenzick et al.[1])

In all of the above measurements, the experimenters have had the problem of detecting neutrons in the presence of high energy photons. Various kinds of neutron detectors were used, e.g., moderated activation foils, silicon diodes, etched-track detectors, etc. Each of these detectors has some photon sensitivity which was often not evaluated at the photon energies being used. It is the purpose of this paper to study the photon response of the silicon diode in the energy range above 15 MeV.

THEORY

Neutron bombardment of the diode crystal causes the displacement of silicon atoms from their lattice sites. The created vacancies and displaced atoms disrupt the conductivity of excess charge carriers in the base of the junction. Thus a measure of the change in conductance can be correlated to the neutron damage in the crystal. A means to monitor the damage is to measure under constant current conditions the equilibrium forward voltage before exposure and at some time after exposure. The increase in forward voltage is a nonlinear function of the neutron dose.[2]

The neutron response has been measured at neutron energies down to 0.2 MeV. Although no response has been seen at lower energies, it is not clear whether this is because the lower-energy neutrons cannot cause the above type of damage or whether it is due to the sharp decrease in the neutron scattering cross section of silicon just below 0.2 MeV. The recoil energy of a silicon atom after a 0.2 MeV neutron scatters off it can be up to ~ 26.6 keV. The energy required to displace a silicon atom in the crystal lattice is much less, of the order of 13-30 eV, so one would expect the neutron threshold energy to be much less than 0.2 MeV. It is possible that a certain minimum size of the cluster of displaced atoms is necessary to be effective. However, Speers[3] was able to predict the energy dependence of diodes by assuming it was proportional to the average energy given to the lattice atoms.

It is reasonable to expect that the diodes would respond in the same manner if photons produced silicon nuclear recoils of sufficient energy. Photons can cause nuclear recoil by the processes of photoelectric absorption, pair production, coherent scattering (Rayleigh, Nuclear Thomson, and Delbruck), nuclear resonance absorption, and through photoproduction processes [(γ,n), (γ,p), (γ,α), etc.]. It can be calculated that the nuclear recoil energy following pair production is too small to produce displacements. The photoelectric process can produce sufficient recoil energy at about 8 MeV or above, but the cross section is $\ll 1$ mbarn and can be neglected. The coherent scattering processes also have sufficiently small cross sections to be neglected. Resonant scattering cross sections are large close to the resonance energy, but the resonance levels are so narrow that the overall effect will be negligible. We are left with the photoproduction processes.

The threshold energies of the (γ,n), (γ,p), and (γ,α) reactions in the stable isotopes of silicon are given in Table I.[4] The natural abundances of ^{28}Si, ^{29}Si, and ^{30}Si are 92.21%, 4.70%, and 3.09%, respectively. It is clear that all of these reactions will produce sufficient recoil energy of the nucleus to displace it from the crystal lattice. The products of these reactions are isotopes of Si, Al, or Mg, and their effects on the diode performance are unknown. Probably, the dominant effect will be due to the displacement of many Si atoms by the recoiling nucleus and the emitted charged particles.

The cross sections of the above photoreactions are not as well-known as one could wish. Ahrens[5] has measured the $(\gamma,\text{anything})$ cross section, which agrees with the data of Wyckoff[6] below 23 MeV. From 23 to 25 MeV, Wyckoff's data are a factor of 2 or more smaller. The partial reaction cross section data of other authors may be combined to give a $(\gamma,\text{anything})$ curve which is in agreement with the measurements of Ahrens, so the Ahrens results have been used in this paper. While there is considerable structure in the cross section curve, it is useful to note that the cross section is of the order of 6 mbarns for neutron energies from about 14 MeV to 17 MeV and 30 mbarns from 18 MeV to 25 MeV.

The neutron reaction cross section with silicon also shows considerable detail,[7] but varies only between 12 barns and 1.8 barns for 0.2 MeV to 20 MeV. The use of a 3 barn cross section will be within a factor of 2 over almost all of this range. From the above discussion it appears that the silicon diode response <u>per photon</u> in the 18-25 MeV range should be of the order of 100 times smaller than the response <u>per neutron</u> (0.2-20 MeV) and 500 times smaller for photons between 14 and 17 MeV.

Dislocations in Si can also be produced by Rutherford scattering of electrons. These electrons may come either directly from the target, or be produced in the diode itself by the photons. The results of Cahn[8] may be used to calculate the displacements produced in Si by photon-produced electrons. Similarly, displacements due to electrons bombarding the Si from the target can be calculated from the results of Oen,[9] who found cross sections for electrons producing a primary recoil Si atom to be on the order of 50 barns. It is immediately apparent that this process may be the dominant mechanism in many cases, being some 17 times greater than the neutron cross section for producing a recoil Si nucleus.

EXPERIMENTAL

For the experiment, Si diodes, Si discs, and moderated activation foil detectors were used. The moderated activation foil detector consisted of a commercial moderator (Reactor Experiments, Inc.) and indium foils 2" in diameter and approximately 2.7 grams each. The moderator is a cylinder of low-density polyethylene $6\frac{1}{4}$" in diameter by 6 1/16" long covered with 0.020" of cadmium. Neutrons are detected by the reaction $^{115}In\ (n,\gamma)\ ^{116}In$ ($T_{\frac{1}{2}} = 54$ min). Photons cannot be detected directly but photoneutrons produced in the moderator assembly can cause a photon response. The photon response of this detector has been reported in a separate paper.[10]

The Si discs were thin slices of single-crystal Si about 1.4 mils thick and 1" in diameter which were used as activation detectors, subsequently being counted on a thin-window pancake G. M. counter.

The Si diode fast neutron dosimeter 5422, manufactured by AB Atomenergi in Studsvik, Sweden, consists of a superdoped silicon wafer with a base width of 0.050 inches between two silver contacts coated with 2 mm of epoxy. For this experiment, we used the technique of measuring the percent change of voltage versus dose. Good precision was obtained using both unirradiated and pre-irradiated diodes. All diodes, calibrated against ^{252}Cf in air, were read out 48 hours after irradiation to account for any room temperature annealing.

The accelerator used for this experiment was a Varian Clinac 35 medical accelerator. The Clinac 35 has facilities for bringing the electron beam out through a thin Be window after the first bending magnet. The accelerator was used in this mode with an external water-cooled aluminum target $1\frac{1}{2}$" thick (0.429 radiation lengths). Aluminum was chosen to minimize neutron production. There are a copper collimator and an energy slit just before and after the first bending magnet, respectively (Fig. 1). This area is shielded with tungsten and lead and was an unavoidable source of neutrons which was independent of the target. There was no instrumentation available to determine the beam current intercepted by the collimator. However, the external target was electrically isolated and thus could be used as a Faraday cup. It is a rather poor Faraday cup since it is not designed to minimize the escape of electrons, is slightly thinner than the maximum range of 25 MeV electrons, and will therefore underestimate the beam current. The accelerator was in a concrete shielded room with dimensions 22' × 21' × 9'8" (Fig. 2). The accelerator was rotated $\sim 65^{\circ}$ from the vertical so that the beam was 5'6" above the floor. Measurements at points marked A in Fig. 2 with moderated In foils and no external target (electrons striking the wall approximately 10 feet from the window) indicated a source of neutrons at the collimator location, another at the wall, and a third near the exit window. These three sources produced a neutron field which did not change too rapidly with position in the area of our measurements. The neutrons from the $A\ell$ target added about 25% to the neutron fluence for our closest measurements. The target neutron yield when measured with the moderated In foils at large angles agreed well with that expected from Barber and George.[11] The agreement was better than would be expected in view of the inaccuracies involved in extrapolating Barber and George's 1 R.L. yield to our thinner target and the uncertainty in our beam current. At small angles it was clear that the moderated In foils were also detecting photons. An array of Si diodes was exposed in the regions denoted by B in Fig. 2. The results of the moderated In foil measurements above showed that for these exposures the total neutron absorbed dose well under 1 rad and therefore not measurable by the silicon diodes. Thus we can attribute all responses of the Si diodes to other effects. We will refer to these as the "apparent neutron responses".

The angular distribution of the apparent neutron response of the Si diodes can be compared with the calculated angular distributions of dislocations produced by photoproduction and by electrons. Monte Carlo calculations using the EGS code[12] were made to provide information on the electrons and photons coming from the target. (The authors wish to thank Dr. W. R. Nelson and Dr. R. L. Ford for running the Monte Carlo calculations.) This code had been checked previously against measured photon yields and photon spectra and excellent agreement found.[13] The calculation provided both electron and photon spectra in various angular bins.

In Fig. 3 is shown the expected angular distribution of (γ, anything) reactions (histogram) using the cross sections of Ahrens and photon data taken from the Monte Carlo calculations. Fig. 3 also shows the distribution of an apparent neutron fluence measured with the Si diodes (open circles) assuming that the measured change in forward conduction of the diodes was neutron-induced and normalized by eye to the histogram. It is clear that the angular distributions are quite different, and so other effects must be examined to explain the diode response.

The shape of the photoreaction angular response curve can be checked by other means such as measuring the activation of Si discs. Cross section data, while incomplete, show that the (γ, p) reaction in Si is the single most important reaction. In ^{28}Si, this reaction leads to stable ^{27}Aℓ, but in ^{30}Si it leads to ^{29}Aℓ with a 6.6 minute half-life which is easily measured. The discs were exposed under the same conditions and the data included in Fig. 3 as solid circles, with the horizontal bars indicating the range of angles subtended by the discs and normalized by eye to the histogram. It is apparent that we observe the expected angular distribution, which gives added confidence in the Monte Carlo calculations.

The dislocations produced in Si from photons and electrons were then calculated using the data of Cahn and Oen respectively. To get absolute values, the number of accelerator electrons incident upon the target must be known. The true current in the experiment was determined by the current measured from the target and corrected for electron escape as determined from the EGS Monte Carlo calculations. As a cross-check, the dose rate was determined using a calibrated ionization chamber placed downstream of the target at 0°. Again using the Monte Carlo results for both electron and photon fluence at that location and correcting for the buildup condition existing, we could calculate the current which would produce the measured dose rate. These two methods gave 7.5 and 7.8 microamps respectively, and we used the former. The Si diodes were exposed for two minutes at this current, or for 5.62×10^{15} electrons of 25 MeV striking the target.

The results of the calculations for electrons and photons, in displacements per gram per 5.62×10^{15} electrons striking the target, are shown in Fig. 4 for two representative values of E_D, the energy required to displace a Si atom. In Fig. 5 we have added the electron and photon components together, and compared the resultant curve with the apparent neutron angular distribution measured by the Si diodes. The apparent neutron data have been normalized to the upper histogram at the smallest angle in this figure. The agreement between the measured angular distribution and the calculated one is rather good, and it seems clear that the Si diodes are really measuring photons and electrons.

It is possible to make an absolute comparison between calculated displacements and the measured response of the Si diodes by converting the apparent neutron rad response into number of displacements. The diodes were calibrated using neutrons from a ^{252}Cf source. At the point near 0^o, the diodes measured an apparent neutron dose of 1.8×10^2 rads which, using data from ICRP Publication 21, would indicate a fluence of about 4.4×10^{10} n/cm^2. This can be converted into the number of displacements knowing the fraction of the absorbed energy that goes into atomic displacement for neutrons, which has been calculated by various authors including Sattler[14] and Rogers.[15] With this information, and using the Kinchin-Pease[16] model, where the number of displacements is given by the atomic displacement energy divided by 2 E_D, the number of displacements in the Si diodes can be determined, and compared with Fig. 5.

We determine the atomic displacement energy by reading the graphs of either Sattler or Rogers et al. at the 2.35 MeV average energy of ^{252}Cf neutrons, obtaining a value of about 3×10^{-9} erg-cm^{-1} per n-cm^{-2}. Sattler includes a fission spectrum measurement of about 2×10^{-9} erg-cm^{-1} per n-cm^{-2} which came from a bare reactor spectrum and should be somewhat softer than that from ^{252}Cf. Using the higher value, we obtain 2.6×10^{12} and 1.7×10^{12} displacement per gram for E_D = 16 and 24 eV respectively. These values are about 20% higher than the values calculated near 0^o in Fig. 5 from photons and electrons, which is quite good agreement. Thus it seems apparent that the Si diodes are responding to photons and electrons from the target.

A useful way to consider the results is that we measured an apparent neutron dose of 1.4×10^{-2} rads per rad of photons measured at maximum buildup. A similar measurement at 15 MeV with the same target gave an apparent neutron dose of 1.6×10^{-3} rads per rad of photons measured at maximum buildup. A practical radiotherapy x-ray beam will have quite a different target, with a beam flattener after it. While this will make a change in the fluence as well as the energy spectra of the photons and electrons, the problem will not change drastically, especially in the forward direction; that is, Si diodes will not be usable for measuring neutron fluences in the beam. The responses above will not be directly applicable.

It is of interest to see if Si diodes can be used to measure neutron leakage, i.e., outside the photon beam. The Monte Carlo program was run in successive thicknesses of tungsten as a representative shielding material. The ratio of the fluence of photons to electrons quickly approaches a value of about 200 to 1 and stays constant. A 25 MeV accelerator with a photon leakage of 0.1% will have a leakage electron fluence of approximately 1.4×10^4 e^-/cm^2 per rad of photons at the isocenter. By comparison with our previous calculation we can estimate that this would give an apparent neutron dose of about 8×10^{-6} rads per photon rad at the isocenter. Therefore, for the purposes of measuring neutron leakage the Si diodes are satisfactory. It should be noted, however, that a diode calibration based on exposure to a fission neutron spectrum will not be satisfactory since the neutron spectrum will be softened by passing through the lead or tungsten shielding material.

The leakage calculation above is also roughly applicable to measurements in the 25 MeV therapy x-ray beam of a machine using a tungsten flattener. A lead flattener has a similar photon/electron fluence ratio. Since the measurement is in the beam, we would expect 8×10^{-3} rads of apparent neutron dose per photon rad at the isocenter. This can be compared with about 5 to 6×10^{-3} rads of neutrons per photon rad at isocenter reported by Wilenzick et al. Their measurement was for a Sagittaire accelerator using a lead flattener. A similar value was found by Oliver on a Clinac 35 with a tungsten flattener. This is a quite reasonable agreement considering the complexity of the therapy beam geometry compared to our simple model.

The reasonable agreement, both in angular distribution and in absolute intensity, of the diode response as measured and calculated assuming electron and photon interactions in the beam, strongly suggests that the apparent neutron doses reported in the literature (Refs. 1 and 17, for example) were actually due to electron and photon rather than neutron interactions in the diodes.

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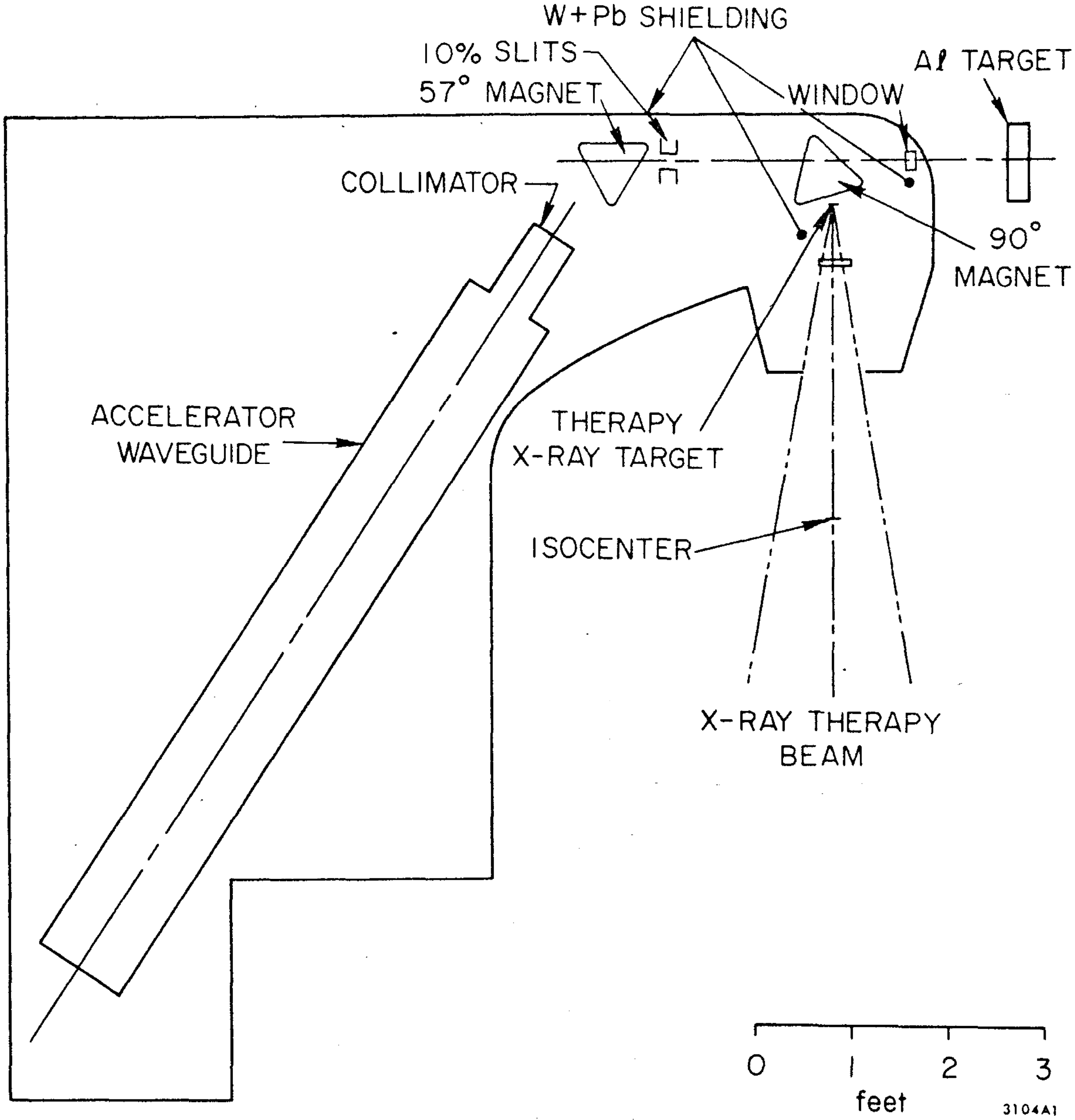
TABLE I

Threshold energies of photon-induced reactions in the stable isotopes of silicon.

Isotope	Threshold Energy (MeV)		
	γ,n	γ,p	γ,α
^{28}Si	17.18	11.58	9.98
^{29}Si	8.48	12.33	11.13
^{30}Si	10.61	13.51	10.60

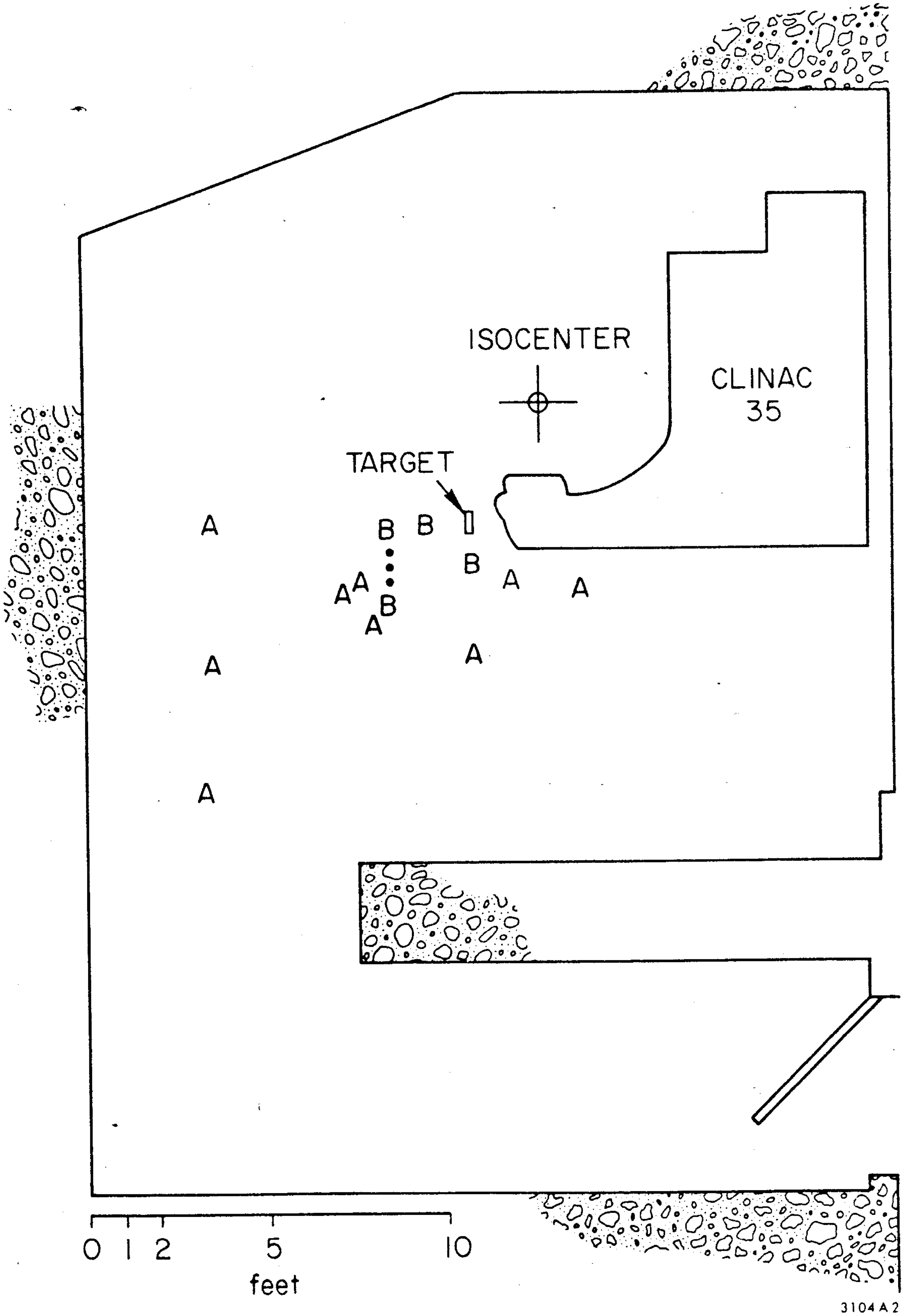
FIGURE CAPTIONS

1. Schematic diagram of the Clinac 35 as used in this experiment.
2. Geometry of the experimental arrangement. Points indicated by (A) denote measurements with moderated In foils. Points and areas marked (B) indicate Si diode measurements.
3. Comparison of relative angular responses of Si (from photoactivation) and Si diodes (from percent change in voltage) with the calculated angular distribution from (γ, anything) reactions on Si for an incident 25 MeV electron beam on an $A\ell$ target. Histogram - calculation; ⊢●⊣ - Si activation with angular occlusion given as error limits; ○ - Si diode response.
4. Calculated angular distribution of dislocations in Si produced by radiation from an $A\ell$ target struck by 25 MeV electrons. Solid histograms - dislocations produced from electrons; dashed histograms - dislocations produced by photons. Two different thresholds are shown.
5. Comparison of the measured angular response curves of the Si diodes with the calculated dislocation density in Si from both electrons and photons. The diode response (circles) has been normalized to the upper histogram near zero degrees.



W+Pb SHIELDING
10% SLITS
57° MAGNET
Aℓ TARGET
WINDOW
COLLIMATOR
90°
MAGNET
ACCELERATOR
WAVEGUIDE
THERAPY
X-RAY TARGET
ISOCENTER
X-RAY THERAPY
BEAM
0
1
2
3
feet
3104A1

Fig. 1


ISOCENTER
CLINAC
35
TARGET
A
B
B
B
B
A
A
A
A
A
A
A
A
A
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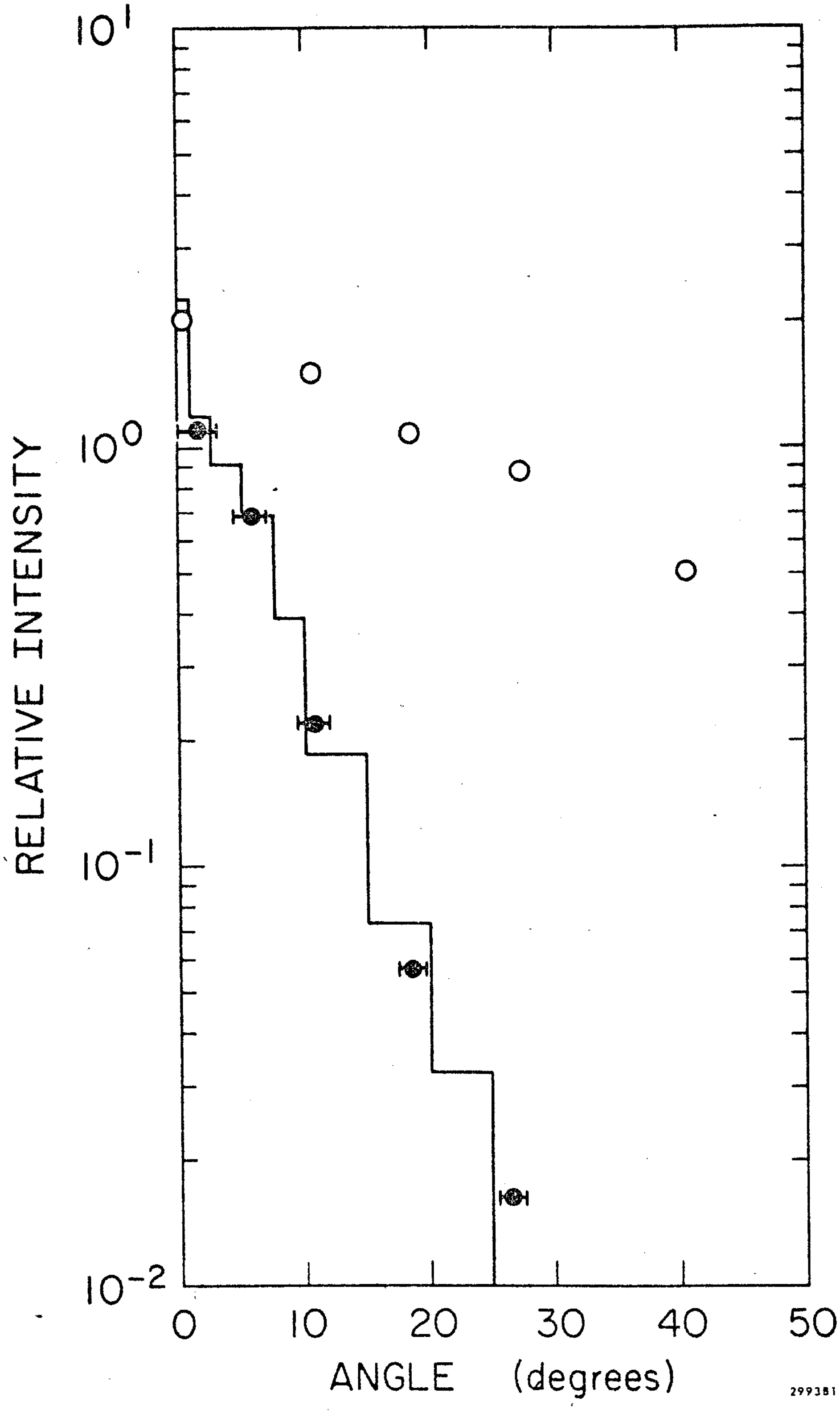
feet
3104A2

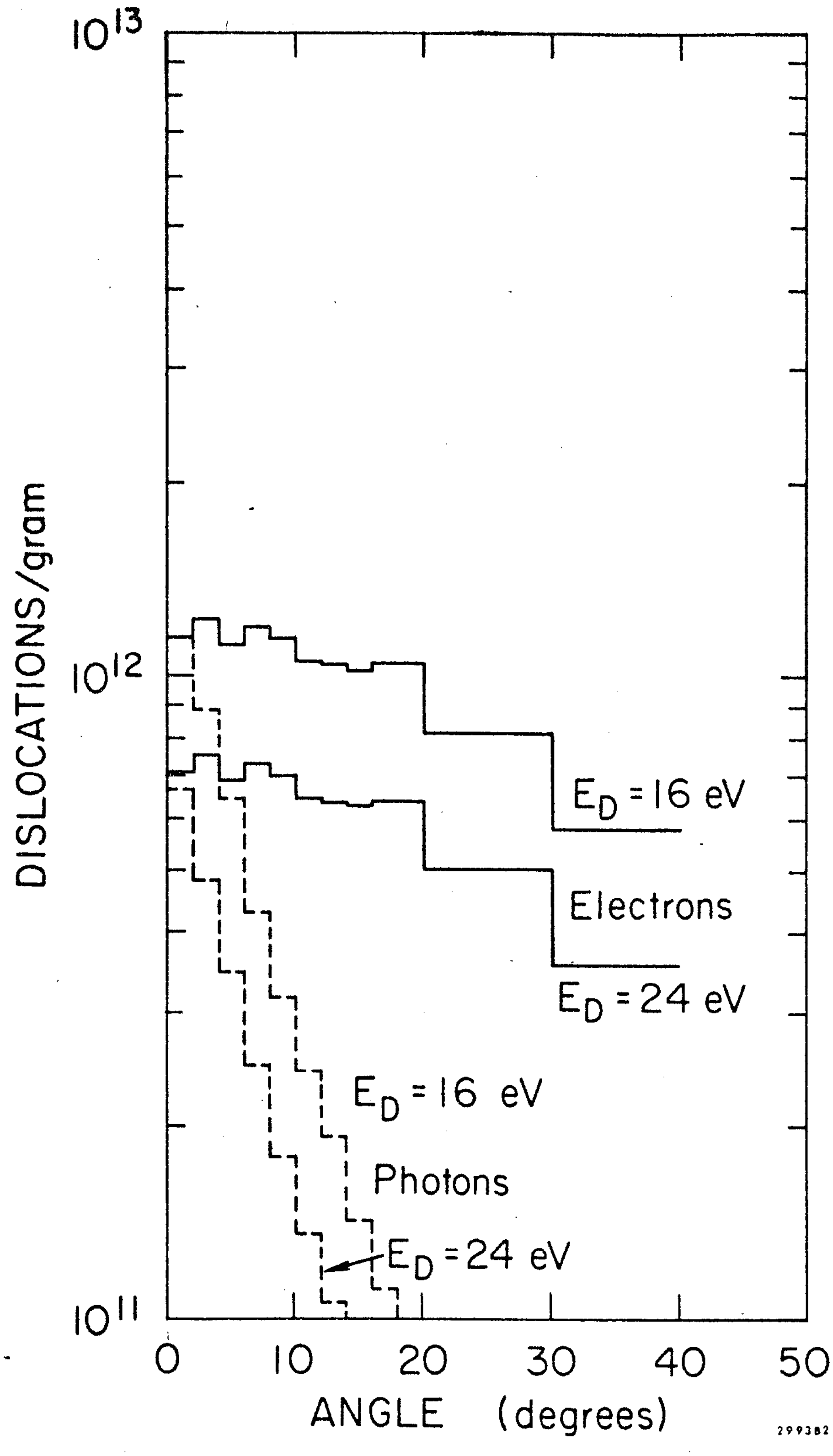
Fig. 2



10^1
10^0
10^-1
10^-2
RELATIVE INTENSITY
0
10
20
30
40
50
ANGLE (degrees)
299381

~~Fig. 1~~

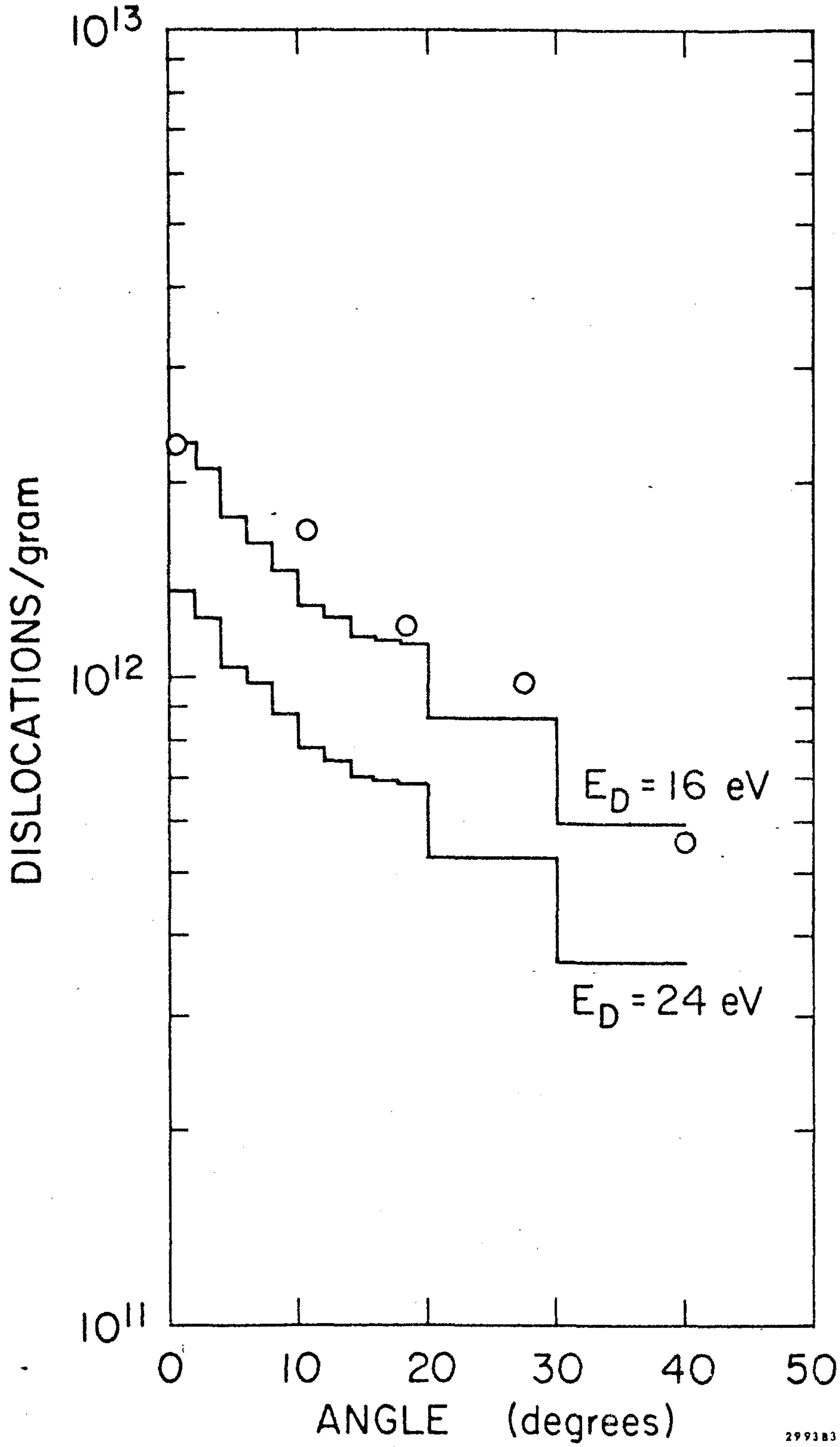
Fig. 3



10^{13}
10^{12}
10^{11}
DISLOCATIONS/gram
$E_D = 16$ eV
Electrons
$E_D = 24$ eV
$E_D = 16$ eV
Photons
$E_D = 24$ eV
0
10
20
30
40
50
ANGLE (degrees)
299382

~~Fig. 2~~

Fig. 4


10^{13}
10^{12}
10^{11}
DISLOCATIONS/gram
$E_D = 16$ eV
$E_D = 24$ eV
0
10
20
30
40
50
ANGLE (degrees)
299383

~~Fig. 3~~

Fig. 5