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A COMPARISON OF SOLAR CELL DAMAGE BY ALPHA PARTICLES AND PROTONS

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SUMMARY

The short circuit current of silicon solar cells illuminated with 2800° K light has been measured after the cells received successive increments of proton or alpha particle bombardment. The incident particle energies were 10. 5 and 42 MeV respectively, and therefore have identical velocity distributions and ranges in the solar cell. The ratio of the proton flux to the alpha particle flux to produce the same degradation in short circuit current is 3. 8. For particles of equal velocity, the ratio of the Coulomb cross section for alpha particles to that of protons to produce silicon recoils of equal energy is 4. If the experimental uncertainties are considered, the experimental result is in agreement with this ratio, and this agreement implies that the relatively few high energy recoils from close alpha particle collisions do not contribute significantly to the cell degradation.

INTRODUCTION

This investigation examines the degradation of solar cells from alpha particle bombardment in order to determine whether the damage rate for these particles is anomalous. The modivation for this study arose from the fact that approximately 10 percent of the particles of a solar flare at any energy are alpha particles (ref. 1). Consequently, the degradation of the solar cells of an interplanetary spacecraft by alpha particles should be evaluated.

While protons and electrons have been used extensively in the degradation of solar cells, alpha particles have not. The only other study (ref. 2) was a cursory examination with 33-MeV alpha particles. In this work one p on n cell and one rather low efficiency (6. 5 percent) n on p cell were irradiated. The conclusions were drawn that the damage rates for the two types are similar and that the rate is roughly a factor of 5 more than for 19-MeV protons.

EXPERIMENTAL ARRANGEMENT

Since the objective was to examine cells for anomalous damage rates, the simplest approach was to make a comparison between alpha and proton damaged cells. The short circuit current and open circuit voltage of a cell with approximately 100 milliwatts per square centimeter of illumination at 2800^0 K, were measured after increments of irradiation. The test conditions were made similar to those of other studies in order to facilitate comparison and prediction of alpha particle degradation for cells not included in this study.

The Lewis Research Center 60-inch cyclotron was the source of particles. The velocity of cyclotron particles is simply the product of 2π times the oscillator frequency and the exit radius. Since the cyclotron is operated at a fixed frequency and fixed exit radius, the alpha particles and protons have identical velocities. This makes the comparison of protons and alpha particles more significant since, when these particles have the same velocity, they have the same range. The velocity and energy of 42-MeV alpha particles, as they penetrate a piece of silicon, are shown in figure 1. These curves were derived from tabulated values (ref. 3) of dE/dx. (Symbols are defined in the appendix.) Radiation defects are initiated by collisions between the primary particle and silicon nuclei; the struck nucleus becomes a primary recoil which causes additional displacements. Most of the collisions between the primary particle and silicon nuclei are

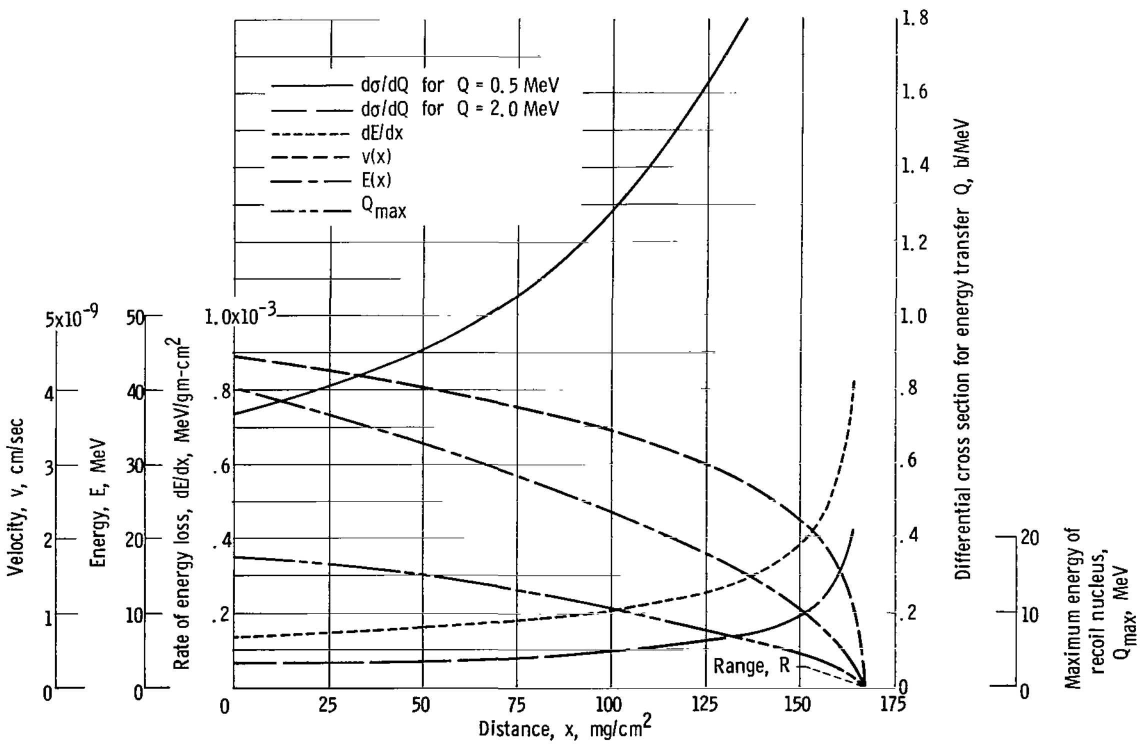
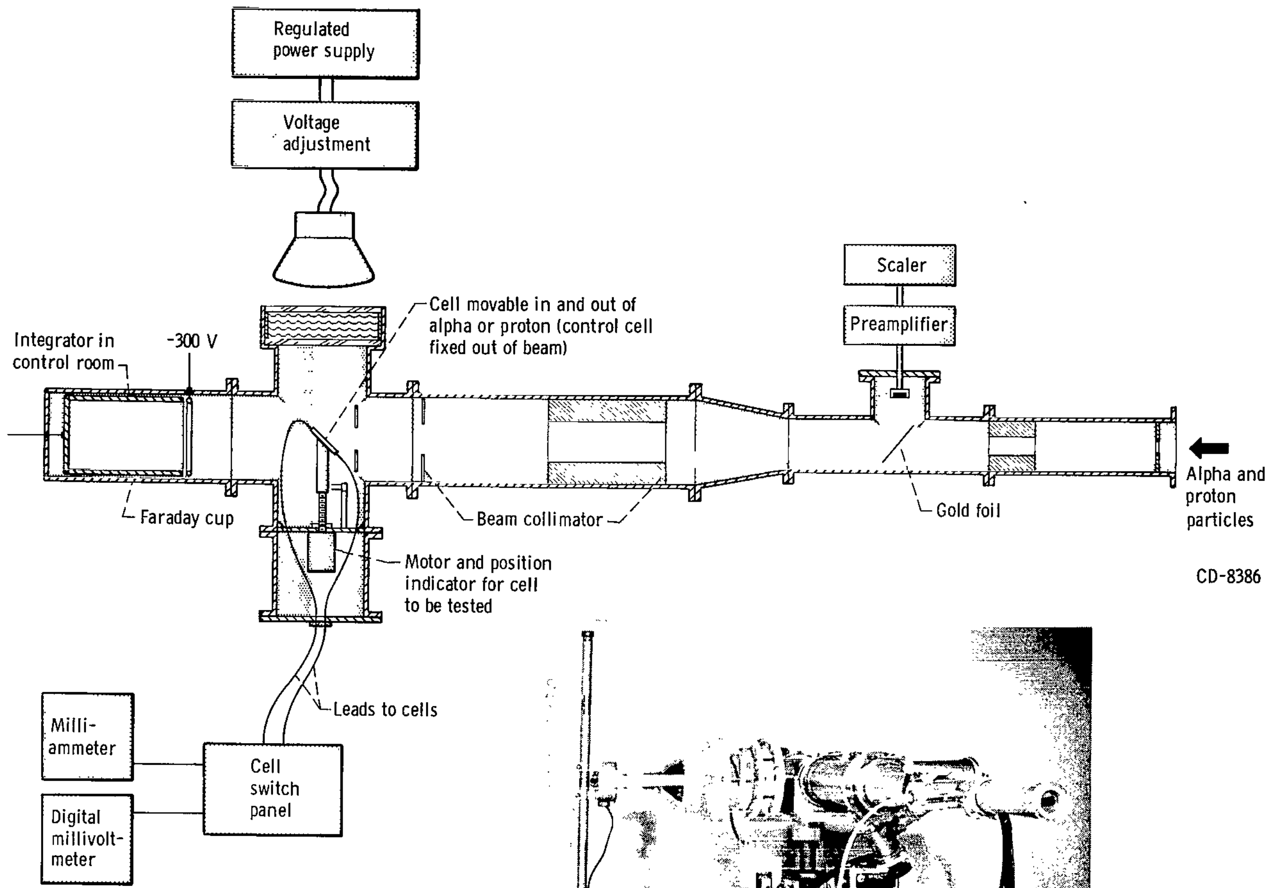
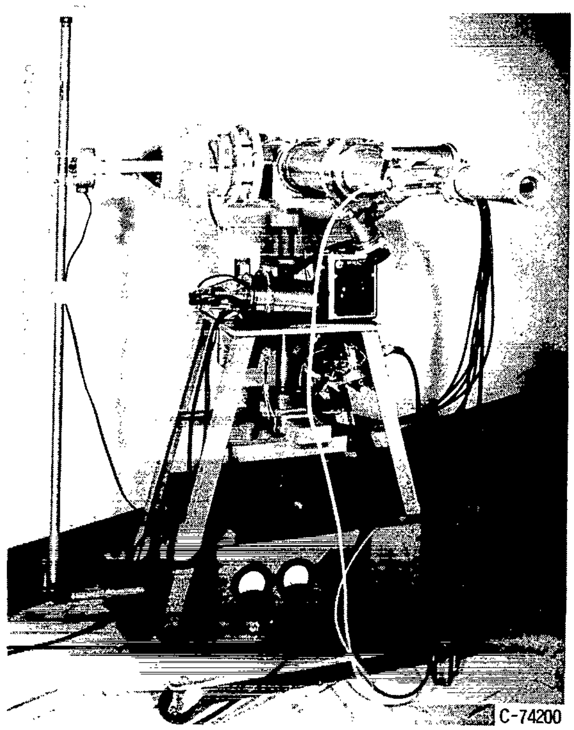


Figure 1. - Display of quantities for alpha particle penetration of silicon.



(a) Schematic drawing.



(b) Overall view.

Figure 2. - Apparatus for irradiation of solar cells.

not close enough to involve nuclear forces; thus, the Coulomb cross section gives a fair approximation to the scattering probability, and curves are shown (fig. 1) for the case of the alpha particle to transfer 0.5- and 2.0-MeV to silicon nuclei. There is, of course, a continuum of recoil energies up to the maximum energy which can be transferred in a head-on collision. This value

$$Q_{max} = 4 \frac{M_\alpha M_{Si}}{\left(M_\alpha + M_{Si}\right)^2} E_\alpha \tag{1}$$

is also plotted (fig. 1) as a function of the penetration in the cell.

A schematic drawing and a photograph of the experimental arrangement are shown in figure 2. A stationary cell is used to standardize illumination and is located below the line of the beam; the cell to be tested can be positioned so as to intercept the beam, or it can be retracted in order to permit the beam to enter a Faraday cup. Figure 3 is a photograph of the cell holder and drive unit. The beam passes through a very thin gold foil, and a small fraction is scattered into a solid-state detector. The constant of proportionality between the number of particles hitting the solid-state detector and the number collected in the Faraday cup is determined with the cell withdrawn. With the cell to be irradiated in the beam, the number of particles hitting the cell is determined by the solid-state detector count, the constant of proportionality, and the fraction of the beam area that the cell intercepts. Special attention was taken to record the first increments of damage at low flux levels.

The area of the beam was determined by irradiating a piece of X-ray film at the cell position; the uniformity was determined by irradiating a copper foil, cutting it into pieces, and determining the relative activity of the pieces. The beam could be made uniform to better than 5 percent by using quadrupole lenses to defocus the beam.

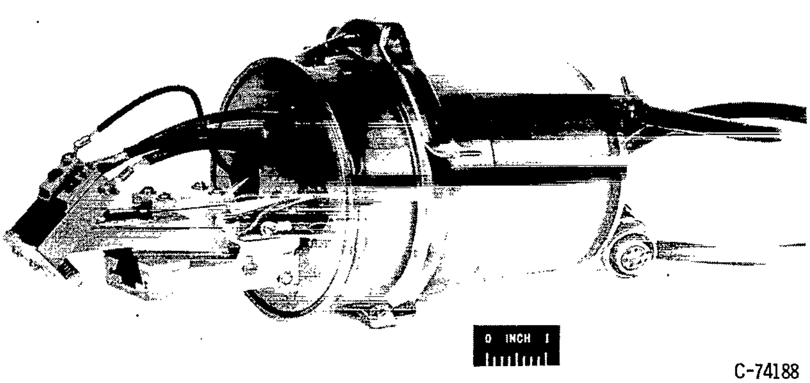


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Figure 3. - Motorized cell assembly.

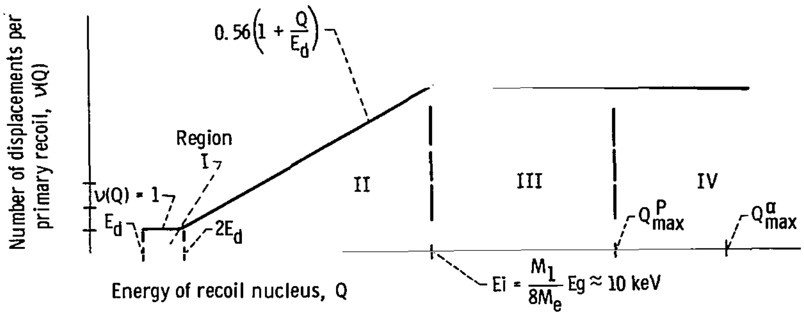

Figure 4. - Assumed variation of number of displacements with silicon recoil energy.

THEORY

The relative number of defects produced by protons and alpha particles will be determined under the following conditions:

(1) Minority carriers diffusing from distances greater than $2L_0$ (L_0 is the initial diffusion length) have such a small probability of reaching the junction that a sharp cutoff of $2L_0$ has been assumed in the calculation.

(2) The primary particle from the Coulomb interaction produces recoil silicon atoms with energies Q, from the displacement energy E_d, to Q_{max}.

(3) The number of displacements per primary recoil $\nu(Q)$ is given by the Seitz-Harrison equation (6) and is shown in figure 4.

(4) The number of radiation defects affecting cell performance is proportional to the number of displaced atoms.

A primary particle (mass M_1, charge Z_1) incident upon n_{si} silicon atoms per cubic centimeter has an energy $E(x)$ after having penetrated some distance x and has some differential probability $d\sigma(E(x), Q)$ of causing a recoil of energy Q to $Q + dQ$. The number of recoils in this energy range, per square centimeter of surface, for an incident particle flux Φ is

$$n_{si}\Phi \int_0^{x(Q) \text{ or } 2L_0} \sigma[E(x), Q]dx \tag{2}$$

The upper limit of the integral is $2L_0$ when $Q < 4\left[M_1M_2/(M_1 + M_2)^2\right]E(x = 2L_0)$ and otherwise, $x(Q)$, which can be obtained for alpha particles from the curve of $Q_{max}(x)$ (fig. 1, p. 2). The Rutherford scattering law for an alpha particle on a bare silicon nucleus can be substituted for the differential cross section to give

$$N(Q)dQ = n_{si}\Phi \frac{2\pi Z_2^2 e^4}{M_2} \frac{Z_1^2}{Q^2} \int_0^{x(Q) \text{ or } 2L_0} \frac{dx}{v^2} \qquad (3)$$

This integral has been evaluated numerically, and the resulting primary recoil spectra are shown in figure 5.

The proton and alpha particle primary recoil spectra are identical in shape and differ by just a factor of 4 in number, for Q less than about 1 MeV. Alpha particle bombardment does differ from protons by producing a continuum of recoil energies to 17 MeV.

Radiation damage is considered to consist of the silicon atoms displaced by the primary recoils. The radiation defects that affect the solar cell behavior appear to be (refs. 4 and 5) the result of the radiation produced vacancy or interstitials combining with impurity atoms. The number of such defects is assumed to be proportional to the number of displaced atoms per square centimeter, which is given by

$$D = \int_{E_d}^{Q_{max}} N(Q)\nu(Q)dQ \qquad (4)$$

The dependence of $\nu(Q)$ is given in figure 4 and can conveniently be considered in four regions of energy for the primary recoil. For region I ($E_d < Q < 2E_d$), the primary recoil can produce no displacements; consequently, $\nu = 1$ for the displacement produced by the primary particle. For region II ($2E_d < Q < E_i$), the Seitz-Harrison equation (ref. 6) is assumed to apply. For recoil particles with energy greater than E_i the particle is assumed to lose energy by electron ionization and to produce no displacements until the energy falls to E_i, at which point it produces $\nu(E_i)$ defects. This energy can be estimated in several ways; the one that is taken, $E_i = (M_1/8m_e)E_g$ (ref. 7), is based upon ionization occurring across the

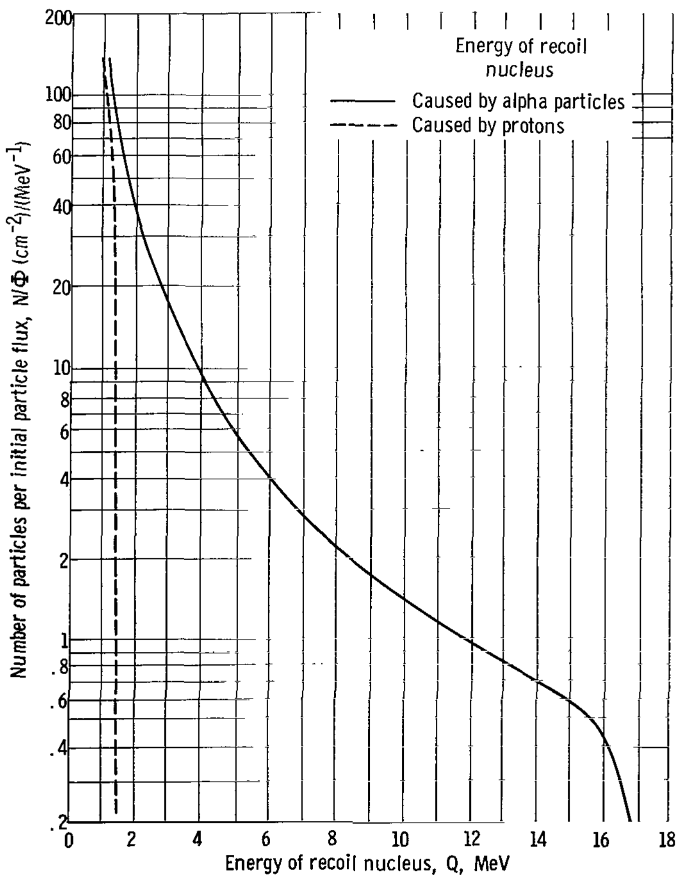

Figure 5. - Spectrum of recoil energies for 42-MeV alpha and 10.5 MeV proton bombardment of silicon.

energy gap E_g. Region III extends to the maximum proton recoil energy and region IV from this energy to the maximum alpha recoil energy. The number of displacements for each of these regions can be obtained in explicit form when it is recognized that the cell region $2L_0$ is thin enough so that the velocity of the particle in the integral for N(Q) can be replaced by its average value. The number of defects per incident alpha particle in the four regions becomes

$$\frac{D_I^\alpha}{\Phi} = \frac{n_{si} 2\pi Z_2^2 e^4}{M_2} \frac{4L_0}{\overline{v^2} E_d} \tag{5}$$

$$\frac{D_{II}^\alpha}{\Phi} = 0.56 \frac{n_{si} 2\pi Z_2^2 e^4}{M_2} \frac{8L_0}{\overline{v^2} E_d} \left(\frac{E_i - 2E_d}{E_i} + \ln \frac{E_i}{2E_d} \right) \tag{6}$$

$$\frac{D_{III}^\alpha}{\Phi} = \nu(E_i) \frac{n_{si} 2\pi Z_2^2 e^4}{M_2} \frac{8L_0}{\overline{v^2} E_i} \left(\frac{Q_{max}^P - E_i}{Q_{max}^P} \right) \tag{7}$$

$$\frac{D_{IV}^\alpha}{\Phi} = \nu(E_i) \frac{n_{si} 2\pi Z_2^2 e^4}{M_2} \frac{8L_0}{\overline{v^2} Q_{max}^P} \left(\frac{Q_{max}^\alpha - Q_{max}^P}{Q_{max}^\alpha} \right) \tag{8}$$

The number of defects per square centimeter produced in the layer $2L_0$ by a 42-MeV alpha particle, for the four regions in consecutive order, is

$$D_{tot}^\alpha = (8.2 + 128 + 9.4 + 0.085)\Phi \tag{9}$$

The numer of defects per 10.5-MeV proton is exactly one-fourth of the alpha particle value for regions I, II, and III because there is one-fourth the number of primary recoils at any energy below about 1 MeV. For protons, there are no recoils with energies in region IV. The number of defects produced by alpha particles in this region is relatively small, so it follows that

$$D_{tot}^\alpha \approx 4D_{tot}^P \tag{10}$$

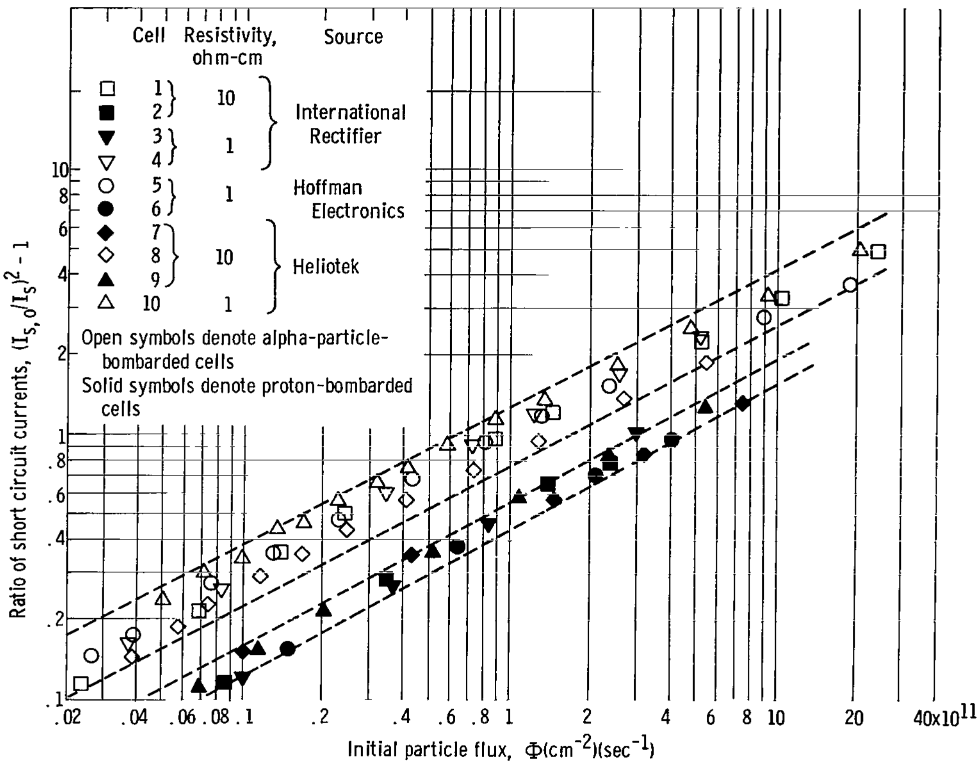

Figure 6. - Irradiation of several n on p cells.

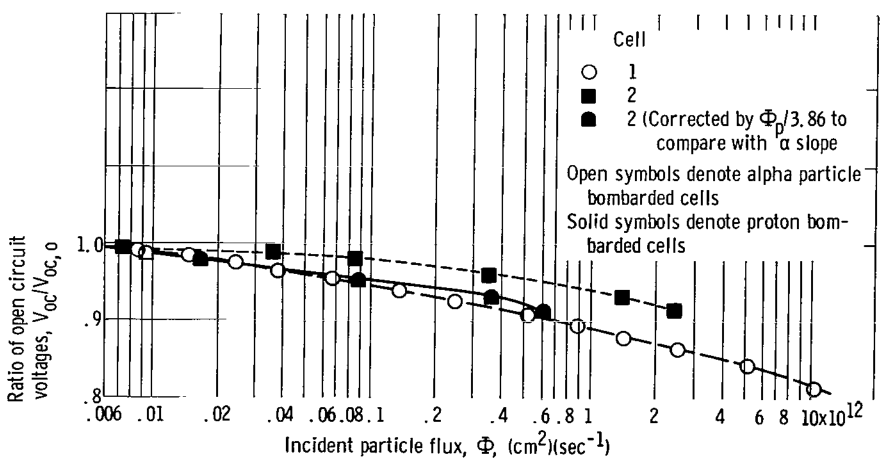

Figure 7. - Change in open circuit voltage with proton and alpha bombardment. Resistivity 10 ohm-centimeters; cells supplied by International Rectifier.

This result, when combined with an assumed proportionality between solar cell defects and the number of displacements, predicts that an alpha particle flux Φ_0 will cause the same reduction in cell output as a proton flux of $4\Phi_0$.

The low estimate of the damage from region IV for the high-energy primary recoils is made under the assumption that has been made for $\nu(Q)$. It should be recognized that there is the possibility of spike phenomena in which the high-energy recoils react with many silicon atoms simultaneously. Such effects are seen in fission fragment damage, an example of which is seen in the work of Fleischer, Price, and Walker (ref. 8) and, if important in this instance, these effects would make the ratio of proton to alpha flux for equal damage greater than 4.

RESULTS AND DISCUSSION

The results from the testing of a number of n on p cells of materials with different resistivities are shown in figure 6. The data are presented as log-log plots of $(I_{s,0}/I_s)^2 - 1$ against Φ in order to give approximately straight curves of the same slope.

The alpha particle irradiated cell data scatter in a wider interval than the proton data; however, the inclusion of a 1 ohm-centimeter Heliotek cell has no counterpart in the proton group. Therefore, the width of the alpha group may not be as wide as shown. A comparison of a cell in one group with its counter part in the other group gives an average of 3.8 for the ratio of proton flux to cause the same degradation as an alpha particle flux.

A test of this equivalence between proton and alpha particle fluxes is shown in figure 7, where the degradation in the open circuit voltage for proton and alpha particle bombardments is shown. In addition, the proton curve has been replotted for flux points at $\Phi_p/3.8$. This procedure makes the reconstructed proton curve coincident with the alpha particle curve.

The scatter between cells of the same type makes it questionable whether the difference between the expected and observed result, that is, 4 and 3.8 for the ratio of equivalent fluxes, is real. Since the experimental ratio is near the predicted value, the high-energy primary recoils do not appear to be contributing to cell degradation anymore than would be predicted from the Seitz-Harrison theory. In other words, "fission" spike phenomena from high-energy recoils, if they take place, are not important to cell degradation. The lower ratio could be understood in terms of an enhanced annihilation between interstitials and vacancies because of the higher density of such defects along the path of a primary alpha particle.

It would be expected that the observed ratio between proton and alpha particle fluxes would hold for other energies as long as the comparison is made between protons of energy E and alpha particles of energy 4E, that is, between particles of the same velocity, for the range of energies where Coulomb scattering is the dominant process. At very low energies, for example where the charge exchange is important, the ratio of fluxes may be different.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, January 27, 1966.

APPENDIX - SYMBOLS

D	number of defects
D^{p}_{tot}	total number of defects produced by protons
D^{α}_{tot}	total number of defects produced by alpha particles
D^{α}_{I}	number of defects produced by alpha particles in region I
D^{α}_{II}	number of defects produced by alpha particles in region II
D^{α}_{III}	number of defects produced by alpha particles in region III
D^{α}_{IV}	number of defects produced by alpha particles in region IV
dE/dx	rate of energy loss, $MeV/(g)(cm^2)$
$E(x)$	energy after penetration of x-distance
E_d	displacement energy, eV
Eg	energy gap
E_i	minimum energy of recoil nucleus for which ionization is dominant energy loss mechanism
E_{α}	energy of alpha particle
e	charge of electron
I_s	short circuit current, mA
$I_{s,0}$	initial short circuit current, mA
L_0	initial minority carrier diffusion length, cm
M_{Si}	mass of silicon atom
M_{α}	mass of alpha particle
M_1	mass of primary (incoming) particle
M_2	mass of target (silicon) atom
m_e	mass of electron
N	number of particles
$N(Q)dQ$	number of recoils/cm^2
n_{si}	silicon atoms/cm^3
Q	energy of recoil nucleus, MeV
Q_{max}	maximum energy of recoil nucleus, MeV
Q^{P}_{max}	maximum proton recoil energy
Q^{α}_{max}	maximum alpha particle recoil energy
R	range of particle
V_{oc}	open circuit voltage, mV
$V_{oc,0}$	initial open circuit voltage, mV
v	velocity, cm/sec
$v(x)$	velocity along x, cm/sec
x	penetration distance
$x(Q)$	penetration distance as a function of (Q)
Z_1	atomic number of primary particle
Z_2	atomic number of target nucleus
ν	number of displacements
$\nu(E_i)$	number of displacements per primary particle when $Q = E_i$

$\nu(Q)$ number of displacements per primary recoil of energy Q

$d\sigma$ differential cross section

$d\sigma/dQ$ differential cross section for energy Q, b/MeV

Φ particle flux, $(cm^{-2})(sec^{-1})$

Φ_p proton flux, $(cm^{-2})(sec^{-1})$

Φ_α alpha particle flux, $(cm^{-2})(sec^{-1})$

REFERENCES

1. Biswas, S.; Fichtel, C.E.; Guss, D.E.; and Waddington, C.J.: Hydrogen, Helium, and Heavy Nuclei from the Solar Event on November 15, 1960. J. Geophys. Res., vol. 68, no. 10, May 15, 1963, pp. 3109-3122.

2. Baicker, J.A.; and Faughnan, B.W.: Radiation Damage to Silicon Solar Cells. Summary Rep., David Sarnoff Research Center, RCA Laboratories, Radio Corp. of America (NASA CR-51043), July 1961.

3. Williamson, C.; and Boujot, J.P.: Tables of Range and Rate of Energy Loss of Charged Particles of Energy 0.5 to 150 MeV. Rep. No. CEA-2189, Commissariat à l'Énergie Atomique, 1962.

4. Watkins, G.D.; and Corbett, J.W.: Defects in Irradiated Silicon. I. Electron Spin Resonance of the Si-A Center. Phys. Rev., vol. 121, no. 4, Feb. 15, 1961, pp. 1001-1014.

5. Watkins, G.D.; and Corbett, J.W.: Defects in Irradiated Silicon. Electron Paramagnetic Resonance and Electron-Nuclear Double Resonance of the Si-E Center. Phys. Rev., vol. 134A, no. 5, June 1, 1964, pp. 1359-1377.

6. Seitz, Frederick; and Koehler, J.S.: Displacement of Atoms During Irradiation. Vol. 2 of Solid State Physics, ed. by Frederick Seitz and David Turnbull, Academic Press, 1956, pp. 305-448.

7. Seitz, Frederick: The Disordering of Solids by Action of Fast Massive Particles. Disc. Faraday Soc., no. 5, 1949, pp. 271-282.

8. Fleischer, R.L.; Price, P.B.; and Walker, R.M.: Tracks of Charged Particles in Solids. Science, vol. 149, no. 3682, July 23, 1965, pp. 383-393.

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