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ECE695: Reliability Physics of Nano-Transistors
Lecture 38: Charge Generation by Particles

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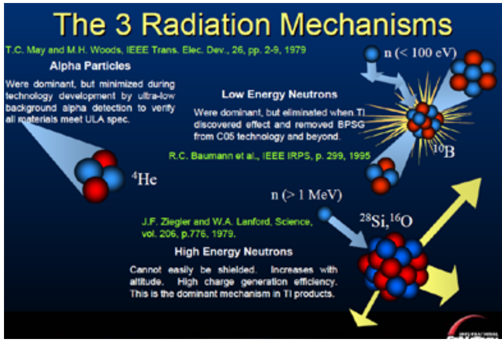
Outline

1. Background information
2. Electromagnetic interaction and charge generation
   a) Proton, neutron, and alpha particles
3. Electron-hole pair generation
4. Permanent damage
5. Conclusions



The 3 Radiation Mechanisms

T.C. May and M.H. Woods, IEEE Trans. Elec. Dev., 26, pp. 2-9, 1979

Alpha Particles

Were dominant, but minimized during technology development by ultra-low background alpha detection to verify all materials meet ULA spec.

Low Energy Neutrons

Were dominant, but eliminated when TI discovered effect and removed BPSG from C05 technology and beyond.

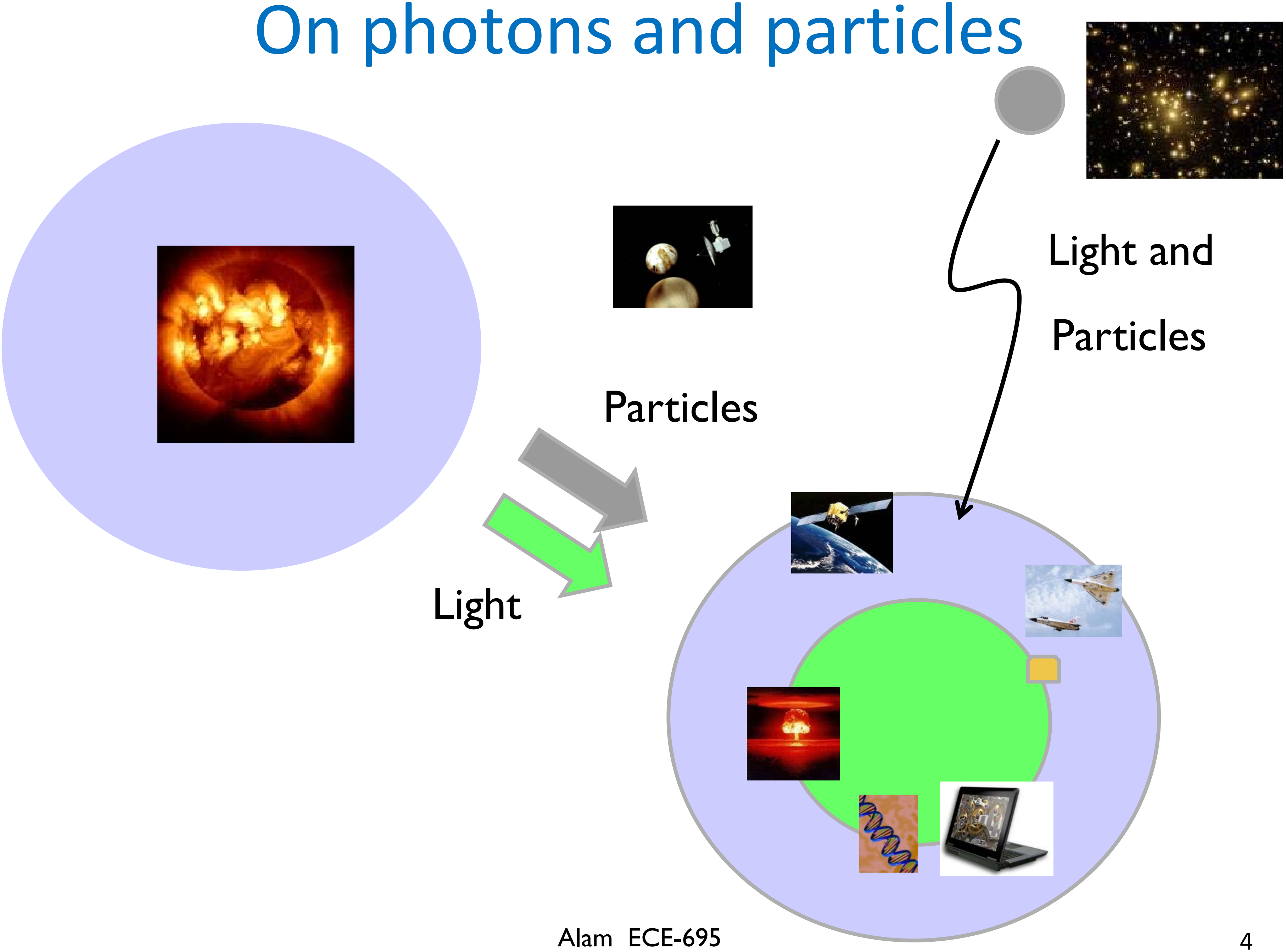
R.C. Baumann et al., IEEE IRPS, p. 299, 1995

J.F. Ziegler and W.A. Lanford, Science, vol. 206, p.776, 1979.

High Energy Neutrons

Cannot easily be shielded. Increases with altitude. High charge generation efficiency. This is the dominant mechanism in TI products.

On photons and particles



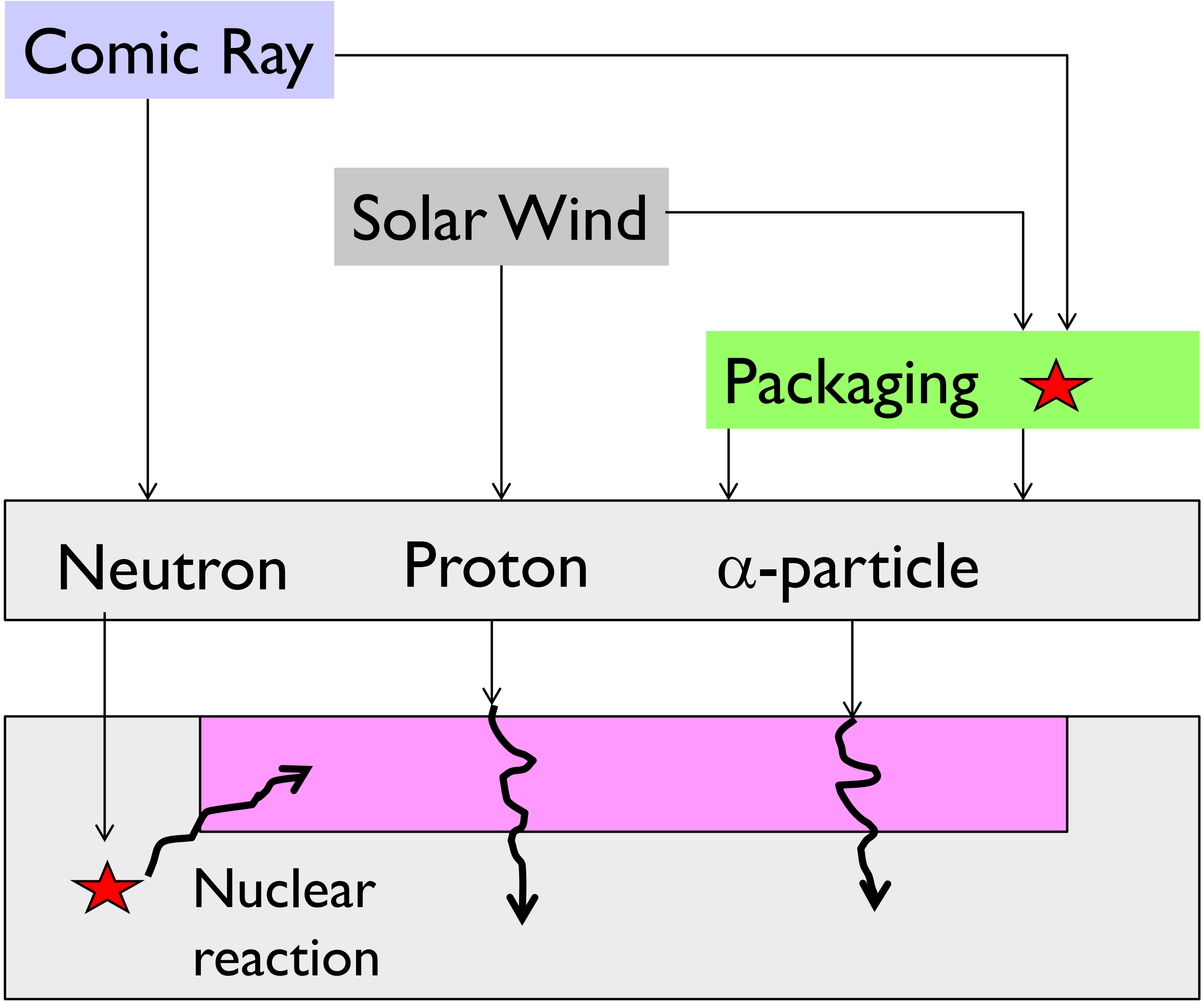
Light and

Particles

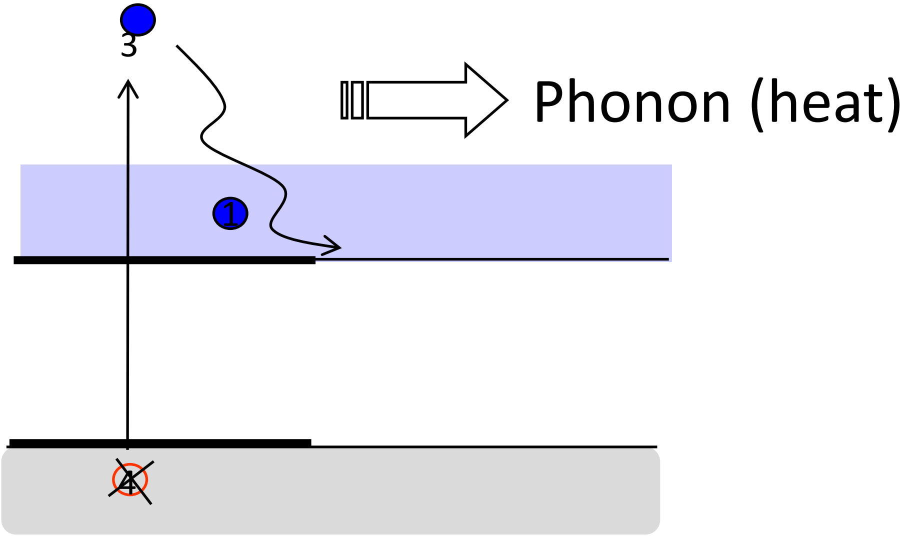
Particles

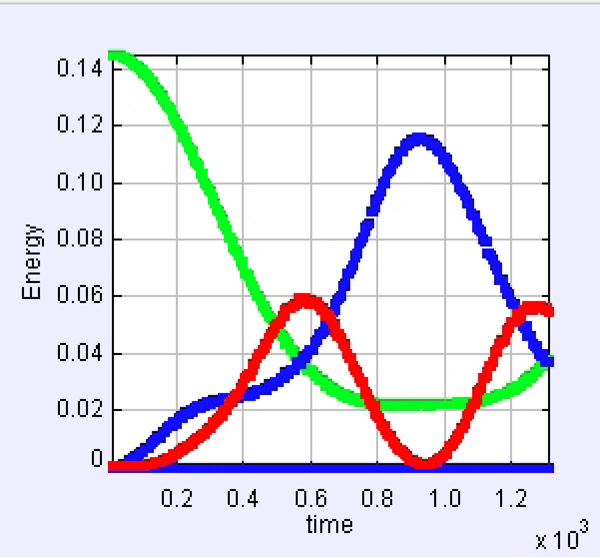
Light

How do particles create charge



Getting Rid of the Energy: Photoelectric Effect and lattice Vibration





Initial mode (k, red) and two neighboring modes k+1 (blue) and k-1 (green).

Fermi-Pasta-Ulam problem ....
Difficulty in reaching equipartition

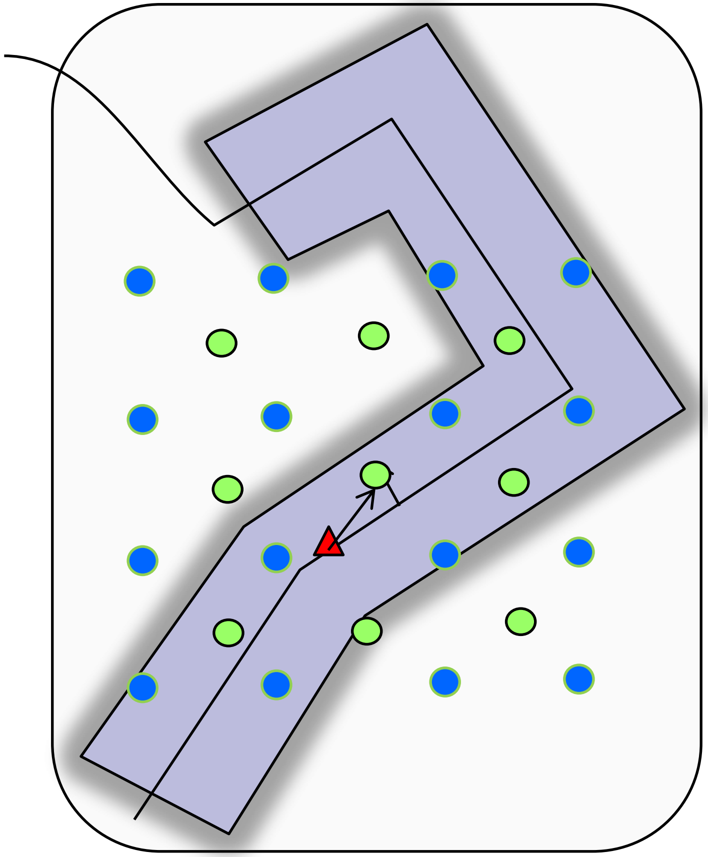
http://www.compadre.org/STP/document/ServeFile.cfm?ID=8643&DocID=1050

2.1 Protons interact with **bound electrons** by electromagnetic interaction

- ➢ Proton interacts with both nucleus and the electron cloud; the nucleus-proton interaction is elastic that randomizes proton momentum, while electron-proton interaction inelastic results in electron-hole pair generation.

- ➢ Proton sees charge distribution only at a single atom level, everything else further out is charge neutral (nucleus-electron cloud).

- ➢ To calculate energy loss, we take one interaction at a time (as it was there on its own) and then sum up over the volume.



2.1 proton, pion, muon: relative LET

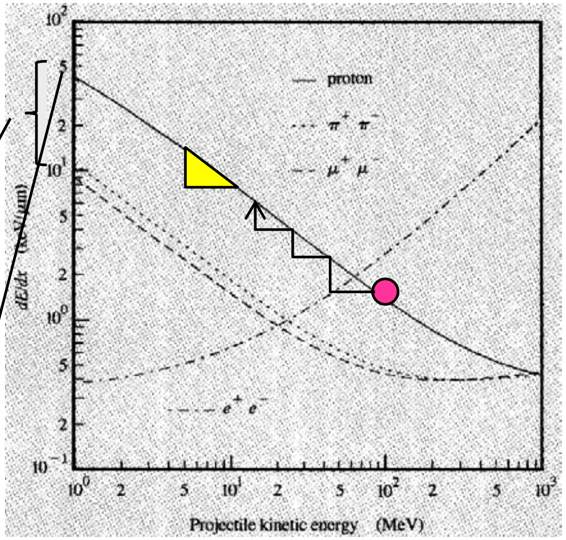
$$-\frac{dE}{dx} = \frac{q^4}{8\pi\varepsilon_0}\frac{(\rho N_{AV}/B) Z_{inc}{}^2 M_{inc}}{m_e E_{inc}} \ln\left(\frac{4E_{inc}}{E_{eh}}\right)$$

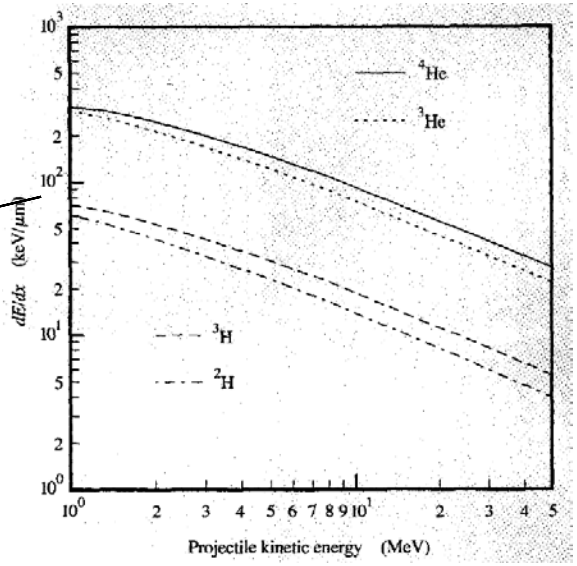
$$-\frac{dE}{dx}\bigg|_A \bigg/ -\frac{dE}{dx}\bigg|_B = \frac{Z_{inc,A}{}^2 M_{inc,A}}{Z_{inc,B}{}^2 M_{inc,B}}$$

$$-\frac{dE}{dx}\bigg|_{pion} \bigg/ -\frac{dE}{dx}\bigg|_{proton} = \frac{Z_{inc,pion}{}^2 M_{inc,pion}}{Z_{inc,proton}{}^2 M_{inc,proton}} = \frac{1}{1}\times\frac{139}{938} = \frac{1}{6.5}$$

$$-\frac{dE}{dx}\bigg|_{proton} \bigg/ -\frac{dE}{dx}\bigg|_{^2H} = \frac{Z_{inc,proton}{}^2 M_{inc,proton}}{Z_{inc,2H}{}^2 M_{inc,2H}} = \frac{1}{2}$$

$$-\frac{dE}{dx}\bigg|_{proton} \bigg/ -\frac{dE}{dx}\bigg|_{^3He} = \frac{Z_{inc,proton}{}^2 M_{inc,proton}}{Z_{inc,^3He}{}^2 M_{inc,^3He}} = \frac{1}{4}\times\frac{1}{3} = \frac{1}{12}$$



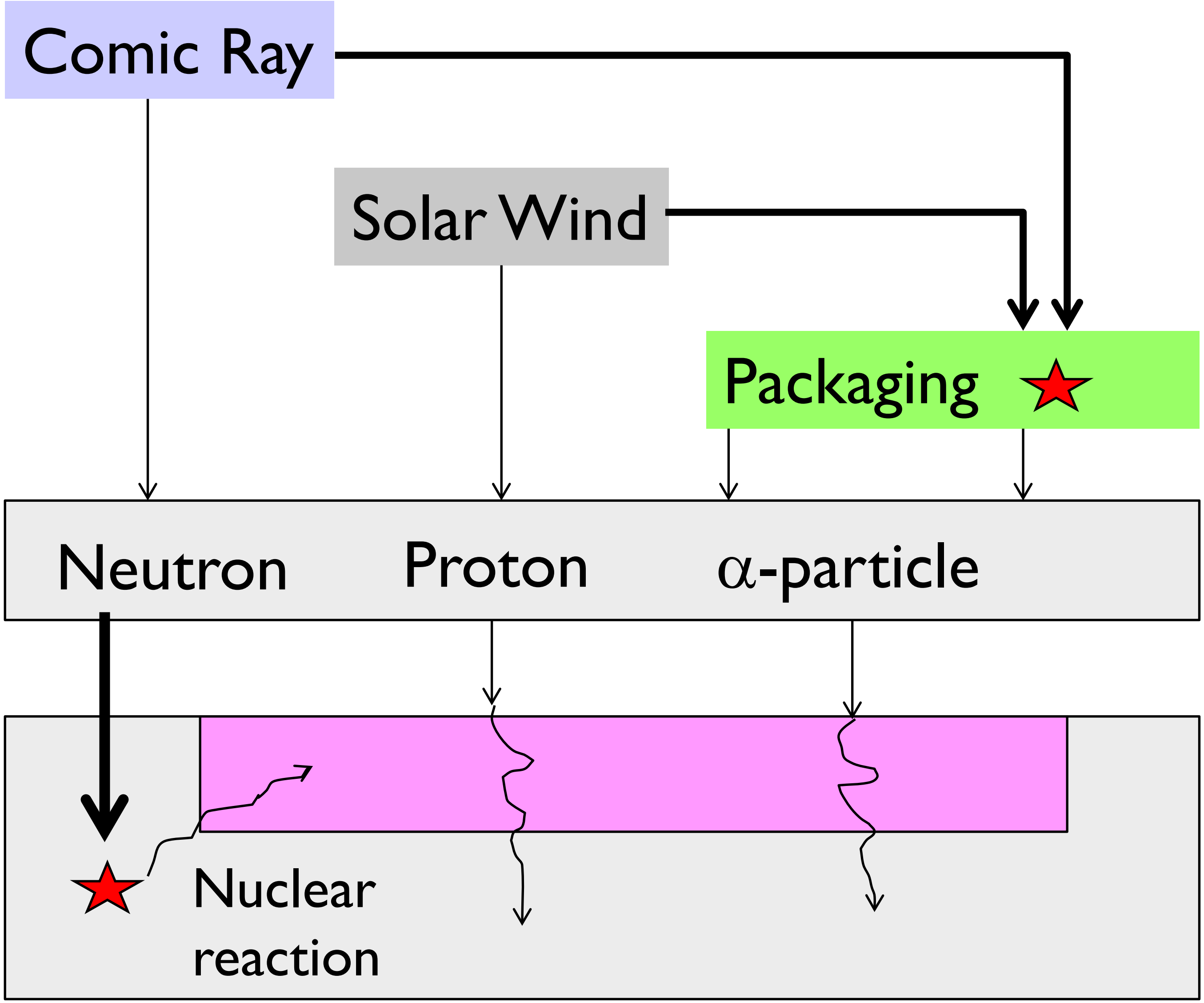


Muon mass 105.658 369(9) MeV/c^2, charge=-1

Pion mass= 139.6 MeV/c^2 charge=1

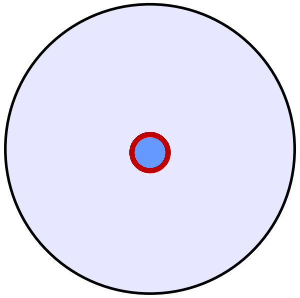
Proton Mass= 938.272013(23) MeV/c^2, charge=1

How do particles create charge

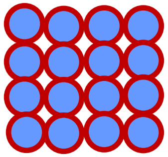


How often does the nuclear reaction occur

$$\sigma = \pi R^2 = \pi\left[(28)^{1/3} r\right]^2 = 5\times 10^{-25}\ cm^2$$



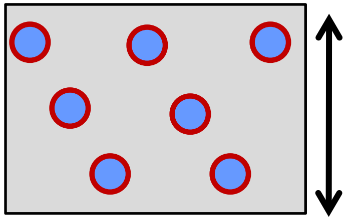
Probability of guaranteed strike ….



Black Wall=1/(area/atom)=2x10^{24} atom/cm^2

Interaction depth=Black Wall/$\left(\text{atoms/cm}^{-3}\right)$

$$= 2\times 10^{24}/5\times 10^{22} = 40cm$$



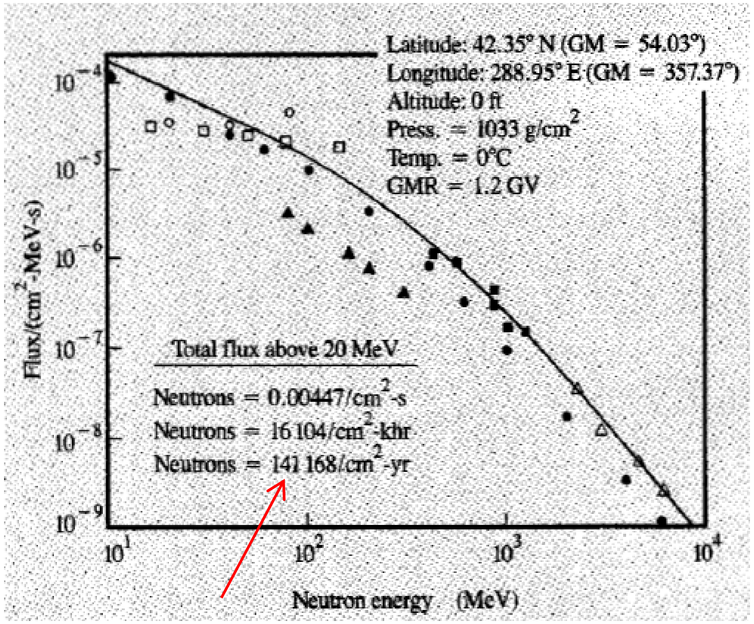
Pr orbability of Hit: 10μm/40cm~1/40,000.

1 in 40,000 neutrons will cause nuclear reaction

Frequency of Nuclear reaction

Integrated neutron in 10 yrs

$= 0.5\text{-}1.5\text{x}10^5\text{x}10=10^6$



Number of hits ~

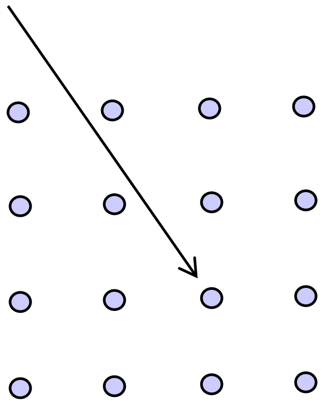
$$10^6 / 40,000 = 25 \text{ hits/cm}^2$$

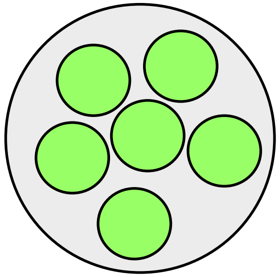
Typical Active Area=0.04 cm^{-2}

Nos. of hits/IC=25x0.04 cm^{-2} $=1$

Almost every chip will have one radiation-induced error

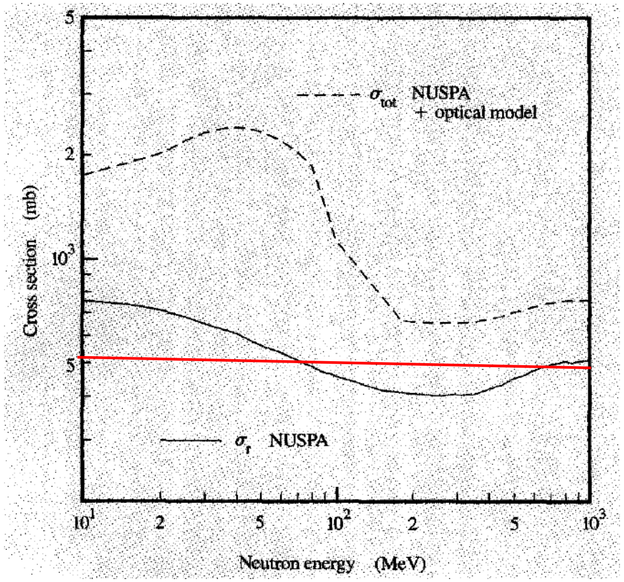
2.2 Neutron-nucleus interaction: Size of an Atomic Nucleus





A nucleons

N neutrons, Z protons



$$r = 1.25 \times 10^{-13} B^{1/3} \text{ cm}$$

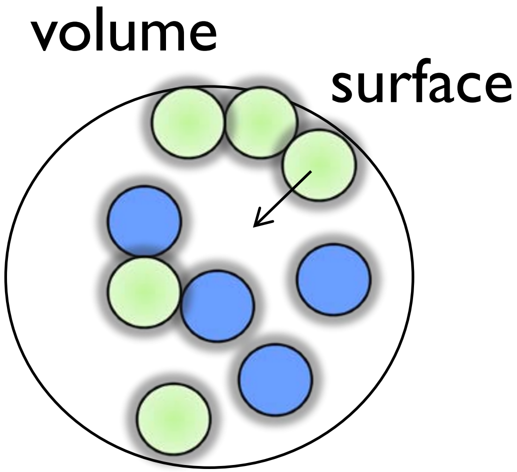
$$\sigma_{0,Si} = \pi r^2 = 45.34 \times 10^{-26}$$

$$= 453.4 \times 10^{-27} \text{cm}^2$$

$$\sim 500 \text{ mBarns}$$

1 barn=10^{-24} cm^2
Defined at Purdue during WWII
Size of a uranium atom is 'as big as a barn'

2.2 Binding Energy of a Nucleus: droplet model



N=neutron
Z=proton
A=N+Z

Weizsacker (1935)

$$B.E = -15.75A + 17.8A^{2/3} + 0.71\frac{Z^2}{A^{1/3}} + 23.7\left(\frac{A-2Z}{A}\right)^2 A + 34\frac{\lambda}{A^{3/4}}$$

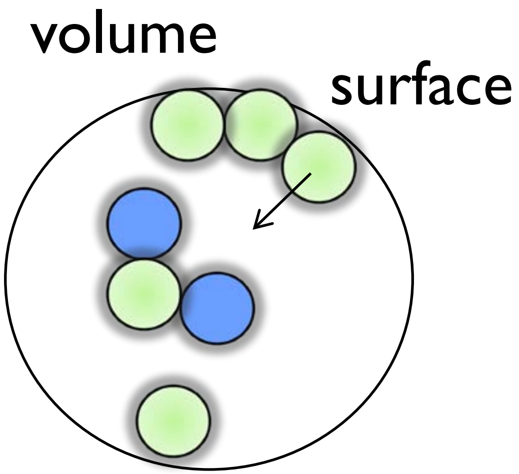
$$\underset{\text{bulk}}{\uparrow} \quad \underset{\text{Surface}}{\uparrow} \quad \underset{\text{Coulomb}}{\uparrow} \quad \underset{\text{n-p Symmetry}}{\uparrow} \quad \underset{\text{Pairing, }\lambda=}{\uparrow}$$

+1, odd-odd
-1, even-even
0, odd-even

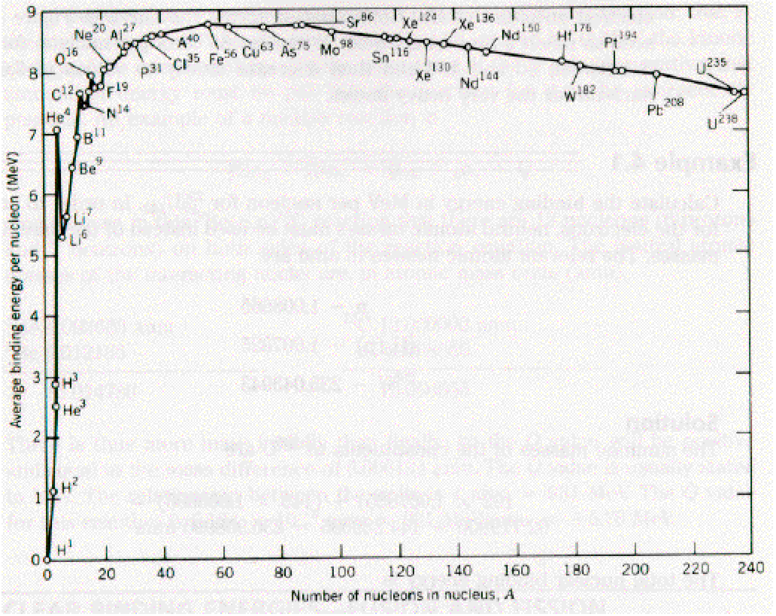
2.2 Binding Energy of a Nucleus

$$B.E = -15.75A + 17.8A^{2/3} + 0.71\frac{Z^2}{A^{1/3}}$$

$$+23.7\left(\frac{A-2Z}{A}\right)^2 A + 34\frac{\lambda}{A^{3/4}}$$



N=neutron
Z=proton
A=N+Z

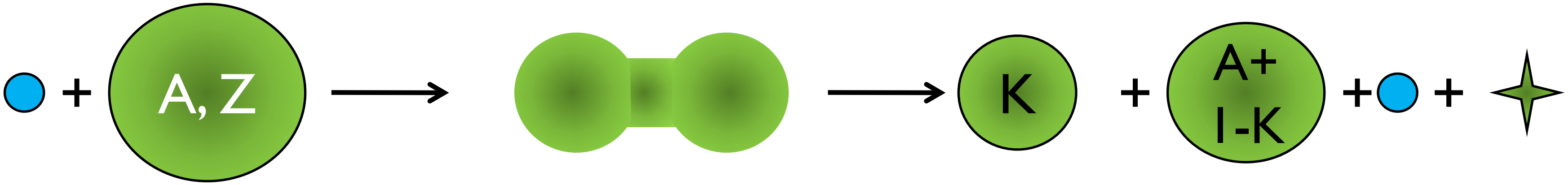


Remarkably good fit
Maximum at Z=20
Eventually limited by Z^2 term.
Fission is exothermic

B.E./A~8 MeV

2.2 Breaking a nucleus by a neutron

Ref. Asoke, p. 93



$$a = R\times(1+\varepsilon)$$

$$b = R/\sqrt{1+\varepsilon}$$

$$V = \frac{4}{3}\pi ab^2$$

$$\Delta(E) = B.E.(ellipsoid) - B.E.(sphere)$$

$$= \frac{1}{5}\varepsilon^2 A^{2/3}\left(2a_2 - a_3\frac{Z^2}{A}\right) > 0$$

$$Z^2 < 17.8\times 2/0.71 = 50\times A$$

A is the baryon number

Same for Boron in packaging materials,
B10 (20%) in BPSG most dangerous

2.2 neutron interaction with SiO2

nucleon + target → x1+x2+…+residual

$$r = 1.25\times10^{-13} B^{1/3}\ \text{cm}$$

$$\sigma_{0,Si} = \pi r^2 = 45.34\times10^{-26}\ \text{cm}^2 \sim 500\ \text{mBarns}$$

$$n + {}^{28}Si \rightarrow 2p + 3n + 3\,{}^{4}He + {}^{12}C + \text{photons}$$

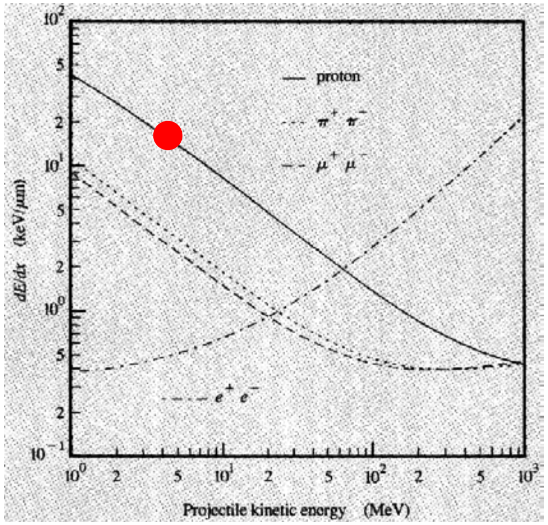
$$200\ \text{MeV} \rightarrow$$

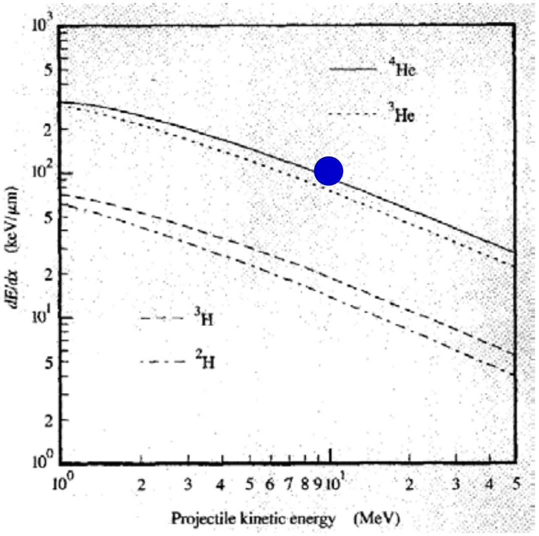
$$(2\times5) + (65.5+23+6.81) + (3\times10) + 4\text{MeV}$$

~ 4k of e-h pair/micron/per proton

~ 25k of e-h pair/micron/per alpha

Energy=8MeV/nucleon,
cascade by 65,23 MeV possible …





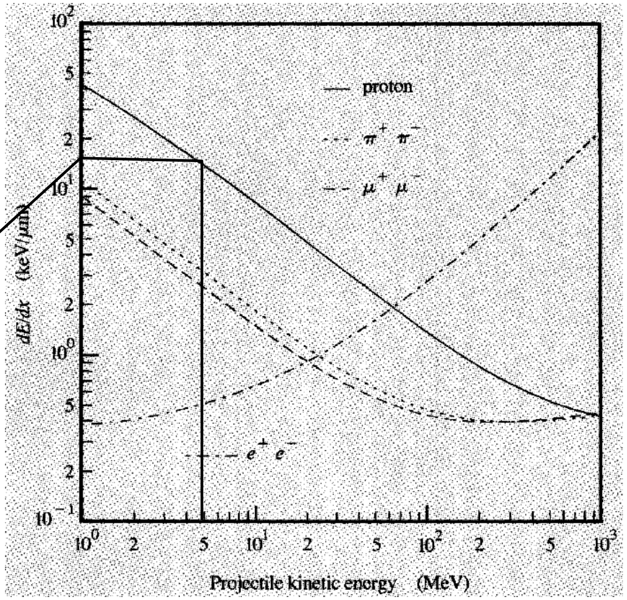
2.2 Reading the tables: example Problem

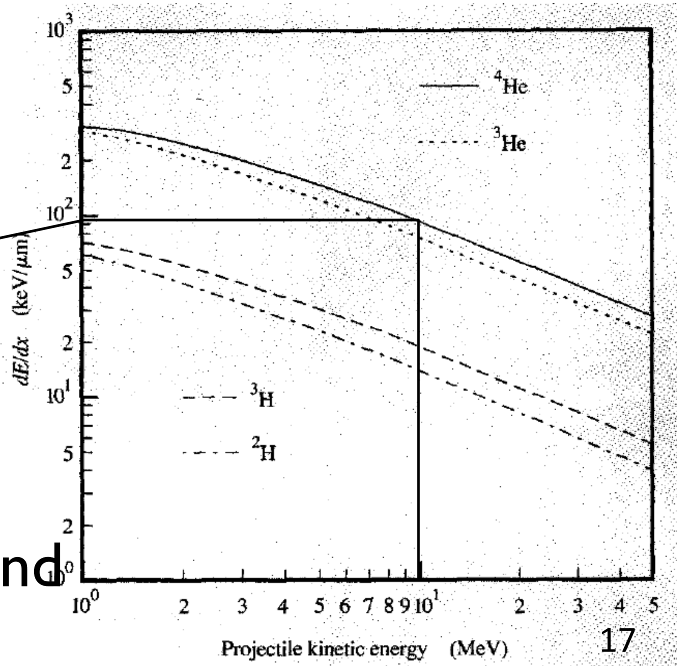
$$n + {}^{28}\mathrm{Si} \rightarrow 2p + 2n + {}^{25}\mathrm{Mg}^*.$$

$${}^{25}\mathrm{Mg}^* \rightarrow n + 3\,{}^{4}\mathrm{He} + {}^{12}\mathrm{C}.$$

Table 2 Example of a high-energy reaction channel for 200-MeV n + ^{28}Si.

Secondary particle	*K. E.* (MeV)	*dE/dx* (keV/μm)	*e-h pairs/μm*	*Range* (μm)
p	5.224	13.51	3.75×10^3	225
p	4.195	15.91	4.43×10^3	155
n	65.478	0	0	∞
n	22.958	0	0	∞
n	6.815	0	0	∞
^{4}He	12.218	79.91	2.22×10^4	90.5
^{4}He	12.025	80.83	2.25×10^4	88.1
^{4}He	7.881	108.84	3.02×10^4	43.6
^{12}C	4.138	1253.34	3.48×10^5	3





Final product … Most occur at the tail end

3.1 Critical charge and single event upset

Assume a transistor is doped to 10^{17} cm^{-3} and $V=1x1x10$ μm^3 vol.)

Number of electrons in the device = $10^{17}x1x1x10x10^{-12}$ = 1 Million

Suppose we need 50% of this charge for an upset (simulation)
500,000 electrons = 80 fC

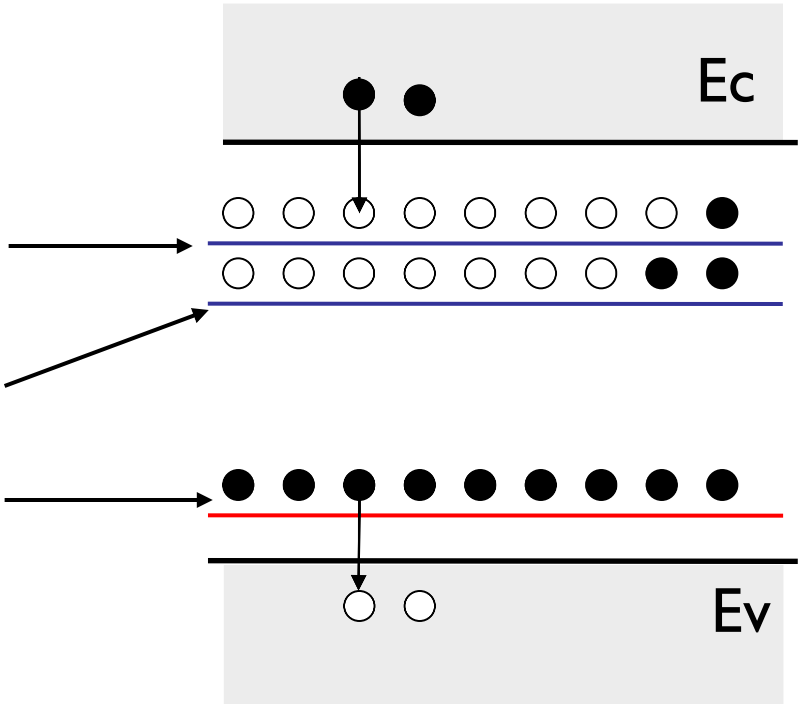
Yield per interaction with products of nuclear reaction…
for alpha particles (3 x 25k x 10 um) = 750,000
for protons (2 x 4k x 10 um) = 400,000

Minimum yield …. 1 Million

Every particle strike can cause an electrostatic upset!

Permanent damage: Perugia Model

Type	Energy (eV)	σ_e (cm^2)	σ_h (cm^2)
Acceptor	$E_C-0.42$	$2.0*10^{-15}$	$2.0*10^{-14}$
Acceptor	$E_C-0.46$	$5.0*10^{-15}$	$5.0*10^{-14}$
Donor	$E_v+0.36$	$2.5*10^{-14}$	$2.5*10^{-15}$



Leads to increased recombination and VT shift
Very important for low-noise detectors.

Conclusions

1. There are three types of particles of interest: alpha particles, high-energy neutrons, and low energy neutrons. Others do not make it to the surface in significant numbers.

2. Once the neutrons and alpha particles interact with nucleus, they may displace the atoms from their usual position, causing permanent damage in the process.

3. The protons released in the process interacts with the lattice by EM interaction and generate electron-hole pairs – which in turn leads to soft-errors and single event upsets.

4. It is relatively easy to calculate the net yield of charge per nuclear interaction in various materials by using semi-empirical approaches.

References

The Bethe-Bloch formula is derived in most textbooks on Nuclear Physics, see for example *Nuclear Physics in a Nutshell, by C. A. Bertulani, 2007* or, P. Sigmund, "Particle Radiation and Radition Effects. Sprigner Series in Solid Sate Sciences, 151, 2006.

Other papers that could be interest are by H.H.K. Tang, G. R. Srinivasan, and N. Azziz, "Cascade Statistical model for nucleon-induced reactions on light nuclei in the energy range 50 MeV-1GeV", PRC, 42, p. 1598, 1990. "Bethe stopping power theory for fast ions moving through two dimensional targets: harmonic oscillator model" Y.-N. Wang and T.-C. Ma, Physics Letters, A 221, p. 134-137, 1996.

Statistical and Nuclear Reactions, V Weisskoff, Physical Review, 52, p. 295, 1937.

The stopping distance formula is derived in "An approximate formula for electron energy vs. path lengths", J. S. Greeneigh and T. Van Duzer, ITED, 1973.

Review Questions

1. What did Fermi-Pasta-Ulam did in 1950s that is relevant for the discussion today?
2. Do you expect the neutron to have longer mean free path than a proton? Why or why not?
3. What is a ‘mass formula’? Why do we need a mass formula for?
4. What is Fermi? How is it related to Barns?
5. What is a blackwall? How does blackwall of Uranium compare to Si?
6. What is the definition of stopping distance? How do you calculate stopping distance?
7. Why is the emission from packaging so damaging to the ICs? Why doesn’t Boron as a p-dopant cause the same problem?