Terrestrial Radiation Induced Soft Errors in Integrated Circuits

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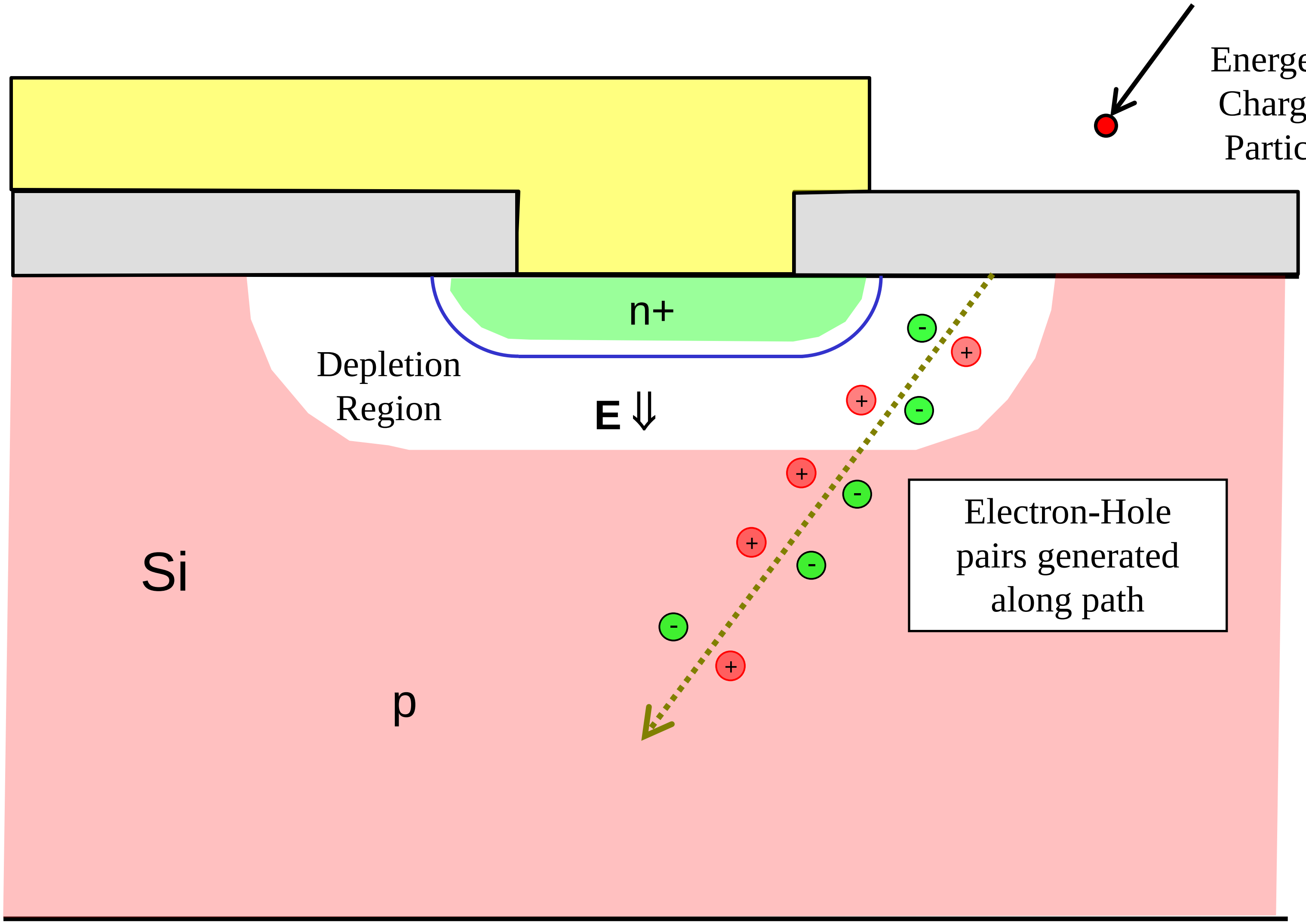
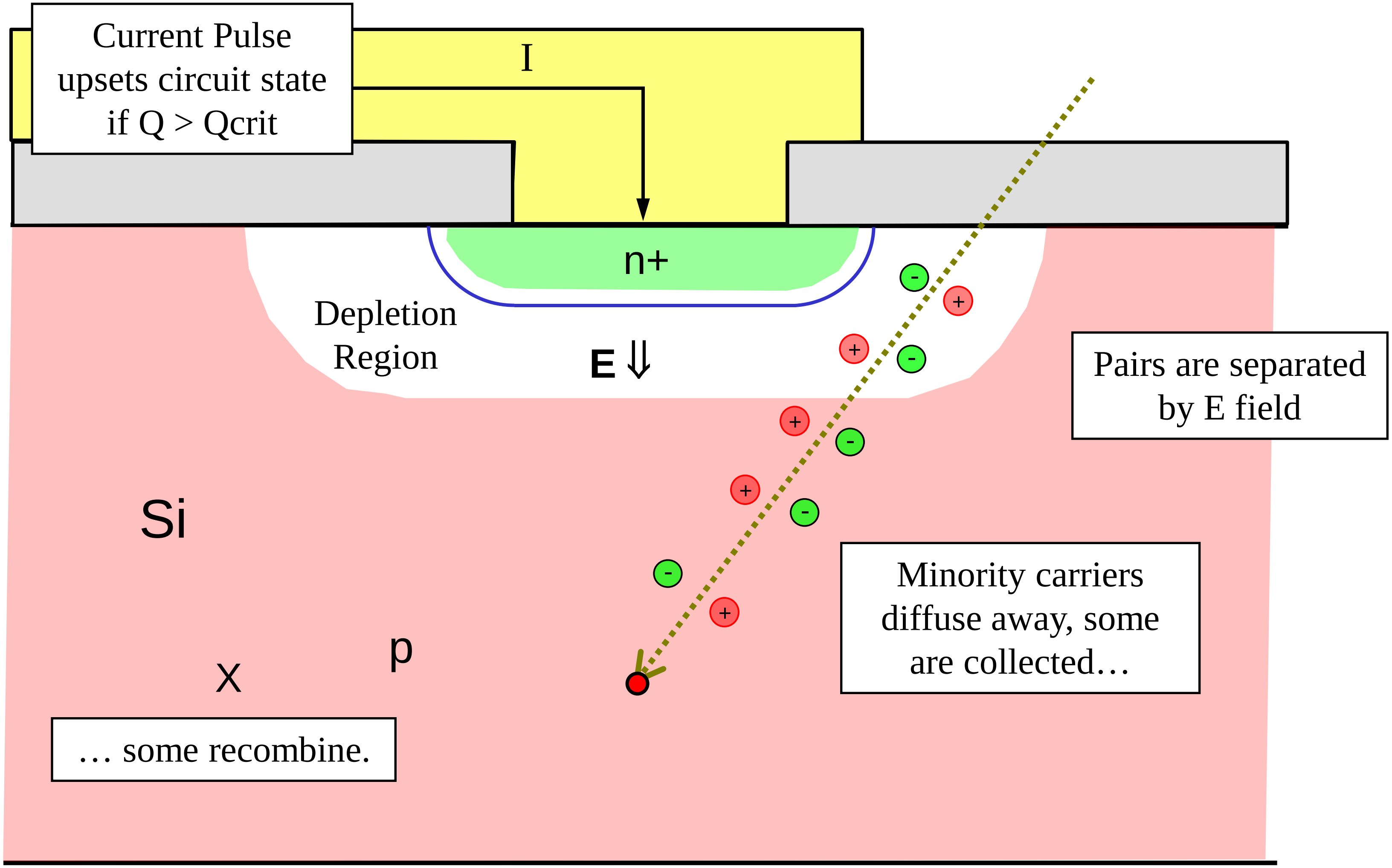
How does radiation cause errors?



Energetic Charged Particle

Electron-Hole pairs generated along path

How does radiation cause errors?



Current Pulse upsets circuit state if Q > Qcrit

Pairs are separated by E field

Minority carriers diffuse away, some are collected…

… some recombine.

Qcrit is the minimum amount of charge that will flip state.
Soft Error is also called “SEU” (*Single Event Upset*.)

Main Sources of Radiation

There are three important sources of radiation that contribute to SEU (Single Event Upset):

1. **Radioactive Contaminants**
2. **Cosmic Rays**
3. **Cosmic Ray / Boron-10**

Part I. Radioactive Contaminants

History

Late 70s: Random fails appeared in Intel 4K 2107 DRAM introduced in 1974.

1978: May and Woods of Intel showed the fails to be radiation induced in a seminal paper.

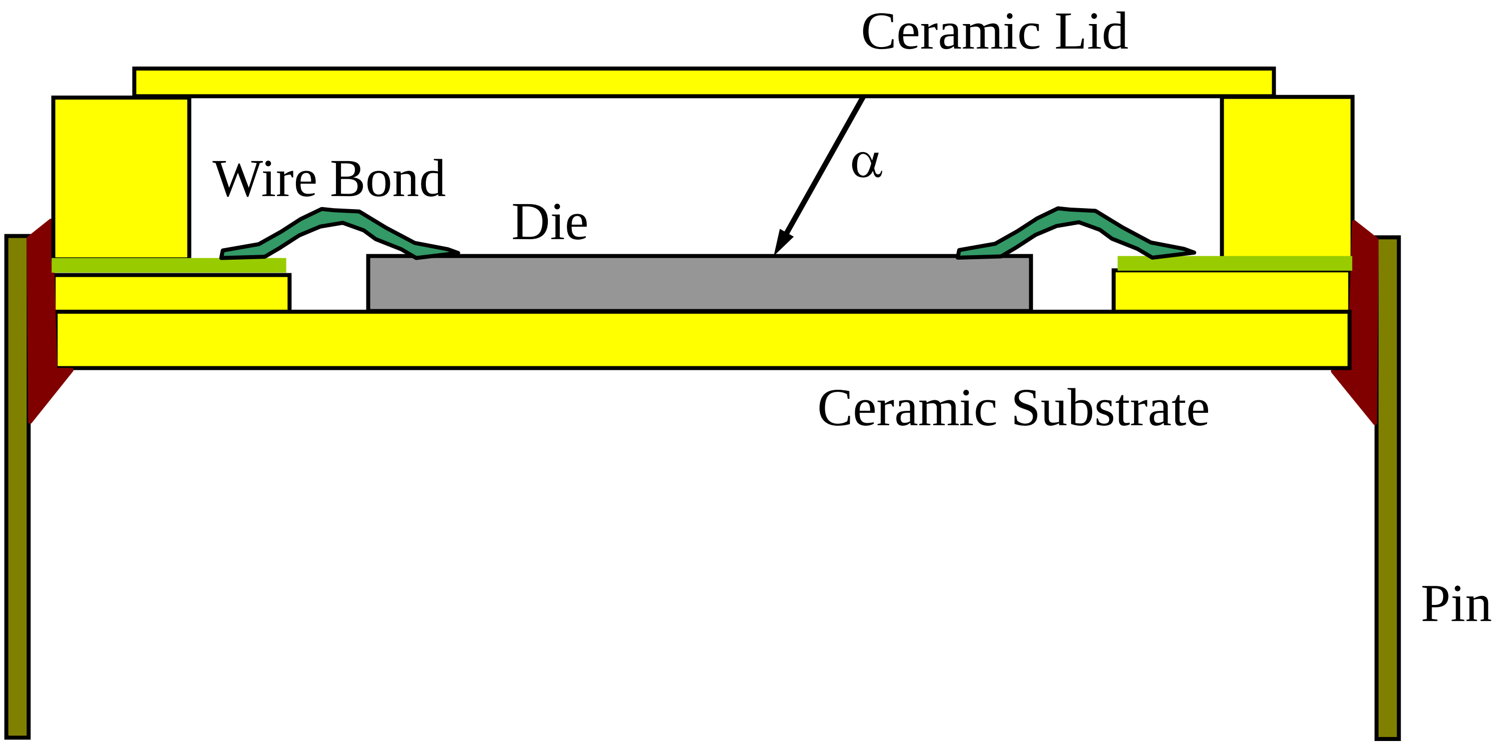
“A New Physical Mechanism For Soft Errors In Dynamic Memories,” Rel. Phys. Symp. 1978, p. 33-40.

(“Alpha-Particle-Induced Soft Errors in Dynamic Memories,” Trans. Elec. Dev. 26, pp. 2-9, 1979.)

Paper is amazingly complete and shows deep understanding

- Proof that the fails are due to alpha particles emitted by U and Th and daughter impurities in ceramic package lid
- Introduction of the Q_{CRIT} concept
- Accelerated testing with ^{210}Po (alpha particle) source
- Analysis of ceramic material
- Measurement of scaling effects
- Simulation of SER

Intel Ceramic Package

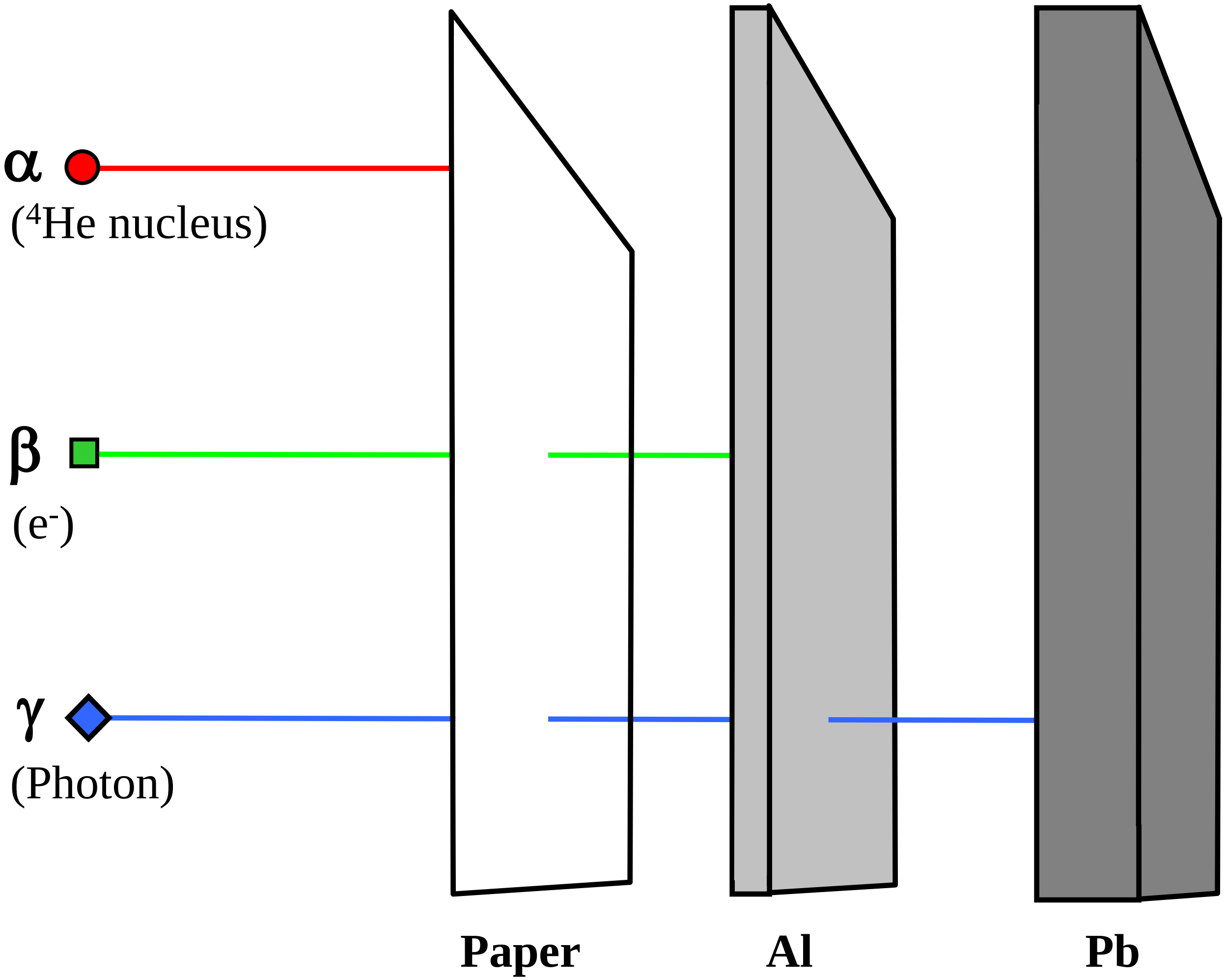


α's emitted by impurities in the ceramic lid strike the active chip area.

Activity = 200 to 700 α/cm^2/khr (Typical Ceramic Spec = 20 - 50)

SER = 1-3% / kHr (2 500 000 - 7 500 000 FIT/Mbit)

Natural Radioactivity: Three Types of “Rays”



α

(^{4}He nucleus)

β

(e^-)

γ

(Photon)

Paper

Al

Pb

Radioactive Decay

Two dominant types of radioactive nuclear decay

- **Alpha Particle decay**

  Unstable heavy nuclei decay by emitting an alpha particle (^{4}He.)

(Various lines)

γ

α Particle
Z=2, A=4

“Daughter” (“Recoil”)
Nucleus
Z-2, A-4

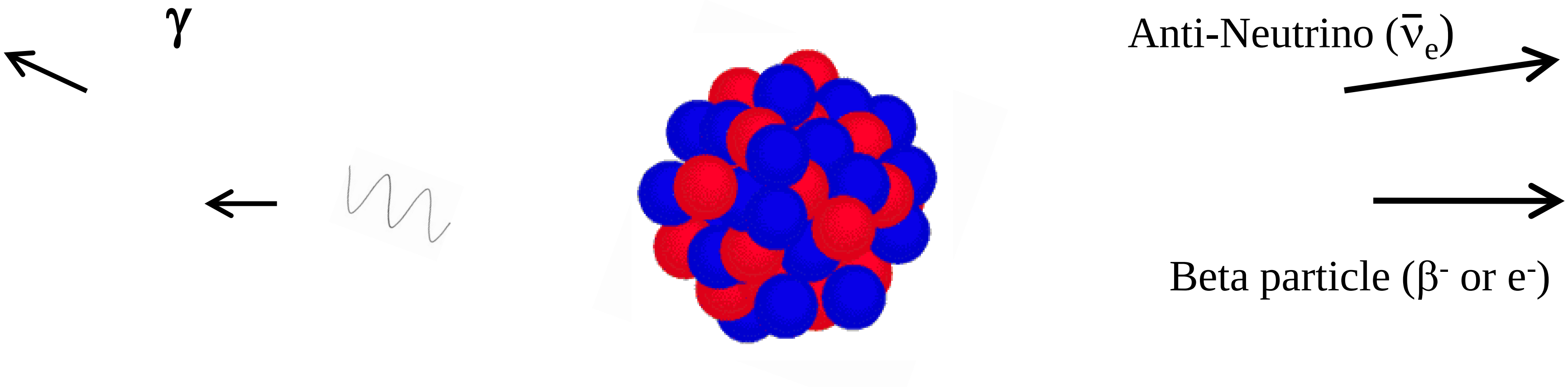
“Parent” or “Mother”
Nucleus
Z, A

Most α energies (discrete energies) ~ 4 – 10 MeV

Radioactive Decay

- **Beta Particle decay**

  Nuclei unstable due to excess neutrons decay by emitting a beta particle (electron.)



(Various lines)

γ

Anti-Neutrino ($\bar{\nu}_e$)

Beta particle (β^- or e^-)

"Daughter" ("Recoil")
Nucleus
Z+1, A

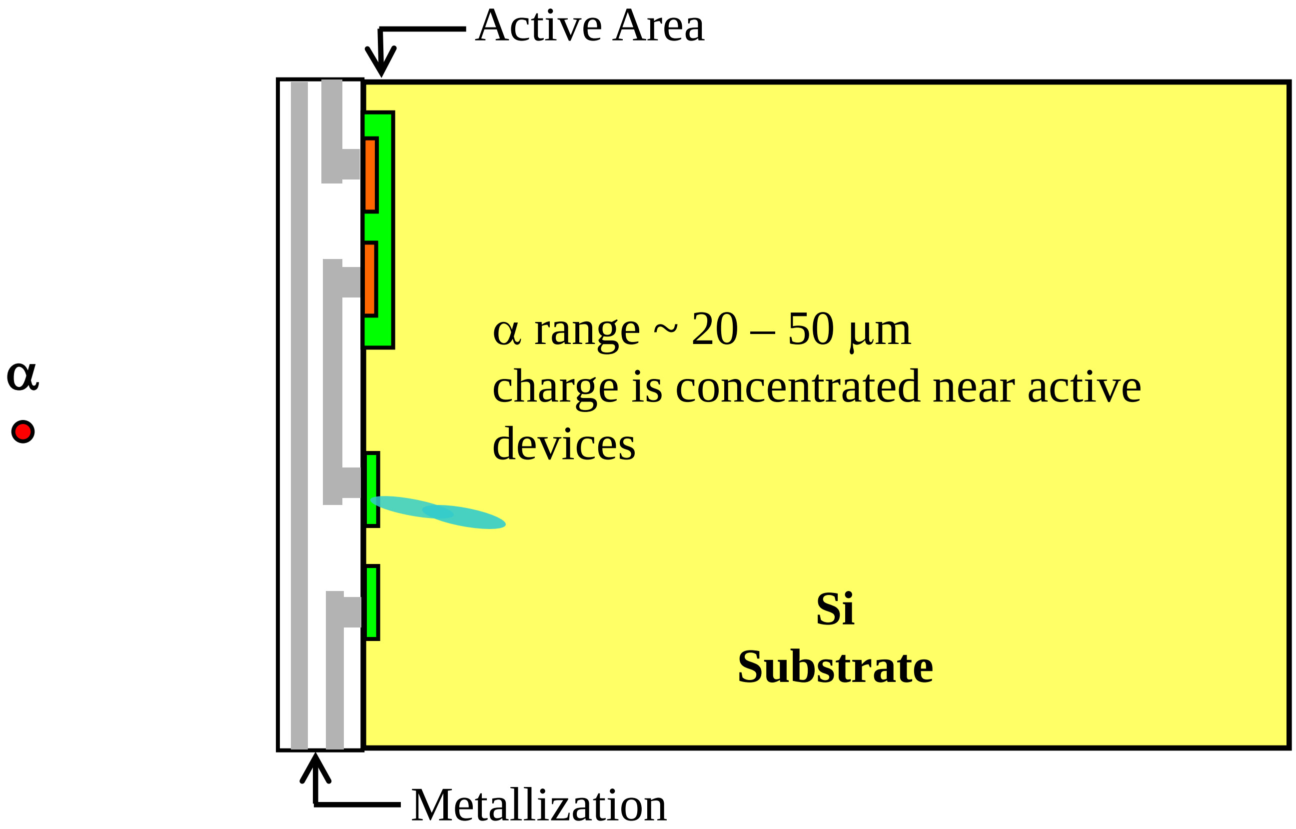
"Parent" or "Mother"
Nucleus
Z, A

Most β energies ~ 0 – 5 MeV

Beta energy is a spectrum; total energy is shared with neutrino.

α, β, γ in Silicon

Why α cause upsets…



Active Area

α

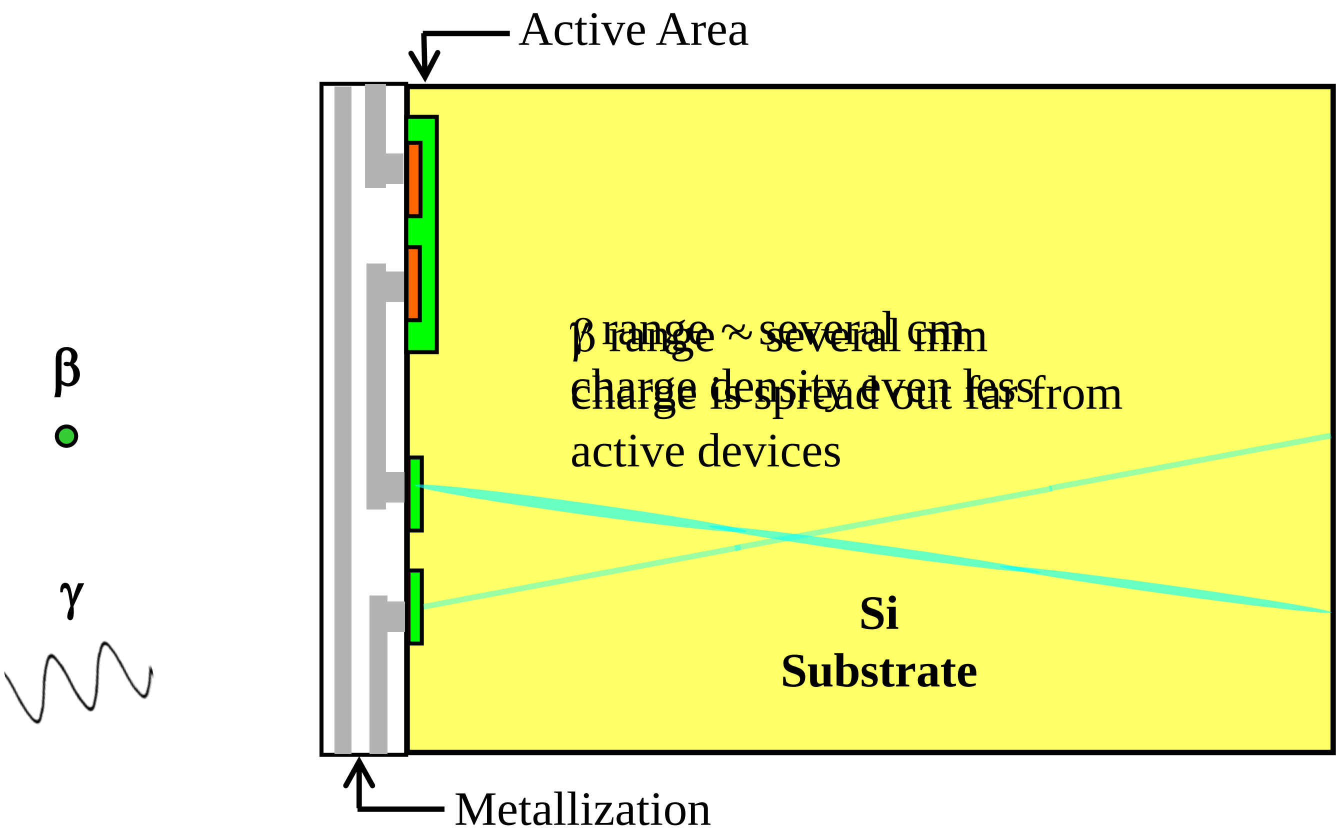
α range ~ 20 – 50 µm
charge is concentrated near active devices

Si
Substrate

Metallization

α, β, γ in Silicon

…while β and γ don't.



β range ~ several cm
charge density even less

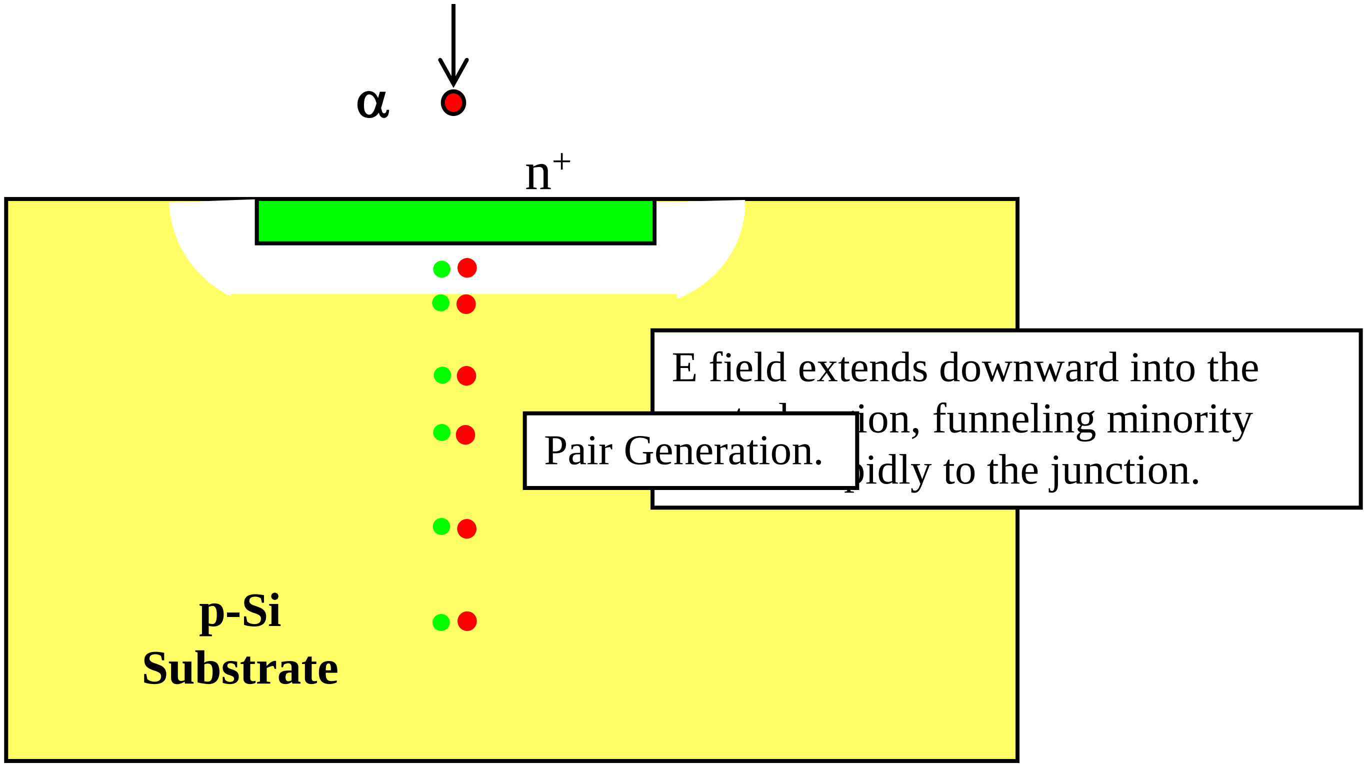
β range ~ several mm
charge is spread out far from active devices

dE/dx, the LET (*Linear Energy Transfer*), or stopping power, is much higher for α than β or γ.

Charge generation is proportional to energy loss - ~44fC/MeV in Si.

Funneling

Induced current flow distorts the E field, increasing the depth of field collection.



E field extends downward into the …ion, funneling minority …idly to the junction.

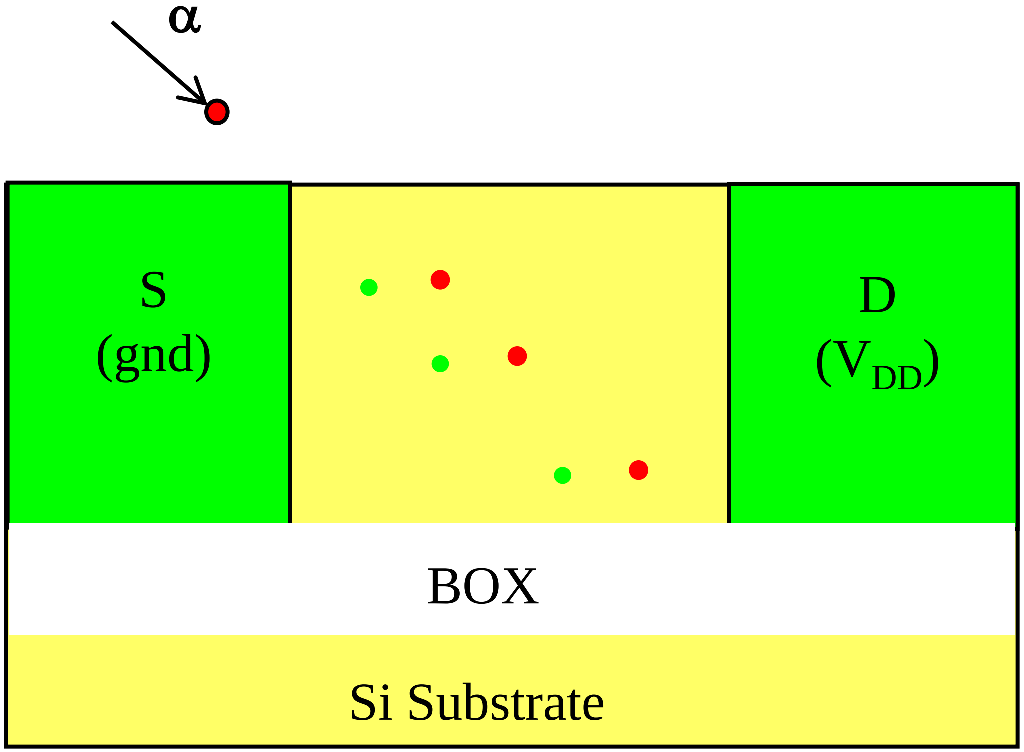
Pair Generation.

The funneling mechanism increases the total amount of charge collected, and speeds up the current pulse.

C.Hsieh et al., “A Field-funneling Effect on the Collection of Alpha-Particle-Generated Carriers in Silicon Devices,” Elec. Dev. Let. 2, pp. 103-105, 1981.

SOI Floating Body Effect

Induced charge forward biases body potential, causing bipolar multiplication.



1. α strike in well => Pair Generation
2. Minority charge collected (mostly into drain) or recombines.
3. Well forward biased. Excess majority charge flows into source, and…
4. Minority carriers emitted by source, collected by drain.

The bipolar multiplication increases the total amount of charge collected, effectively lowering Qcrit.

Natural Radioactive Contaminants

Heavy unstable nuclei decay into stable nuclei via chains of successive unstable intermediate nuclei.

There are two important parent isotopes: **^{238}U and ^{232}Th**.

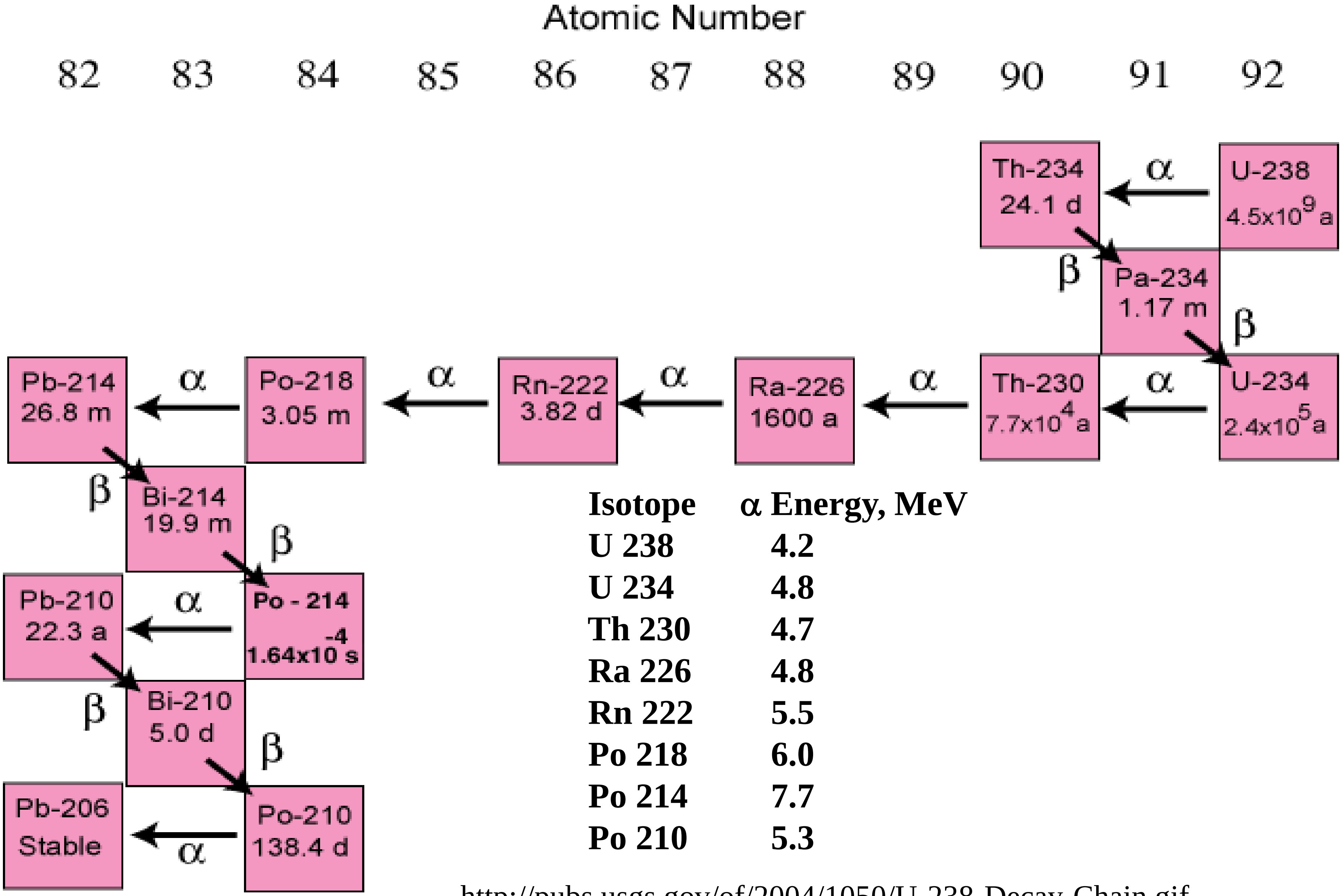
^{238}U → 13 unstable daughters → ^{206}Pb

^{232}Th → 9 unstable daughters → ^{208}Pb

Systems will reach *secular equilibrium*, where the activity (decays/time) for each stage will equalize.

These two chains (plus ^{40}K) are thought to provide the major source of heat in the Earth's core, keeping the outer core molten, which drives plate tectonics and Earth's magnetic field.

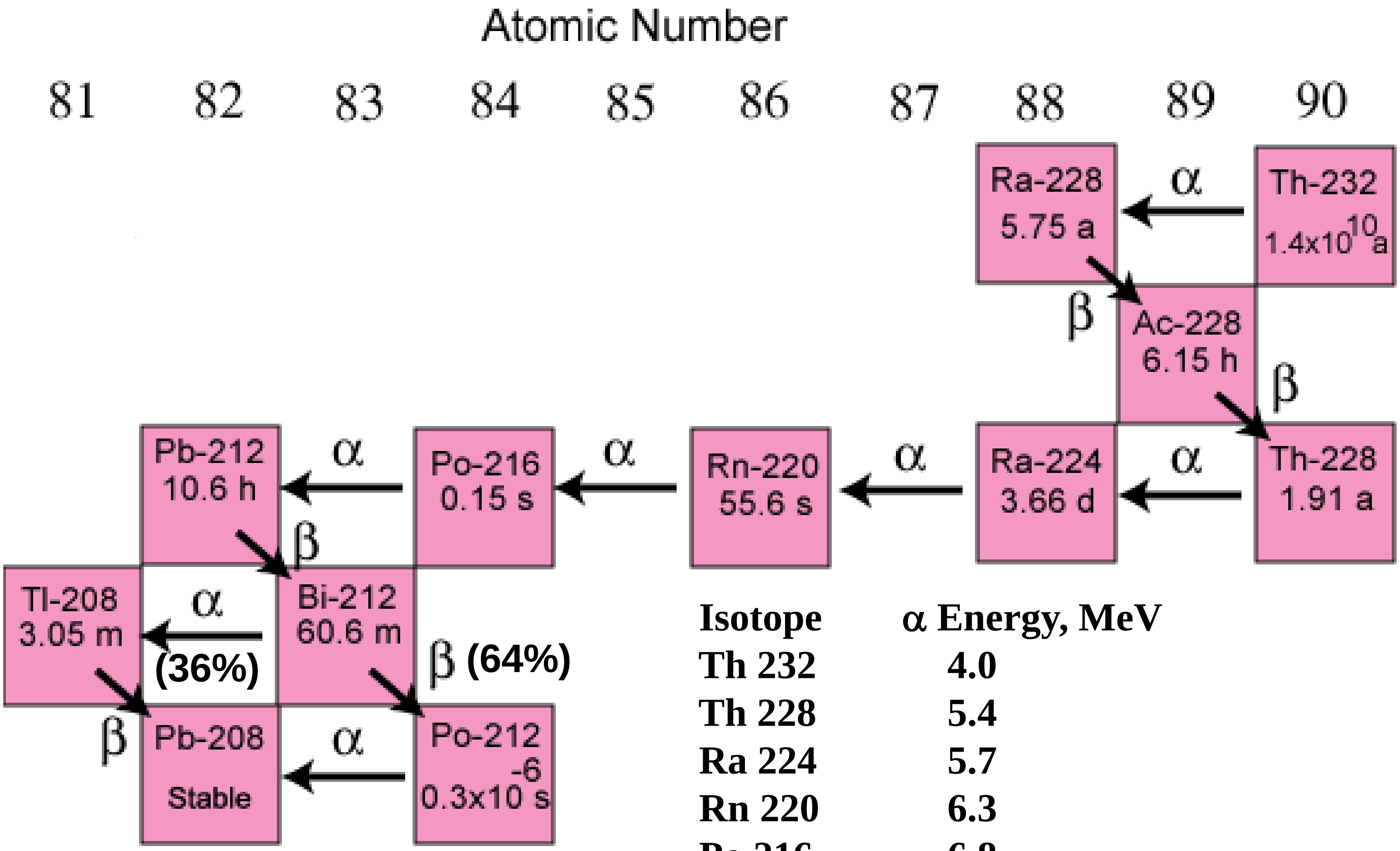
The Uranium-238 Decay Chain



Isotope	α Energy, MeV
U 238	4.2
U 234	4.8
Th 230	4.7
Ra 226	4.8
Rn 222	5.5
Po 218	6.0
Po 214	7.7
Po 210	5.3

http://pubs.usgs.gov/of/2004/1050/U-238-Decay-Chain.gif

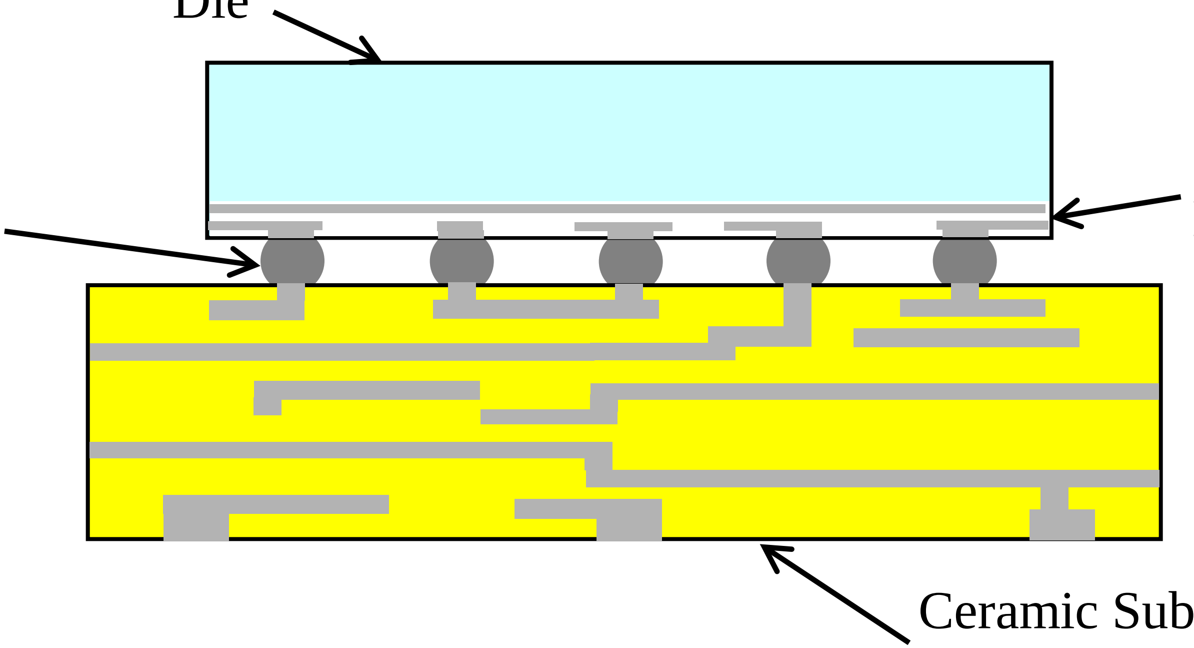
The Thorium-232 Decay Chain



Isotope	α Energy, MeV	
Th 232	4.0	
Th 228	5.4	
Ra 224	5.7	
Rn 220	6.3	
Po 216	6.8	
Bi 212	6.1	(36%)
Po 212	8.8	(64%)

http://pubs.usgs.gov/of/2004/1050/Th-232-Decay-Chain.gif

Common Sources of Radiation



Die

Chip
Metallization

Solder
Bumps

Ceramic Substrate
or Board

1. Ceramic – contains ^{238}U and ^{232}Th and daughters (20 - 50)
2. Solder Bumps – Pb contains ^{210}Pb (^{210}Po daughter) (20 – 100)
3. Contamination (U/Th) in chip BEOL (<1)

α/cm^{2}/khr

Two Cases of Unintentional Contamination

1. **Early Intel DRAM**

   The Intel ceramic vendor plant in Colorado was found to be using water contaminated by upstream uranium mine tailings.

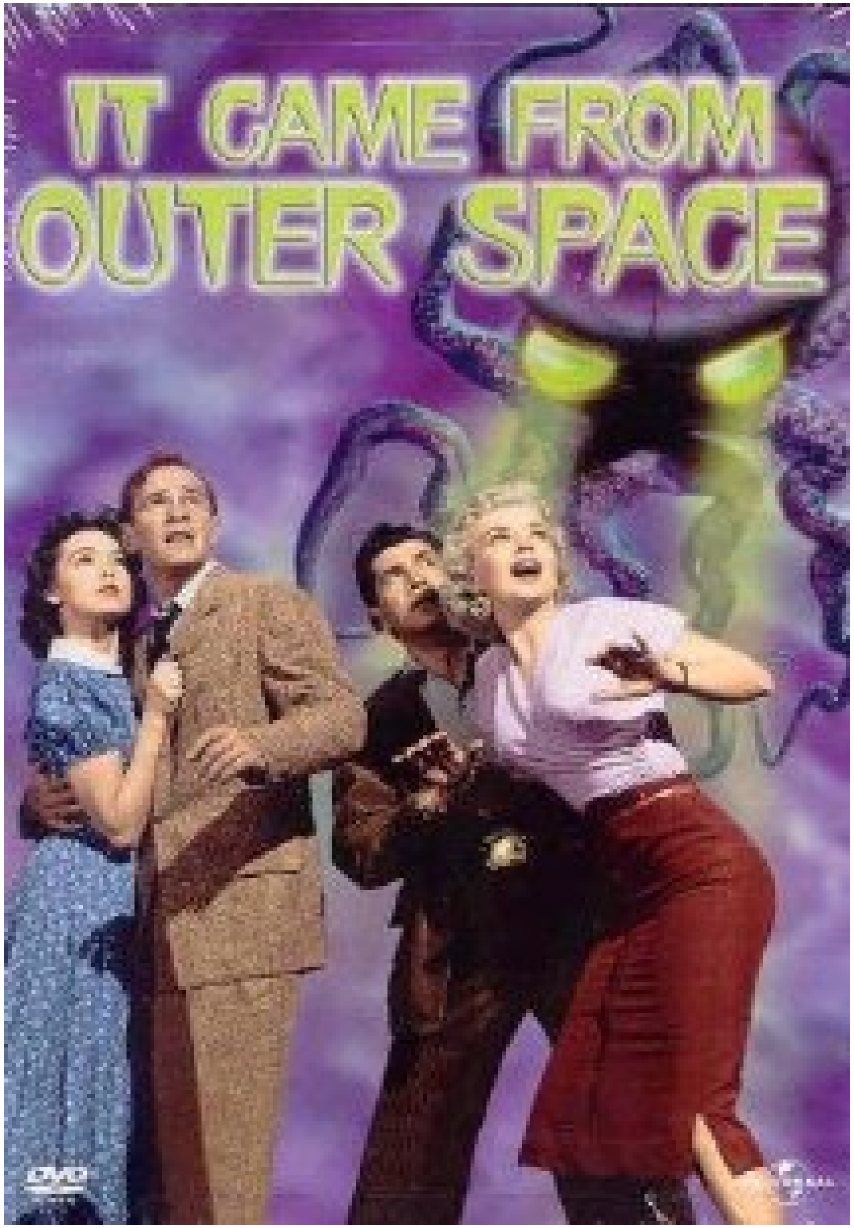
2. **IBM “Hera” Problem**

   A brief incident of high SER on a particular SRAM was traced to ^{210}Po contamination of nitric acid used in processing. The source of the contamination was a faulty air ionizer (containing ^{210}Po) at the chemical vendor site. Ionized air was blown into bottles to remove dust before filling.

Ziegler et al., “IBM experiments in soft fails in computer electronics (1978-1994),” IBM J. Res. Dev. 40, pp 3-18, 1996.

Part II. Cosmic Rays

Origin of Cosmic Rays



It seems like Science Fiction, but the most important contributions to terrestrial Cosmic Rays and SER are from galactic (GeV – PeV) and extragalactic (PeV – EeV) sources.

Your next laptop system crash may be due to a supernova explosion in our galaxy which happened 10,000 years ago.

http://www.imdb.com/title/tt0045920/

Cosmic Rays blamed for…

New theory blames cosmic rays for helping CFCs deplete ozone
Qing-Bin Lu, Physics Reports 487 p141-167,(2010).

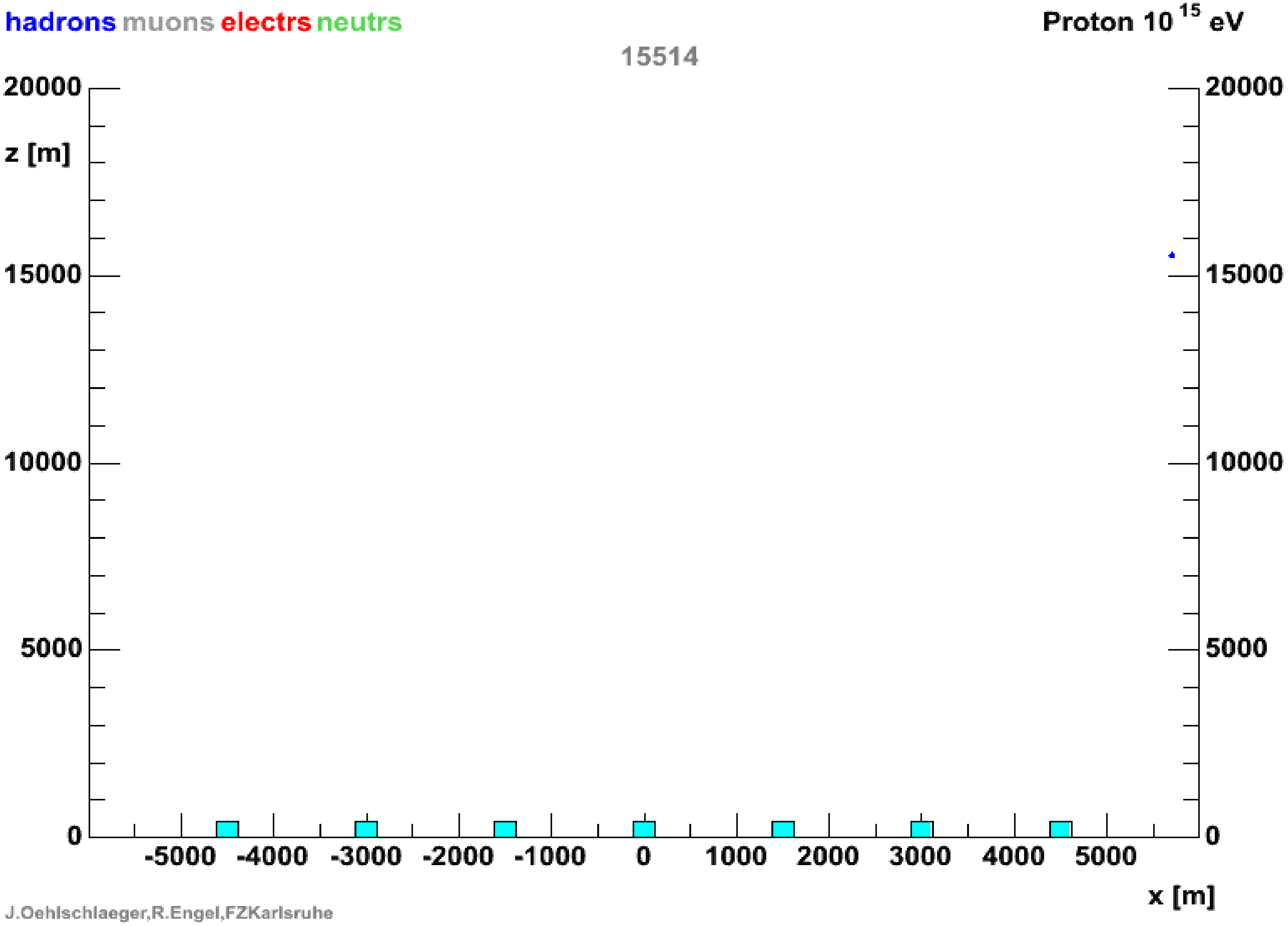
Cosmic rays blamed for global warming
Henrik Svensmark and E. Friis-Christensen, J. Atmos. Sol. Terr. Phys. 59, pp.1225–1232, 1997.

'Cosmic rays' may have caused Qantas jet's plunge
ATSB TRANSPORT SAFETY REPORT, Aviation Occurrence Investigation AO-2008-070, Interim Factual No 2, 2008

Toyota Recall Might Be Caused by Cosmic Rays
www.livescience.com/technology/toyota-recall-cosmic-rays-100326.html

Ancient Mass Extinctions Caused by Cosmic Radiation
Mikhail Medvedev and Adrian Melott, J. Astrophys. 664, pp879-889, 2007.

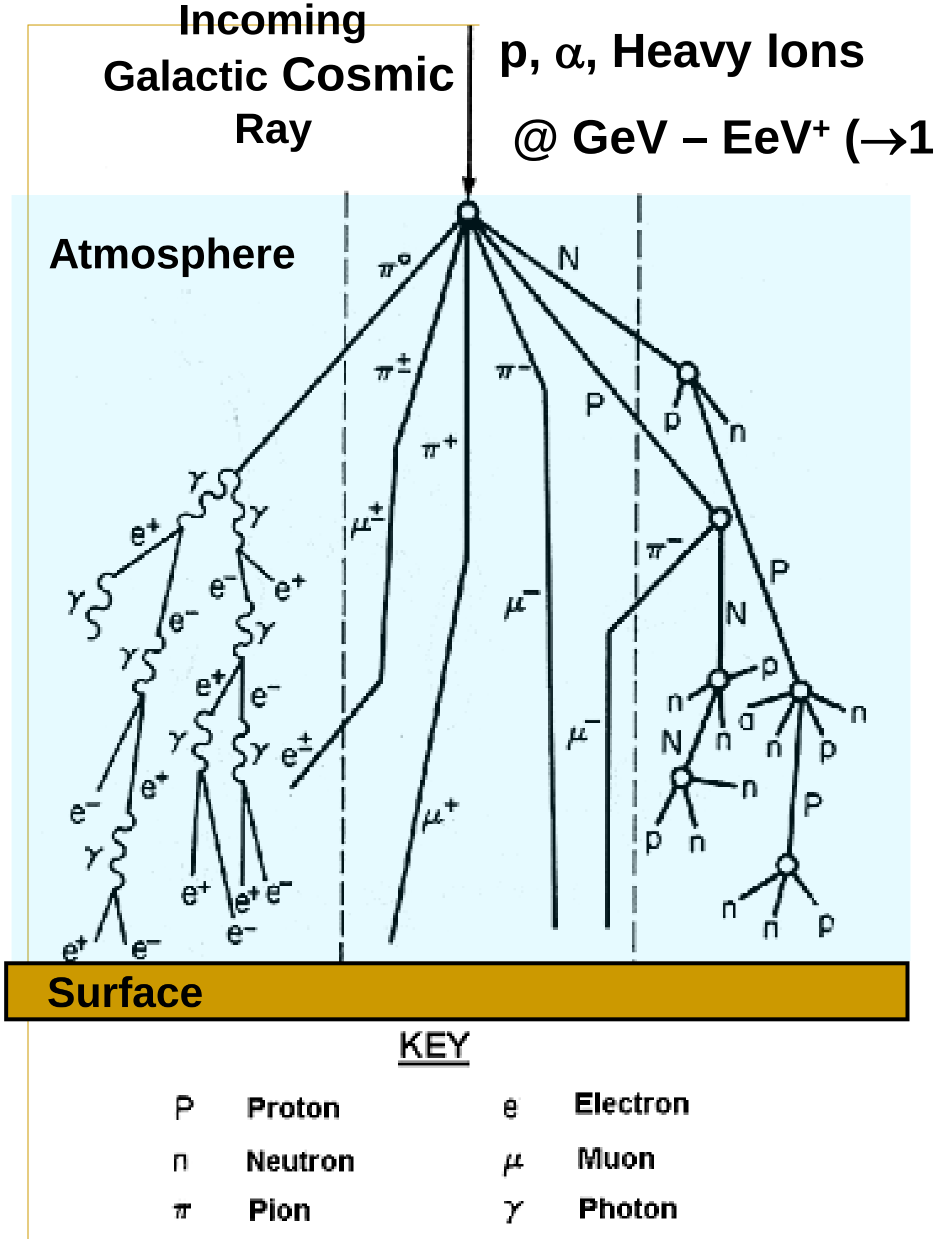
Movie: Cosmic Ray Shower (side view)



J.Oehlschlaeger,R.Engel,FZKarlsruhe

(H.-J. Drescher drescher@th.physik.uni-frankfurt.de)

Cosmic Rays Showers



Incoming Galactic Cosmic Ray

p, α, Heavy Ions

@ GeV – EeV$^+$ (→10^{20} eV)

Atmosphere

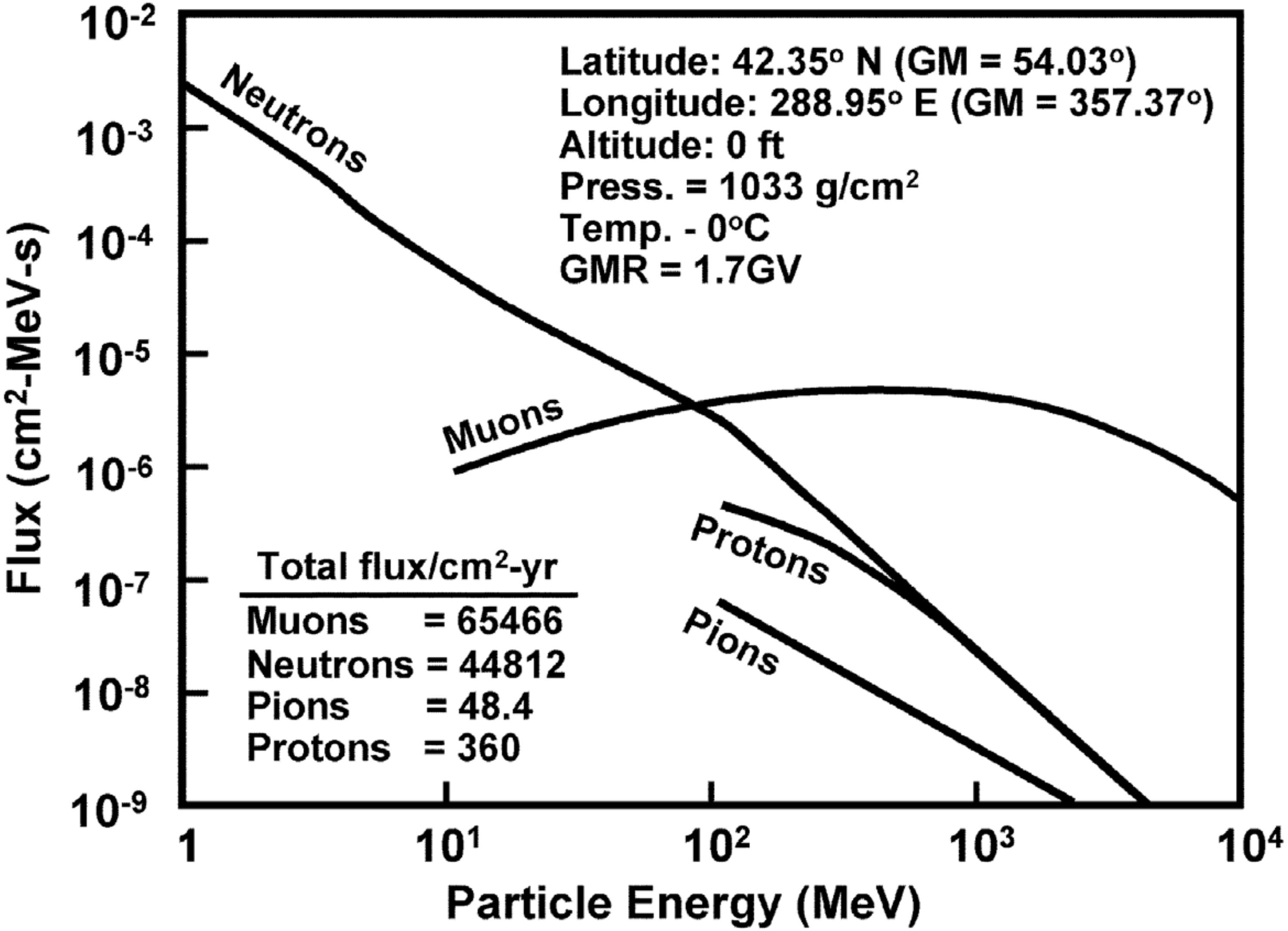
Surface

When the incoming galactic cosmic ray hits the atmosphere, it creates a cascade (or air shower) of millions or billions of secondary particles.

What are left at the surface are primarily n, β, μ, p. Neutrons dominate. (Muons above 100 MeV; LET too small.)

(http://neutronm.bartol.udel.edu/catch/cr2b.gif)

Surface Cosmic Ray Flux (Boston)

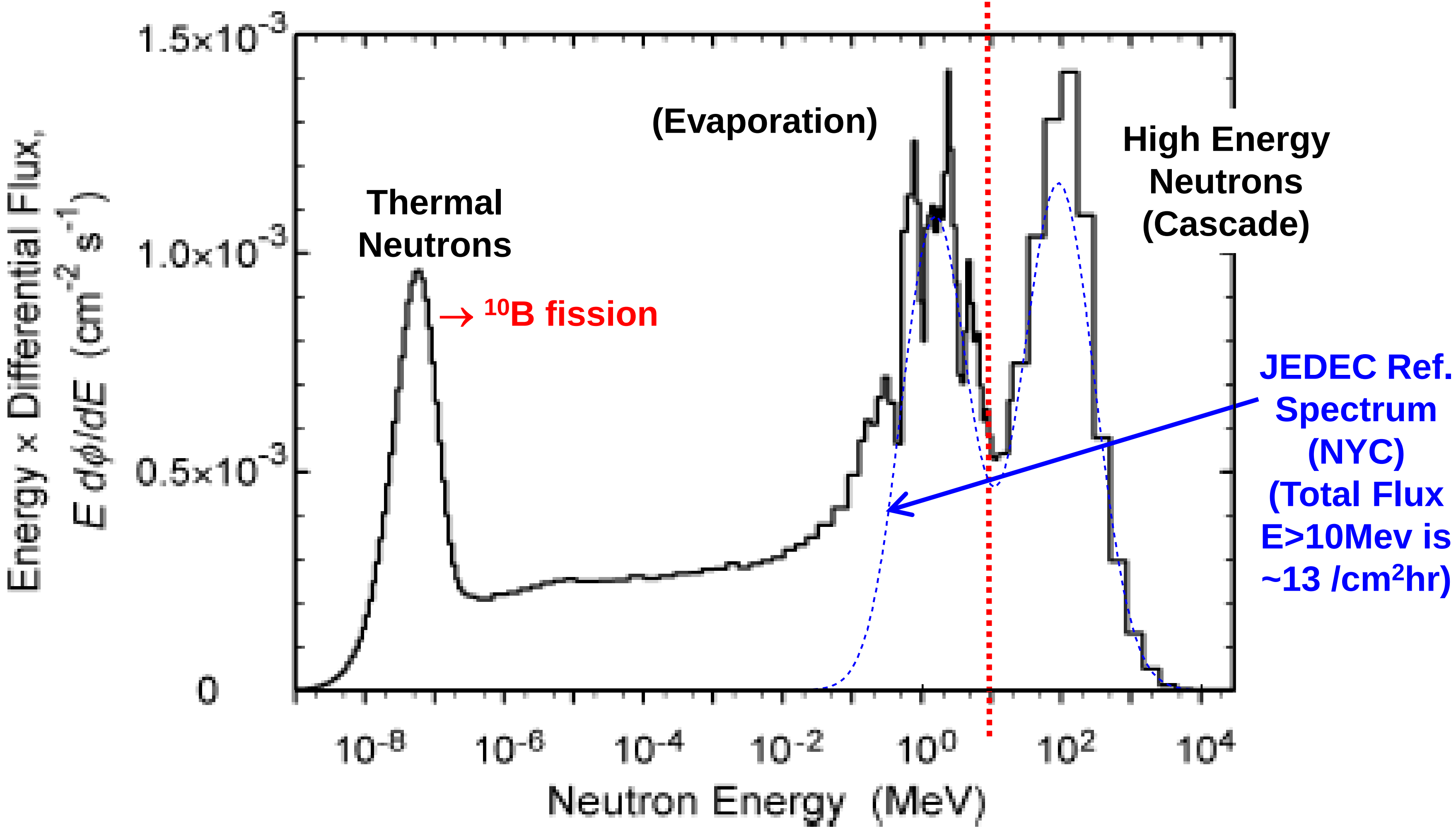


Barth, "Space, Atmospheric, and Terrestrial Radiation Environments," Trans. Nuc. Sci., v. 50, pp. 466-482, 2003.

Terrestrial Neutron Flux (Burlington, Vt)

Flux is a function of altitude and location.

These cause almost all fails



→ ^{10}B fission

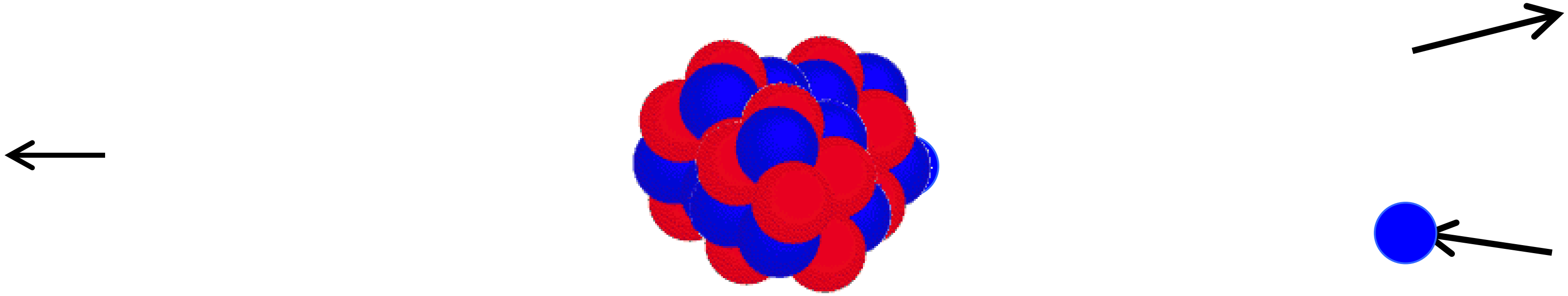
JEDEC Ref. Spectrum (NYC) (Total Flux E>10Mev is ~13 /cm^{2}hr)

M. Gordon et al., “Measurement of the Flux and Energy Spectrum of Cosmic-Ray Induced Neutrons on the Ground,” Trans. Nuc. Sci., v. 51, pp. 3427-3434, 2004.

How neutrons produce ionization

Since neutrons have no charge, they do not directly ionize Si.
⇒ neutrons are extremely penetrating.
High energy neutrons will interact with Si (or O, Cu, etc) nuclei in two ways:

I. Elastic Collision



Recoil Si Nucleus

Si Nucleus in lattice

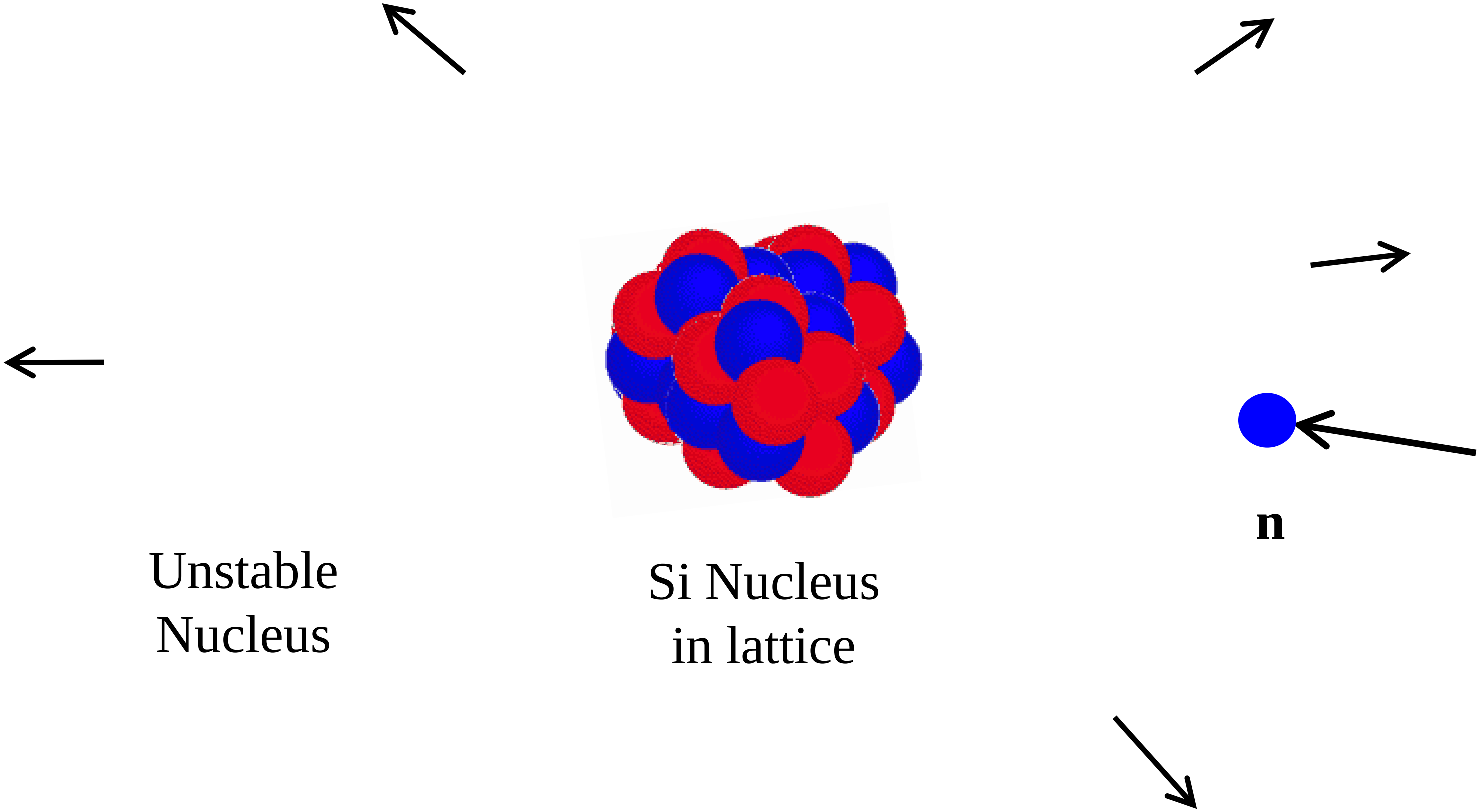
n

The recoil Si nucleus will carry charge. Range is very limited ~ a few μm.
Not the dominant SER mechanism.

How neutrons produce ionization

II. Inelastic Collision – Spallation

“Cascade” Phase

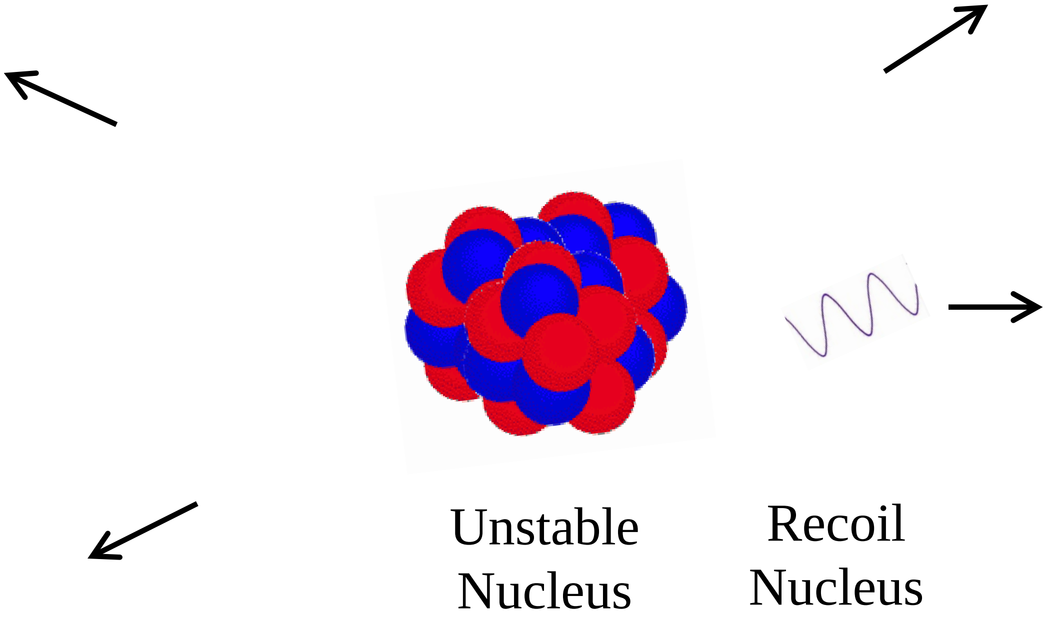


Step 1. A neutron impacts a Si nucleus, producing an unstable nucleus + particles: π, p, n, d (^{2}H), t (^{3}H), α (^{4}He), etc.

How neutrons produce ionization

II. Inelastic Collision - Spallation

“Evaporation” Phase



Step 2. The unstable nucleus decays into a stable nucleus + particles: more p, n, d (^{2}H), t (^{3}H), α (^{4}He), etc.

Example: $n + {}^{28}Si \rightarrow 2p + 2n + {}^{25}Mg^{*}$; ${}^{25}Mg^{*} \rightarrow n + 3\,{}^{4}He + {}^{12}C$

History

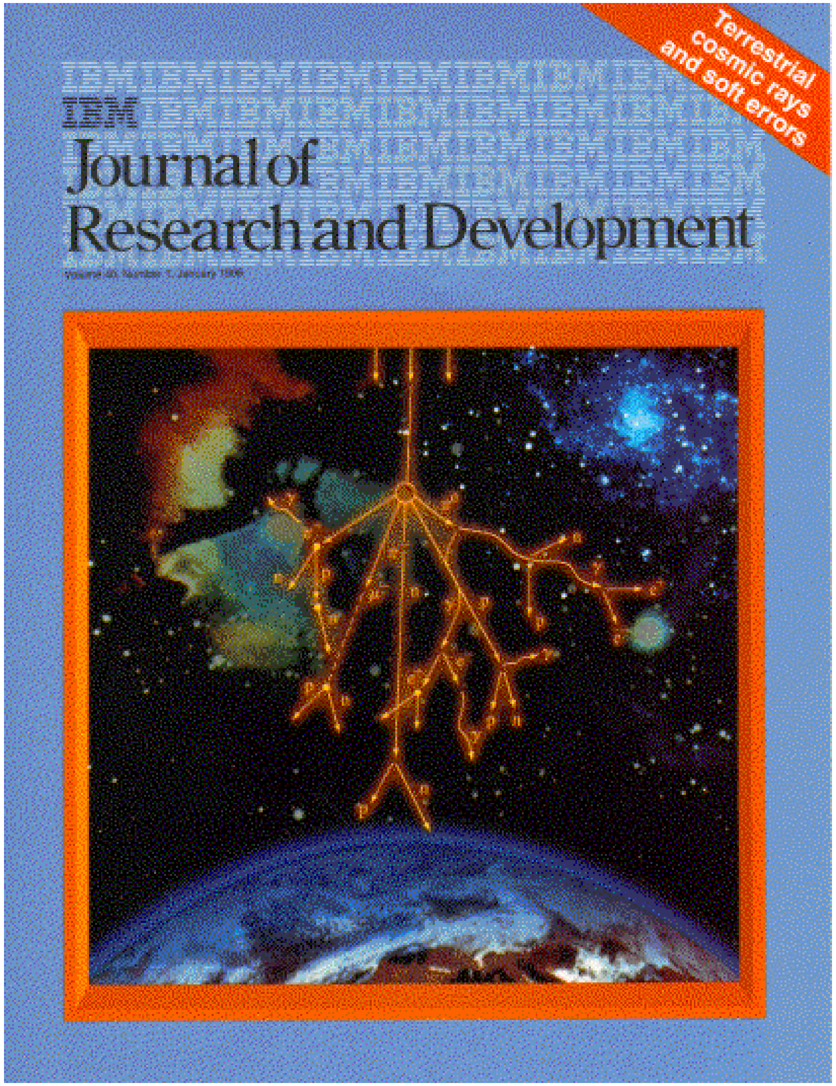
1975: Binder, Smith, and Holman of Hughes Aircraft attribute satellite electronic upsets to heavy ions in 1975.
“Satellite Anomalies From Galactic Cosmic Rays,” Trans. Nuc. Sci. 22, pp. 2675-2680, 1975.

1979: Jim Ziegler of IBM and Lanford of Yale publish prediction of SEU due to terrestrial cosmic rays in 1979.
“Effect of Cosmic Rays on Computer Memories,” Science 206, pp. 776-788, 1979.

1994: Tim O’Gorman of IBM reports the first experimental evidence for terrestrial cosmic ray soft error rate.
“The Effect of Cosmic Rays on the Soft Error Rate of a DRAM at Ground Level,” Trans. Elec. Dev. 41, pp. 553-557, 1994.

1996: Special Issue of IBM Journal of Research and Development dedicated to “Terrestrial Cosmic Rays and Soft Errors” discloses IBM involvement from 1978-1994.

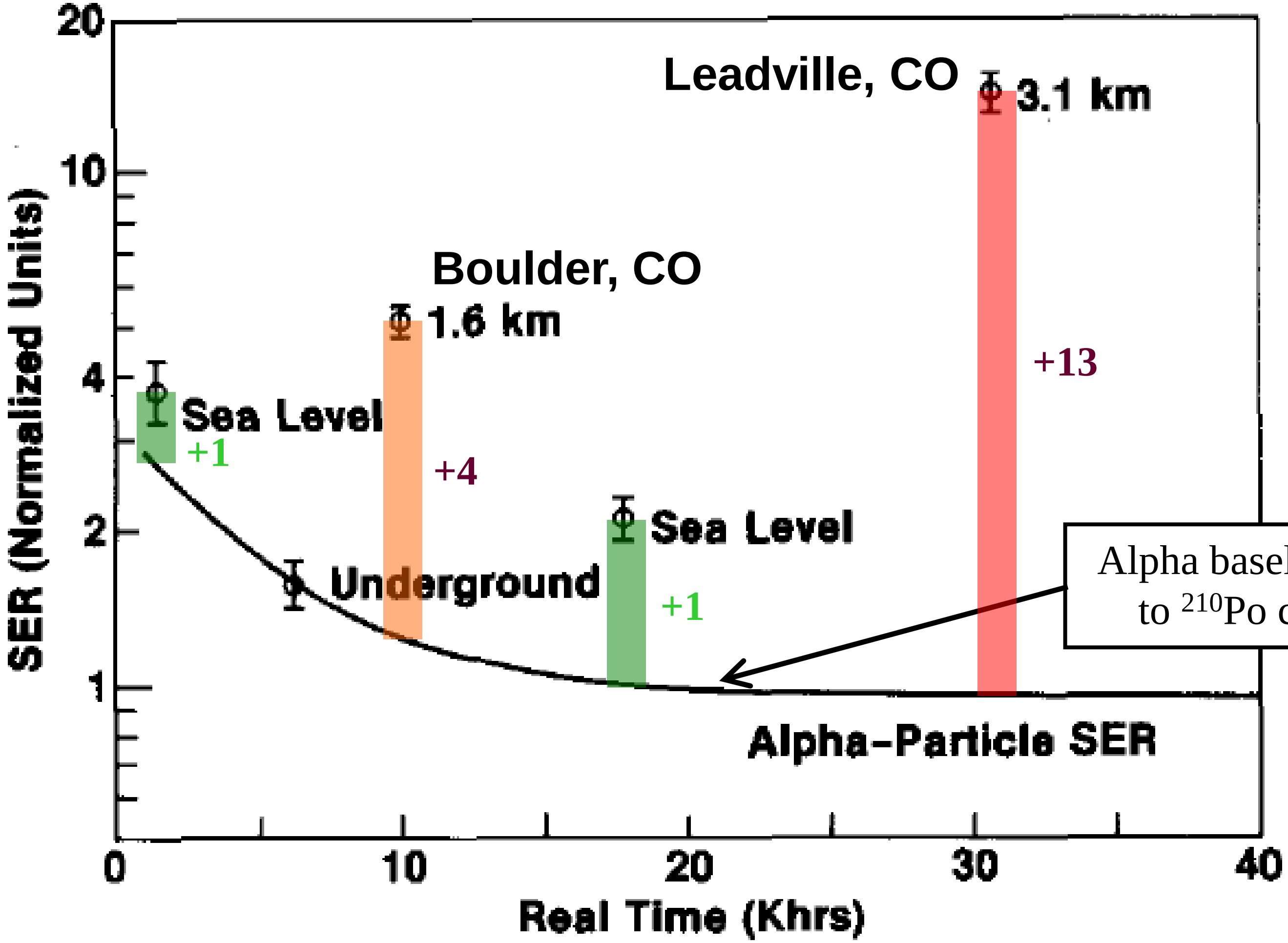
IBM Journal of R&D Special Issues



1996

2008

Experimental Evidence



Alpha baseline curves down due to ^{210}Po contaminant decay.

Note: The relative alpha (final) and cosmic contributions are about equal at sea level.

SER measurements on the same DRAM at different altitudes and underground showed large differences. Unfortunately, the DRAM suffered from the “Hera” problem. (O’Gorman, 1994.)

Part III. Boron - 10

History

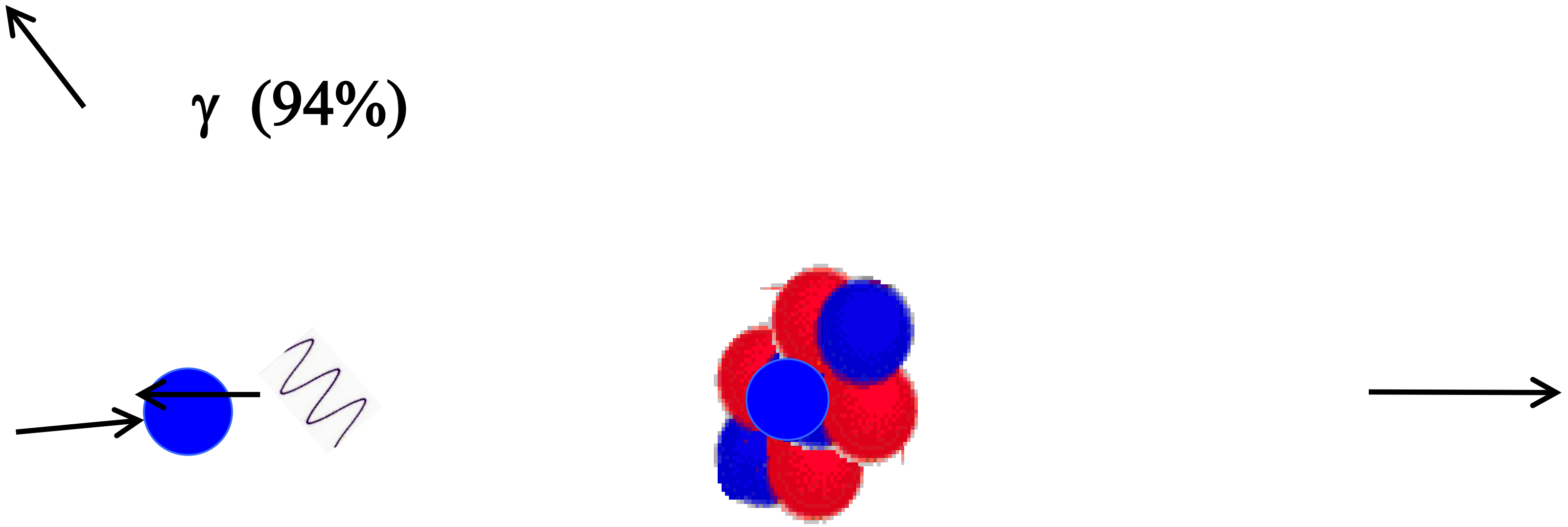
1983: Fleischer of GE raises the possibility of a new SER mechanism based on thermal neutron flux and ^{10}B in Si (as B dopant) and in packaging borosilicate glass.

"Cosmic Ray Interactions with Boron: A Possible Source of Soft Errors," Trans. Nuc. Sci. 30, pp. 4013-4015, 1983.

- Based on slow neutron capture and fission reaction of ^{10}B:
  - $^{10}B + n \rightarrow {}^{7}Li\ (0.84\ MeV) + \alpha\ (1.47\ MeV) + \gamma\ (0.48\ MeV)$ [94% Branch]
    $^{7}Li\ (1.01\ MeV) + \alpha\ (1.78\ MeV)$ [6% Branch]
  - Boron commonly used in BSG (borosilicate glass), a common sealant for ceramic packages.
  - Natural Boron is 80% ^{11}B and 20% ^{10}B.
- These sources are now unimportant, since:
  - Industry shifted to ion implantation of ^{11}B, virtually eliminating ^{10}B as a dopant.
  - The low energy particles generated are not very penetrating through metallization.

Boron 10 Fission Process

γ (94%)



Slow n

^{7}Li

α

^{11}B*

^{10}B Nucleus

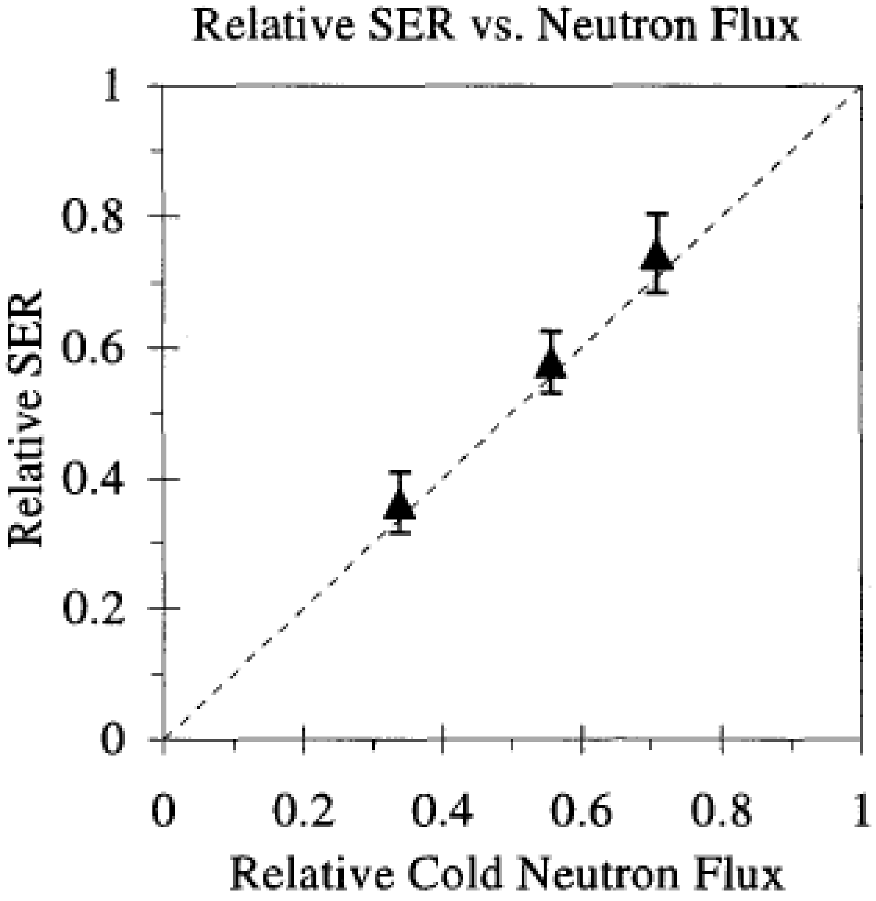
Excited Boron 11 nucleus fissions into ^{7}Li + α.

Boron 10 nucleus captures a slow neutron.

History

2000: Baumann and Smith of TI report first experimental evidence of SRAM SER caused by ^{10}B and cold neutrons.

“Neutron-Induced Boron Fission as a Major Source of Soft Errors in Deep Submicron SRAM Devices,” Proc. IRPS, pp. 152-157, 2000.



Measurements of SRAM (0.25 μm technology with BPSG) in cold (20K) neutron beam shown.

SER of SRAM built with 0.18 μm technology containing no BPSG was less by a factor of ~1500.

Field projection ~ 5x high energy neutron SER

Part IV. SER Testing

SEU Accelerated Testing

Methods:

- **Alpha**
  - Radioactive source is placed on front of chip, tested at wafer level.
  - usually ^{232}Th, ^{230}Th, ^{241}Am source used (^{232}Th: ~4×10^8 $\alpha/cm^2/khr$)
  - Th close match to Th/U contamination spectrum.
    - Am closer match to ^{210}Po contamination spectrum common in Pb.
- **Cosmic**
  - Chip (on module) is exposed to high energy proton or neutron source (accelerator)
  - Proton and Neutron (spallation) effects are very close at high energies
    - Neutron sources tend to be broad spectrum in an attempt to simulate natural background. (Also easier to produce)
    - Proton usually monoenergetic – SER can be measured as a function of energy
    - At IBM, we use the proton accelerator at MGH Proton Therapy Center (Boston) E = 20 to 220 MeV (using energy “degraders”)

SEU Accelerated Testing

Methods (continued):

- **Boron-10**
  - Chip is exposed to thermal or cold neutron source (accelerator, or reactor)

- **Technology elements:**
  DRAM, SRAM, Latch Chains (SAIL), and Logic Chains (SET)

- **Products:**
  DRAM, SRAM

Part V. Simulation and Modeling

Why Simulate?

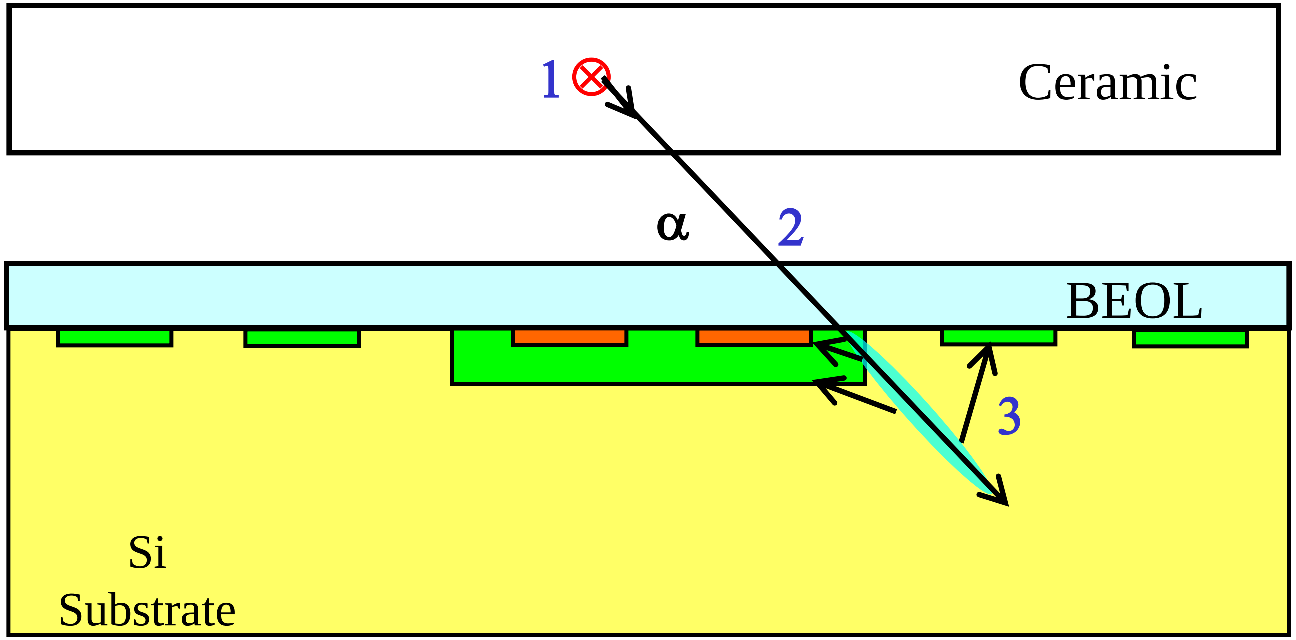
It would be nice if we could just scale accelerated test results to estimate field SER. However, there are several problems with this:

- It is unclear how to scale properly from either neutron or proton testing.
- From a technology standpoint it is not practical to measure all possible circuits (e.g., multiple SRAM cells, and latch designs.)
- The geometrical effect of contaminated solder bumps or metallization is not determined from testing with a blanket source.
- Technology may have multiple metallization options with differing thickness.
- Measuring a product is too late – SER mitigation, if necessary, should have been included in technology definition or product design.

Simulation Approach

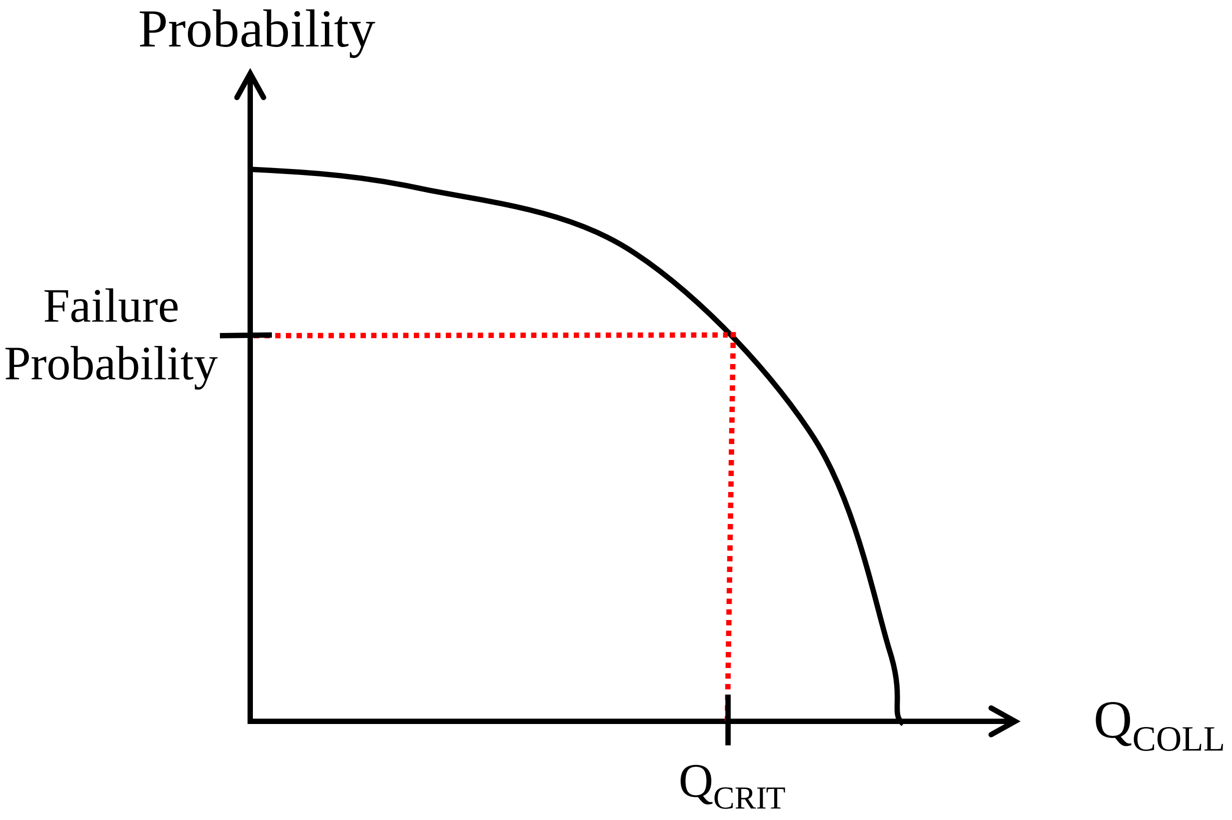
SEMM (Soft Error Monte Carlo) (ceramic/alpha example)

1. Generate a random decay (⊗) at a random location, with random angles.
2. Calculate alpha track through back end, then silicon.
3. Calculate pair generation, and charge collected, based on device layout.
4. Repeat 1-3, accumulating Q_{COLL} data on each node/device.



Murley and Srinivasan, “Soft-error Monte Carlo Modeling program, SEMM,” IBM J. Res. Dev. 40, pp. 109-117, 1996.

Typical Simulation Output



Simulation output is a collected charge (Q_{COLL}) probability distribution for each node. This must be combined with the circuit Q_{CRIT} for that node (determined by circuit simulation) to estimate probability of failure (P_F.) Summing the P_F over all nodes, times the count rate for the radioactive source (or neutron flux for cosmic) yields the projected field failure rate.

Simulation Field Projection Example

SRAM field projections

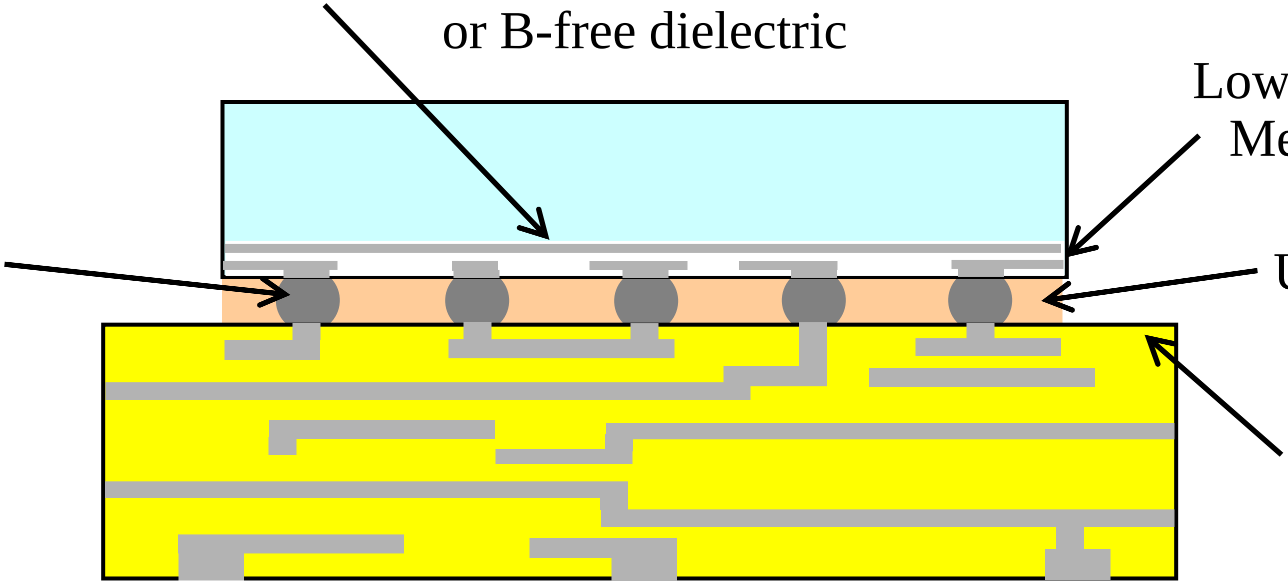
Contributor	**Cosmic**	**Ceramic**	**Solder Bump**
Flux	NYC[1]	30 ct/cm^2/khr	20 ct/cm^2/khr
SER, FIT/Mbit	300	1200	400

1. “NYC” = reference cosmic ray flux in New York City.

   (EF flux = 1.1 x NYC)

Part VI. Mitigation Examples

Material Mitigation



BPSG: Depleted B (low ^{10}B content)
or B-free dielectric

Low Alpha
Metallization

Low
Alpha
Solder
Bumps

Underfill

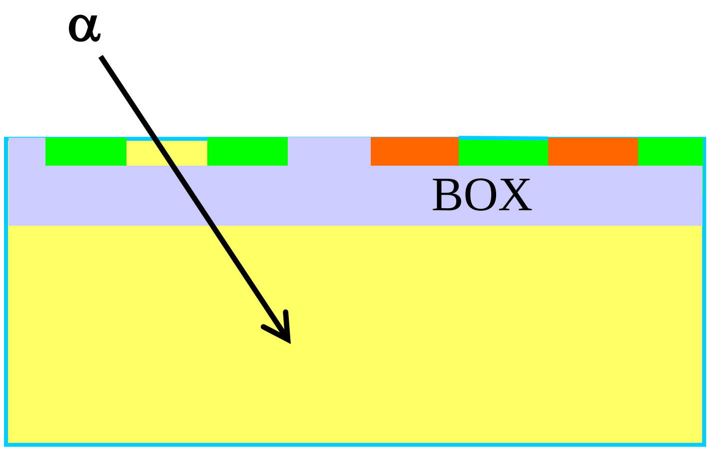
Low Alpha
Ceramic
on surface
layer

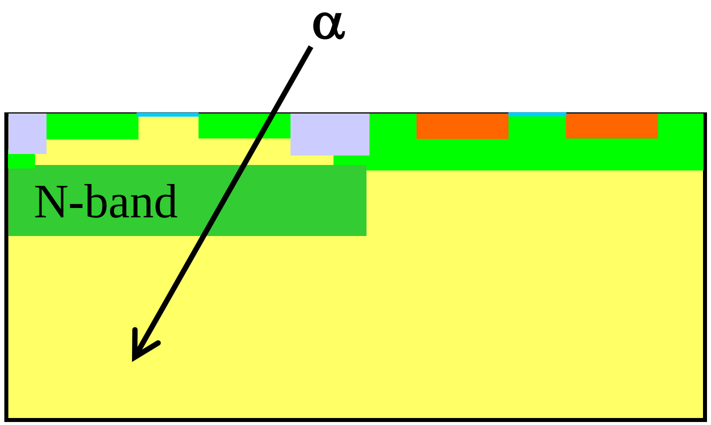
Underfill is a polymer injected between chip and package or board and cured. It eliminates the ceramic/board contribution and reduces the solder bump contribution.

Low alpha materials add cost and require periodic monitoring (alpha counting) of incoming material.

Technology Mitigation

Substrate Isolation Techniques



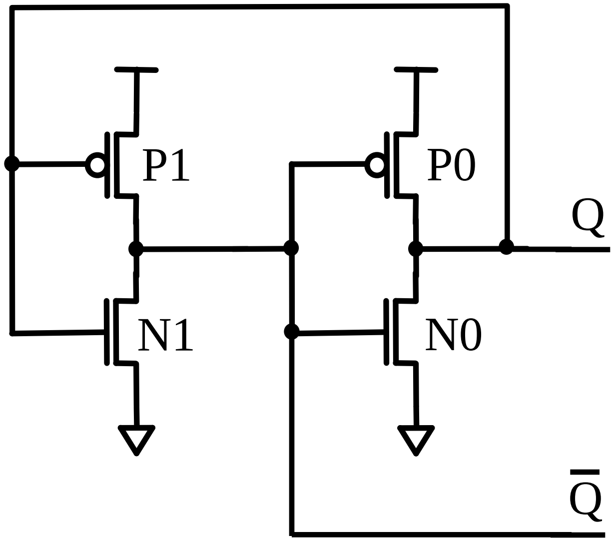


SOI:
FETs are isolated from the substrate by the back oxide (BOX.)

Triple Well:
NFETs are isolated from the substrate by N-Band.

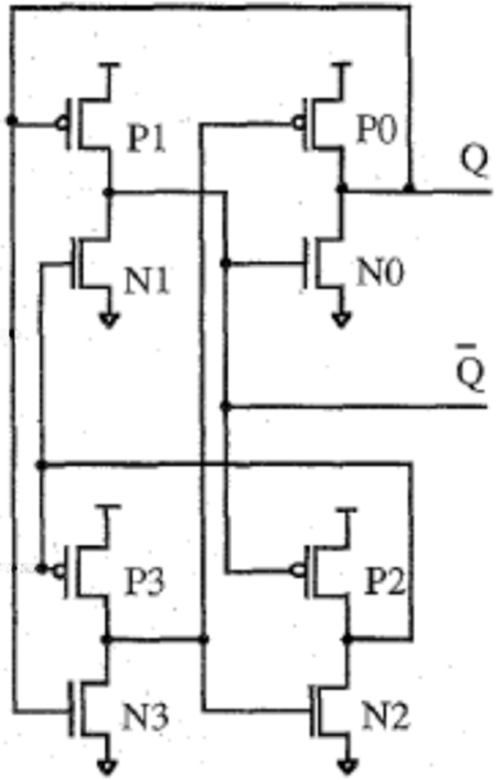
Circuit Mitigation

Hardened Latch Designs



Conventional Storage Cell

(1 X)



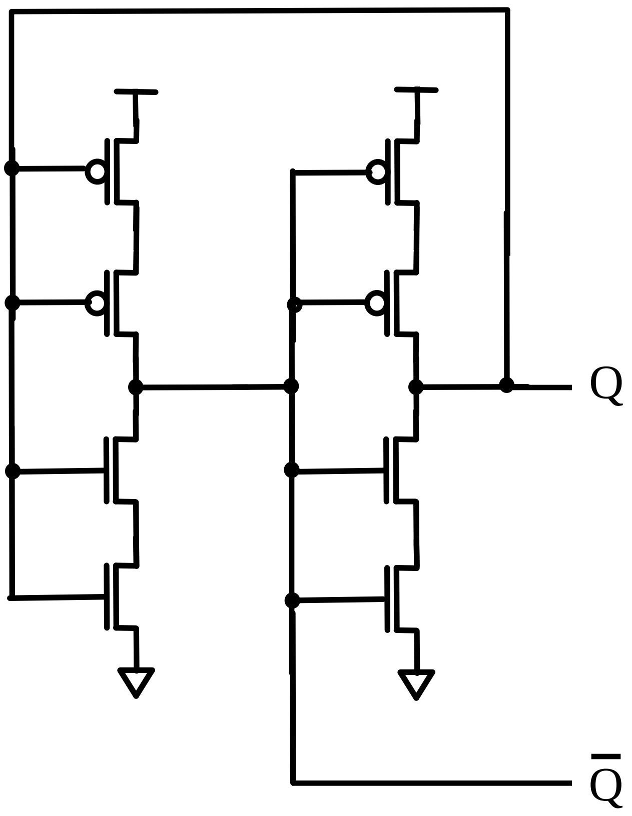
DICE Storage Cell

(0.01 X)

Pro: Two devices must be hit simultaneously to flip state.
Cons: Twice the power and chip area required.

Circuit Mitigation

Hardened Latch Designs



Stacked Storage Cell

Finger (0.1 - 0.2 X)

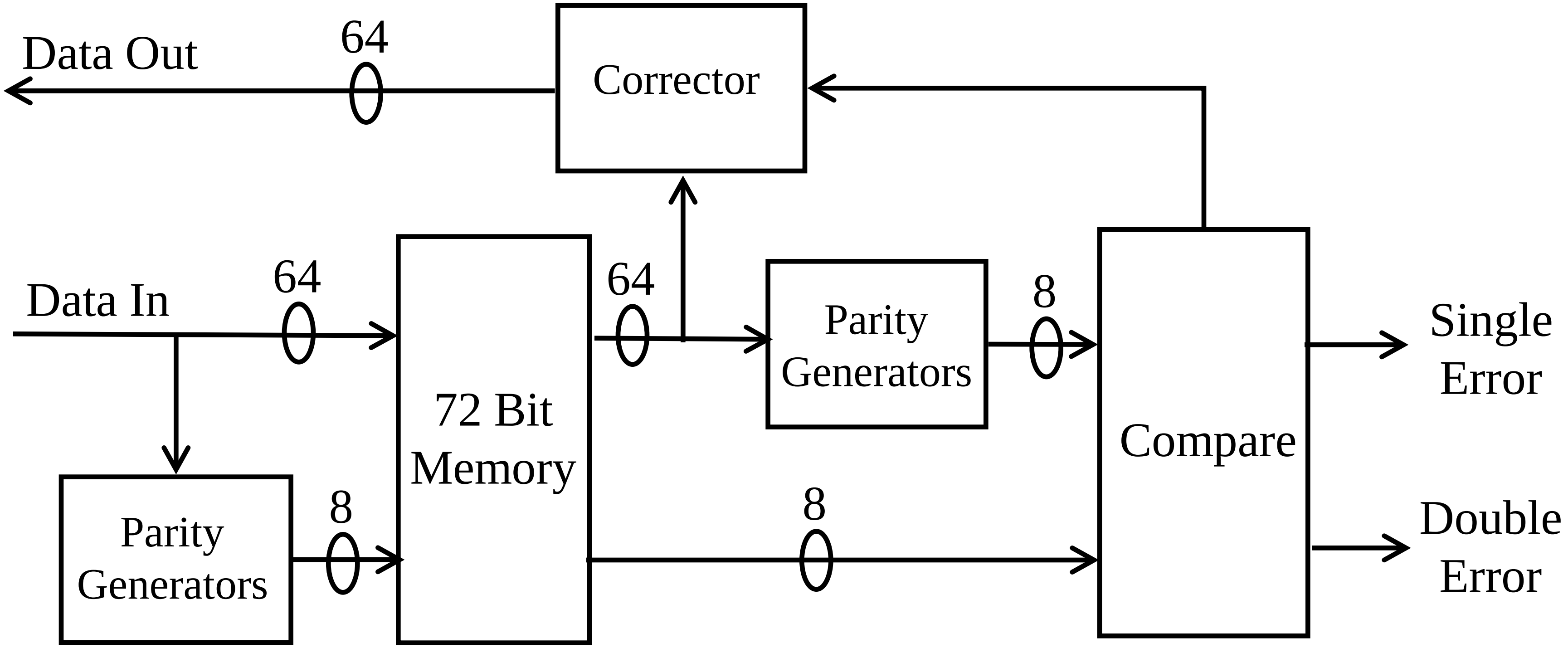
In-Line (0.01-0.05 X)

Pro: Device pair must be hit simultaneously to flip state.
Less density and power impact than DICE.

System Mitigation

Error Correcting Code (ECC)

Most common: SEC – DED (Single Error Correct, Double Error Detect)

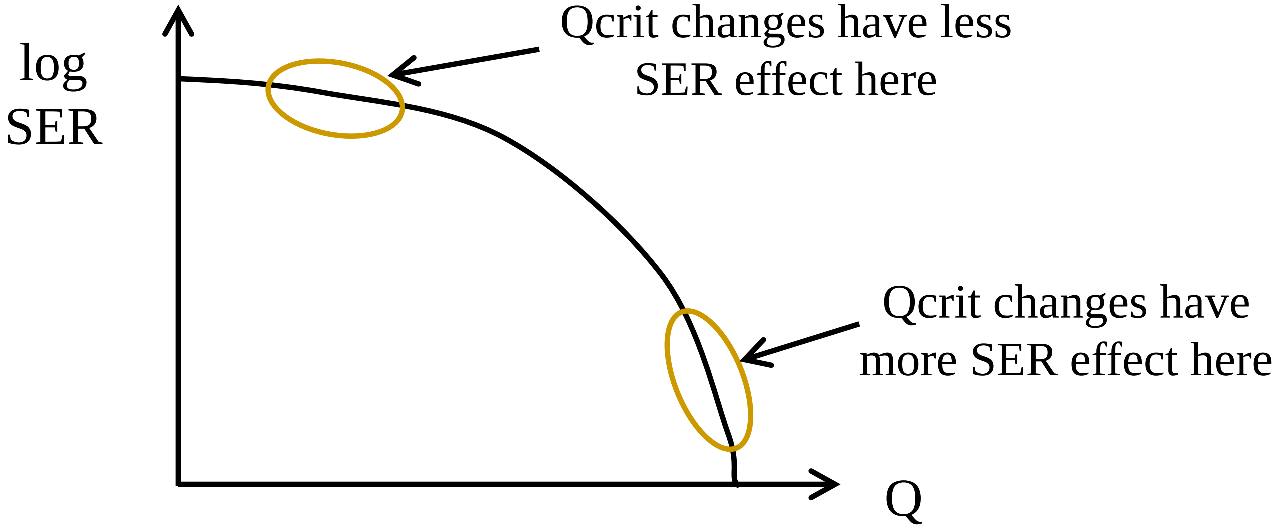


Cons: Additional memory overhead, added delays in both read and write.

Effects of Technology Scaling on SER

Two main competing effects:

- **Collection Volume** – As technology features scale down, the effective volume (per bit) for charge collection decreases. Q_{COLL} decreases as well.
- **Q_{CRIT}** - Critical charge decreases with node capacitance and supply voltage.
  - The effect of decreasing Qcrit depends on Qcrit level:



Qcrit changes have less SER effect here

Qcrit changes have more SER effect here

General Scaling Trends

- **DRAM**

  Q_{CRIT} not scaling to maintain required voltage margins

  ⇒ SER/bit is decreasing with scaling.

- **SRAM**

  Q_{CRIT} and CV scaling approximately canceling out

  ⇒SER/bit nearly flat with scaling

  (For latest technology nodes Q_{CRIT} is small, and CV scaling wins out – SER has a slightly decreasing trend)

- **Latch**

  Latch Q_{CRIT} is higher than SRAM. Q_{CRIT} scaling stronger.

  ⇒Somewhat increasing SER/bit with scaling.

  (For recent nodes, becoming flat.)

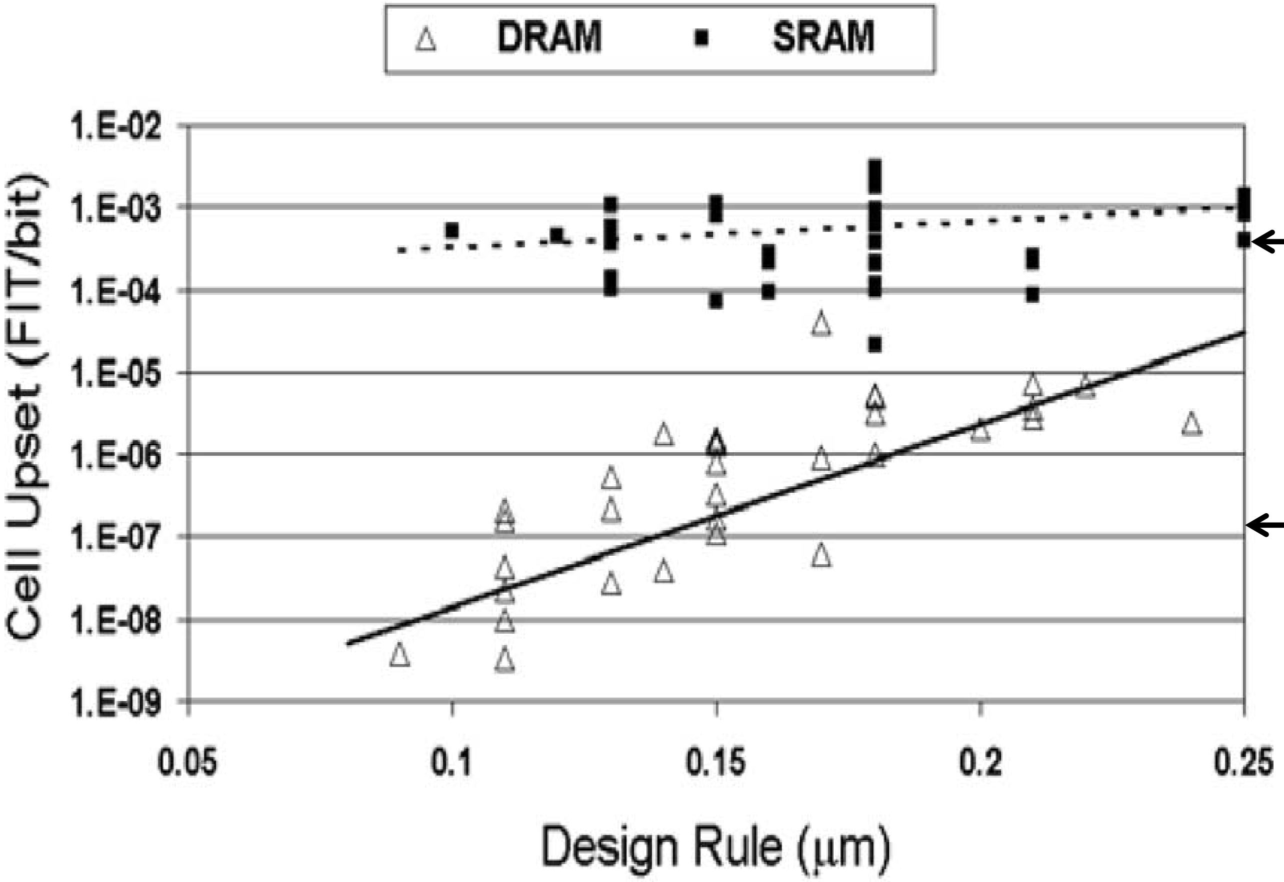
- **Logic**

  SET (Single Event Transient) is a possible future concern.

Current SER Comparison: SRAM > Latch > DRAM > Logic

DRAM and SRAM SEU Scaling

Industry Trends



2% failure/MByte/yr

1% failure/GByte/yr

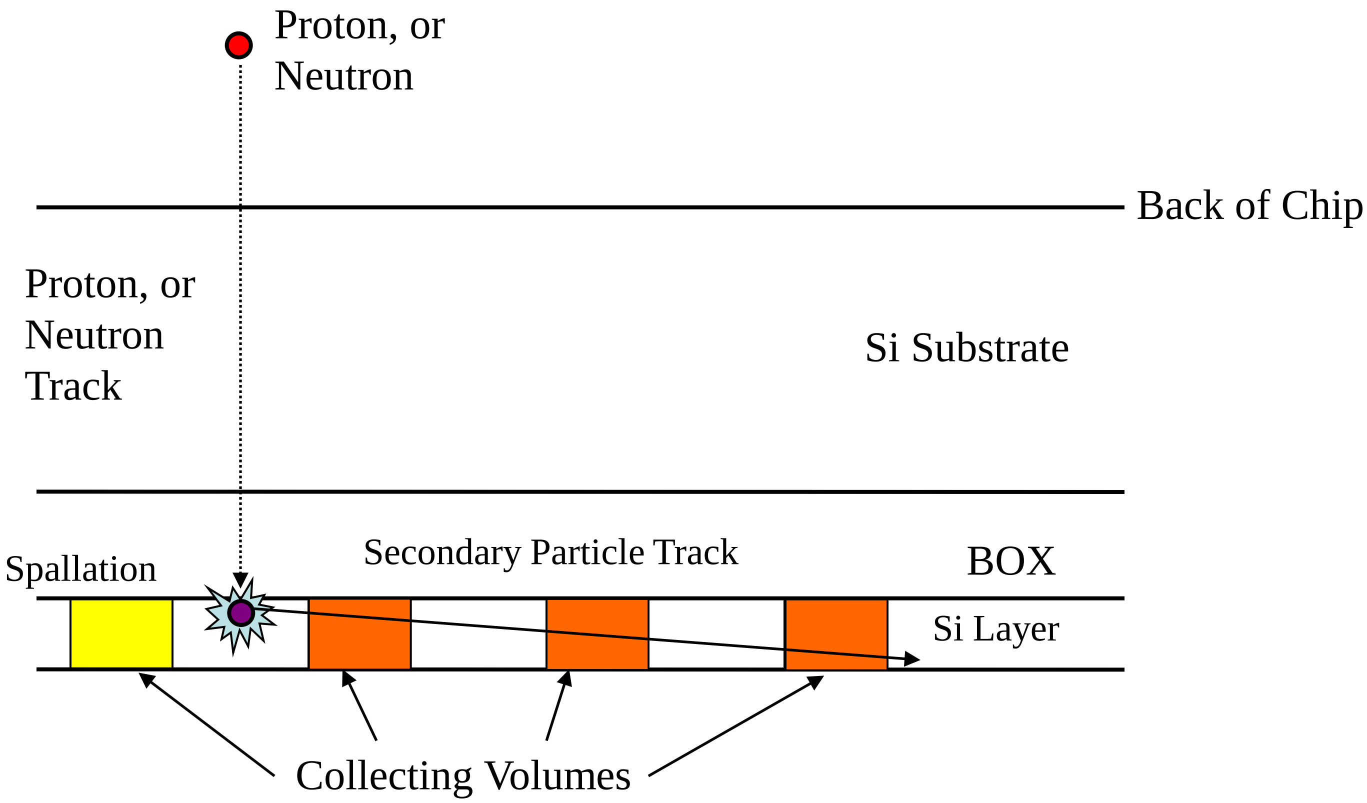
Black Symbols = C. Slayman, “Cache and Memory Error Detection, Correction, and Reduction Techniques for Terrestrial Servers and Workstations,” Trans. Dev. Mat. Rel. 5, pp. 397-404, 2005.

MBU/MCU Scaling Concern

Technology scaling does not seem to be a big SEU concern. However, MBU (multi bit upset), or multiple node hit, is an SER problem of the future:

- Increasing sharply with scaling
  - MBU is a strong function of distance between nodes.
- Potentially causing a double error in one memory word (not correctible with standard SEC DED ECC.)
  - Cell interleave must ensure minimum safe separation between bits in the same word.
- Mitigation techniques (such as DICE) becoming less effective.
  - Layouts must be adjusted for this. Clever layouts take advantage of the effect by placing canceling nodes adjacent.

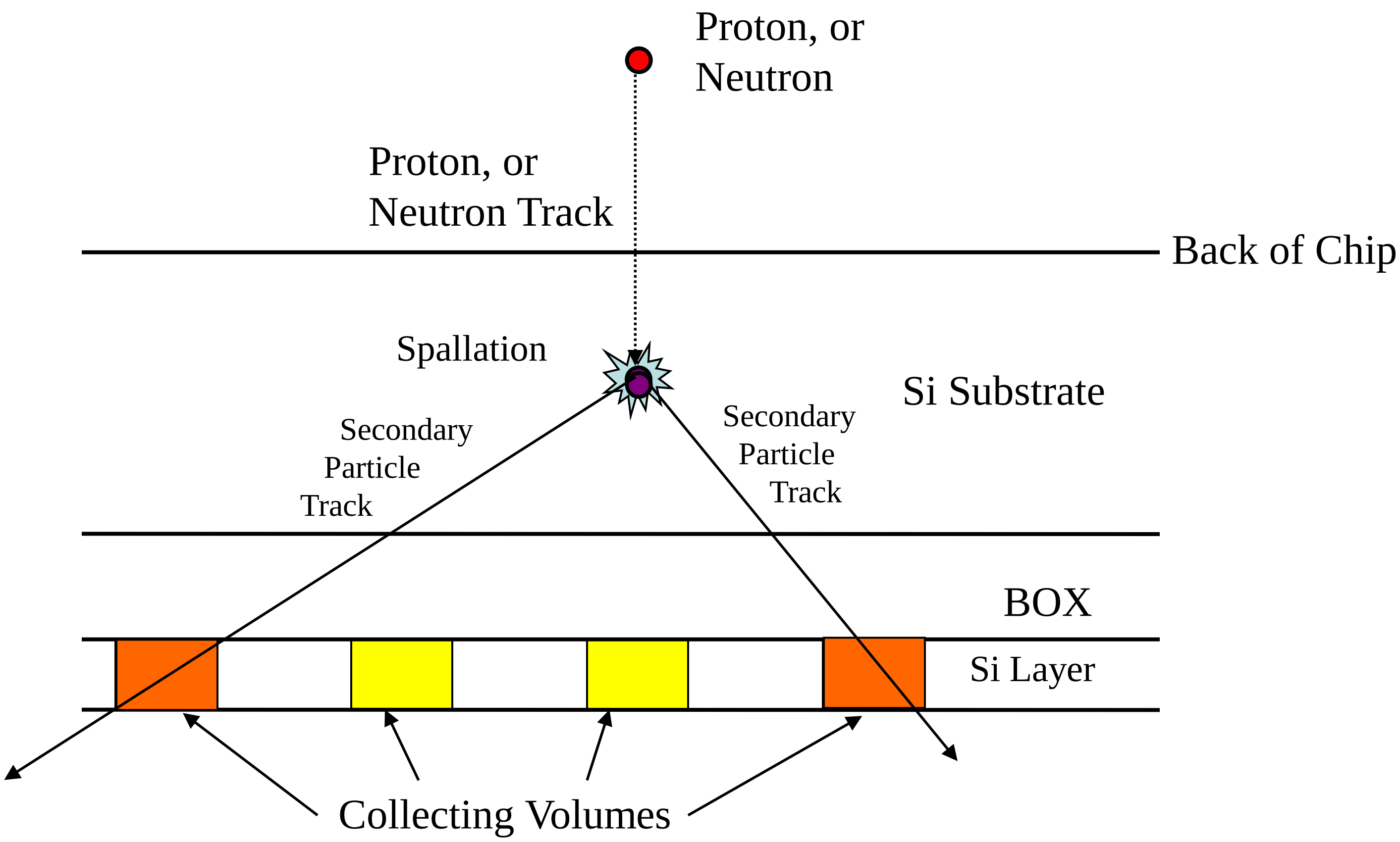
Type I Cosmic MBU/MCU (SOI)



Example of Type I Cosmic MCU (One Secondary)

As much as 10% MCU/SEU !!!

Type II Cosmic MBU/MCU (SOI)



Example of Type II Cosmic MCU (Multiple Secondaries)

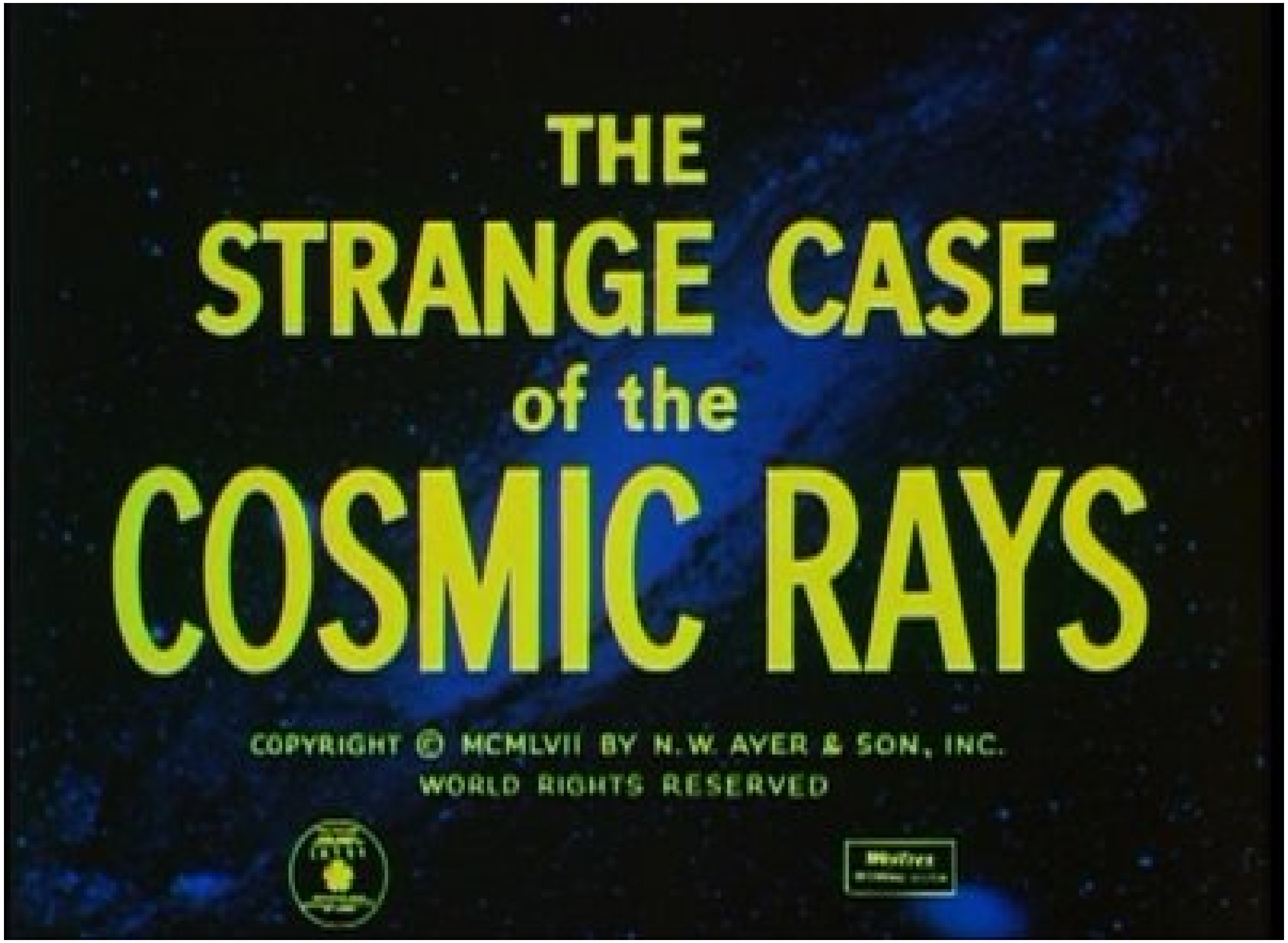
< 1% MCU/SEU (But larger separation!)

Conclusions

1. The major SER mechanisms in current integrated circuits are fairly well understood. However, new mechanisms may always emerge.
2. Radioactive contamination in chip and package materials must be controlled, or shielded from the active circuit area.
3. Established testing and simulation methods exist to characterize a technology or product SER, within limits.
4. Many SER mitigation techniques, spanning the full hierarchy from the material level to the system level, have been, and continue to be, developed. Patents abound!
5. Scaling is not a major concern for SEU. SET (logic transient) may become important.
6. MBU/multiple node effects will become more important at future technology nodes.

Back-up

History



THE
STRANGE CASE
of the
COSMIC RAYS

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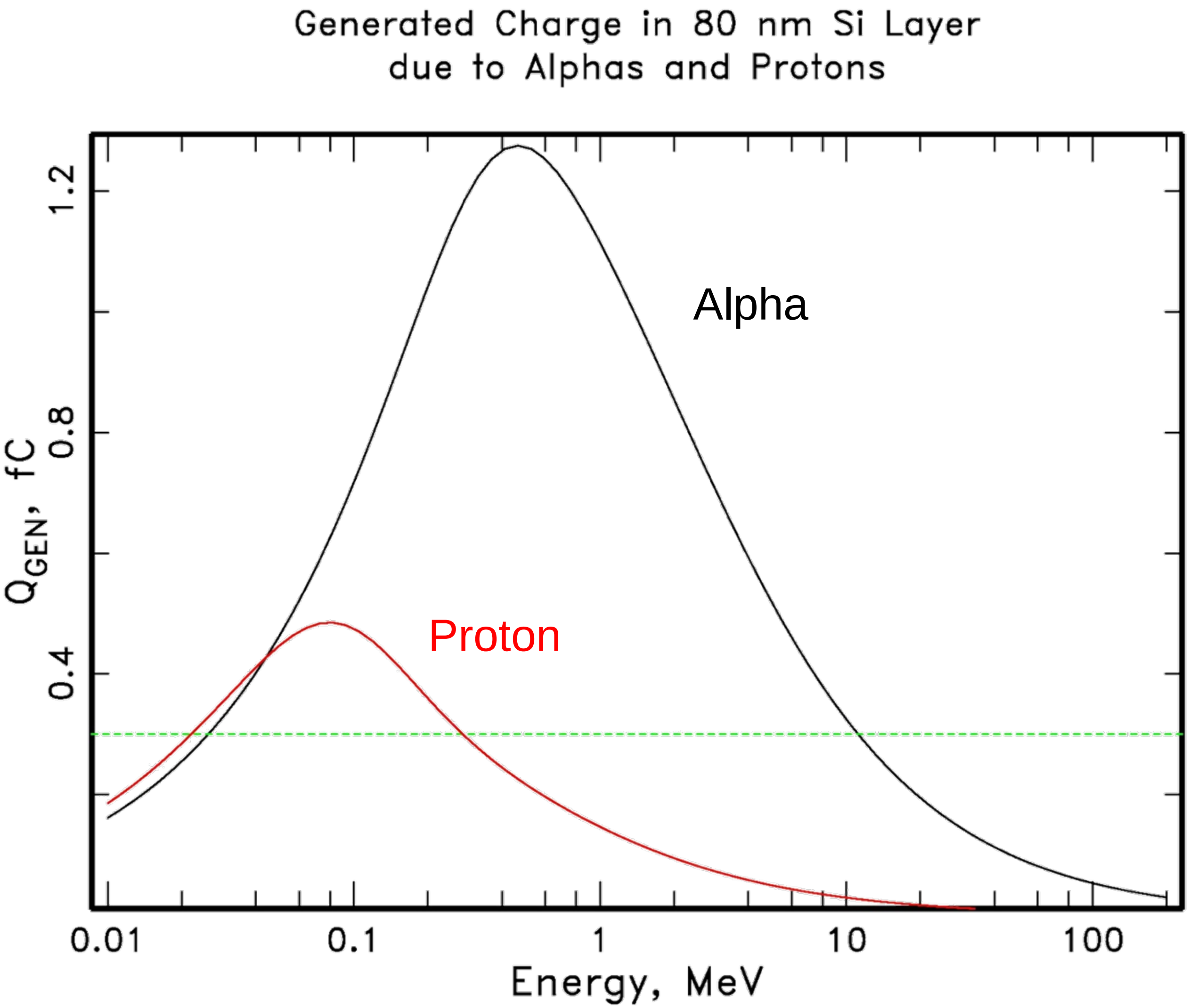
Cosmic rays were well known and in popular science by 1960.

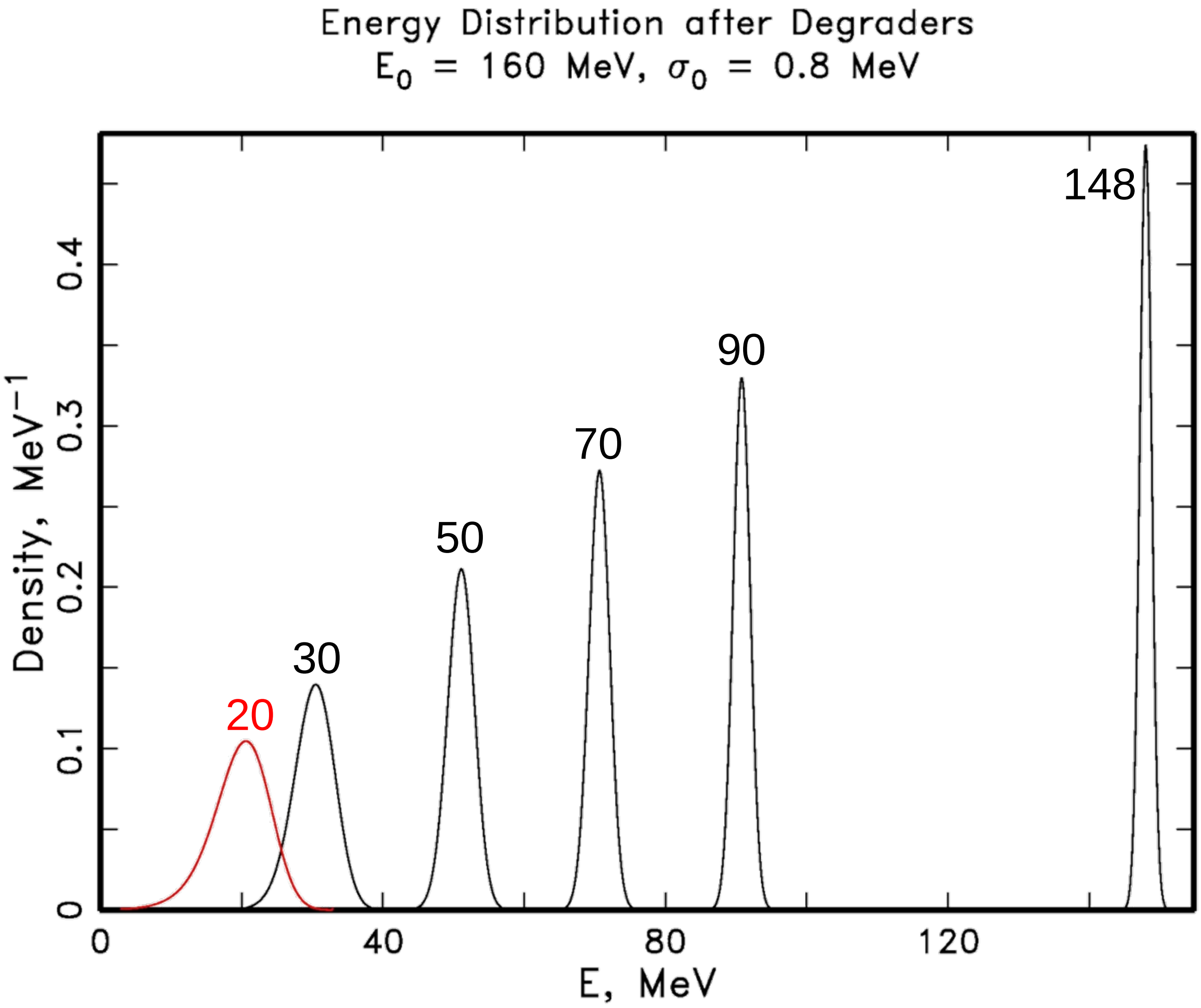
(Bell Telephone Science Hour TV Episode, 1957)

Proton/Alpha Ionization Curves



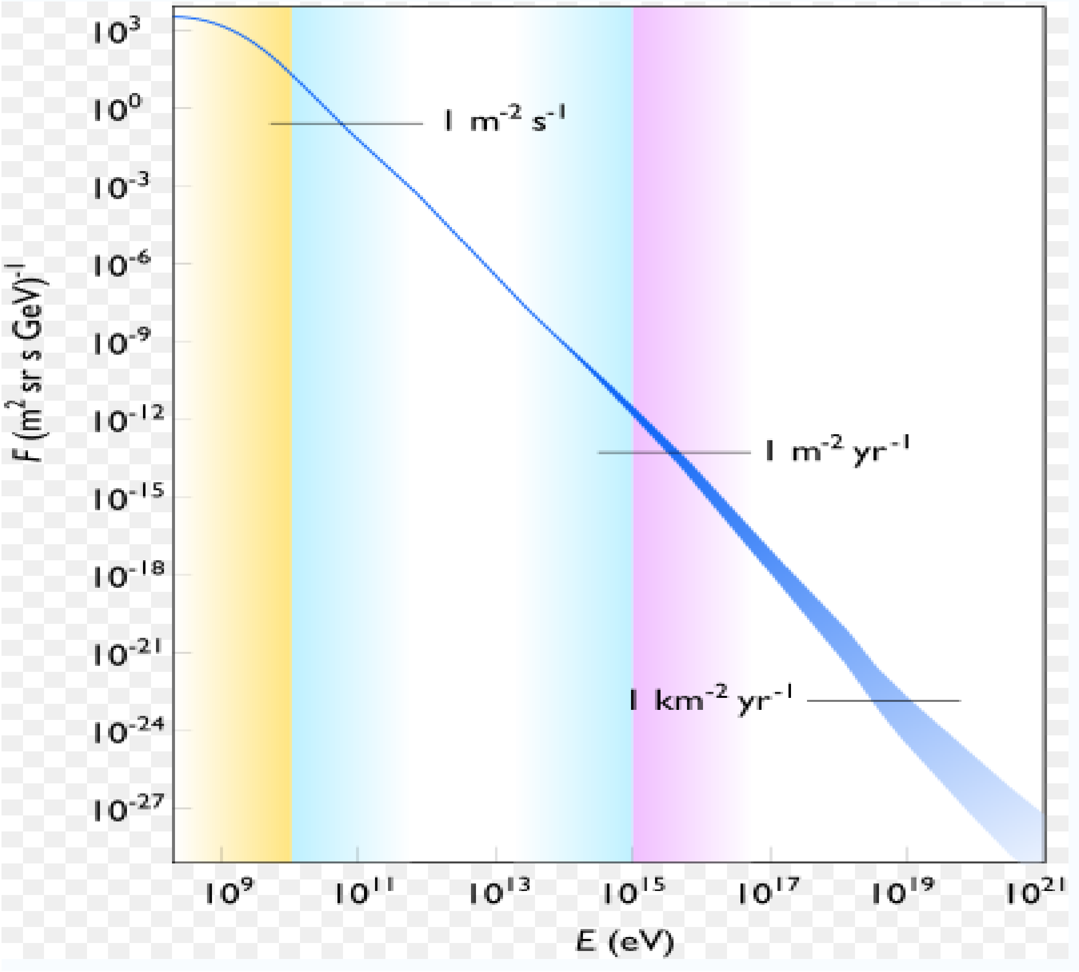
Charge generated by protons is much less than by alphas, except at very low energy. Because of this, SEU by direct proton ionization is very sensitive to Qcrit.

Effect of Energy Degraders we use



Degrader Method of Proton Energy Adjustment

(Primary) Cosmic Ray Spectrum



Yellow region - Solar

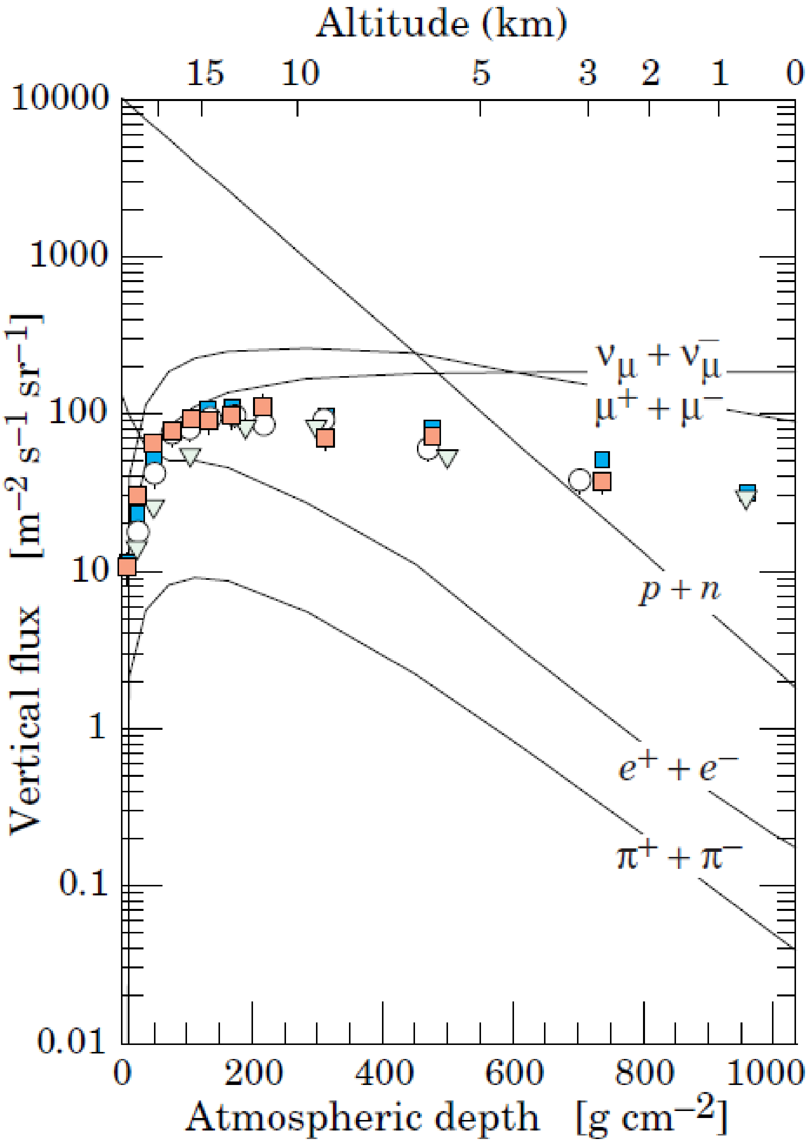
Blue region - GCR

Purple region - EGCR

Swordy, “The energy spectra and anisotropies of cosmic rays,” Space Science Reviews 99, p85, 2001.

Cosmic Ray Shielding Effects

Two main effects help shield us from most cosmic rays:

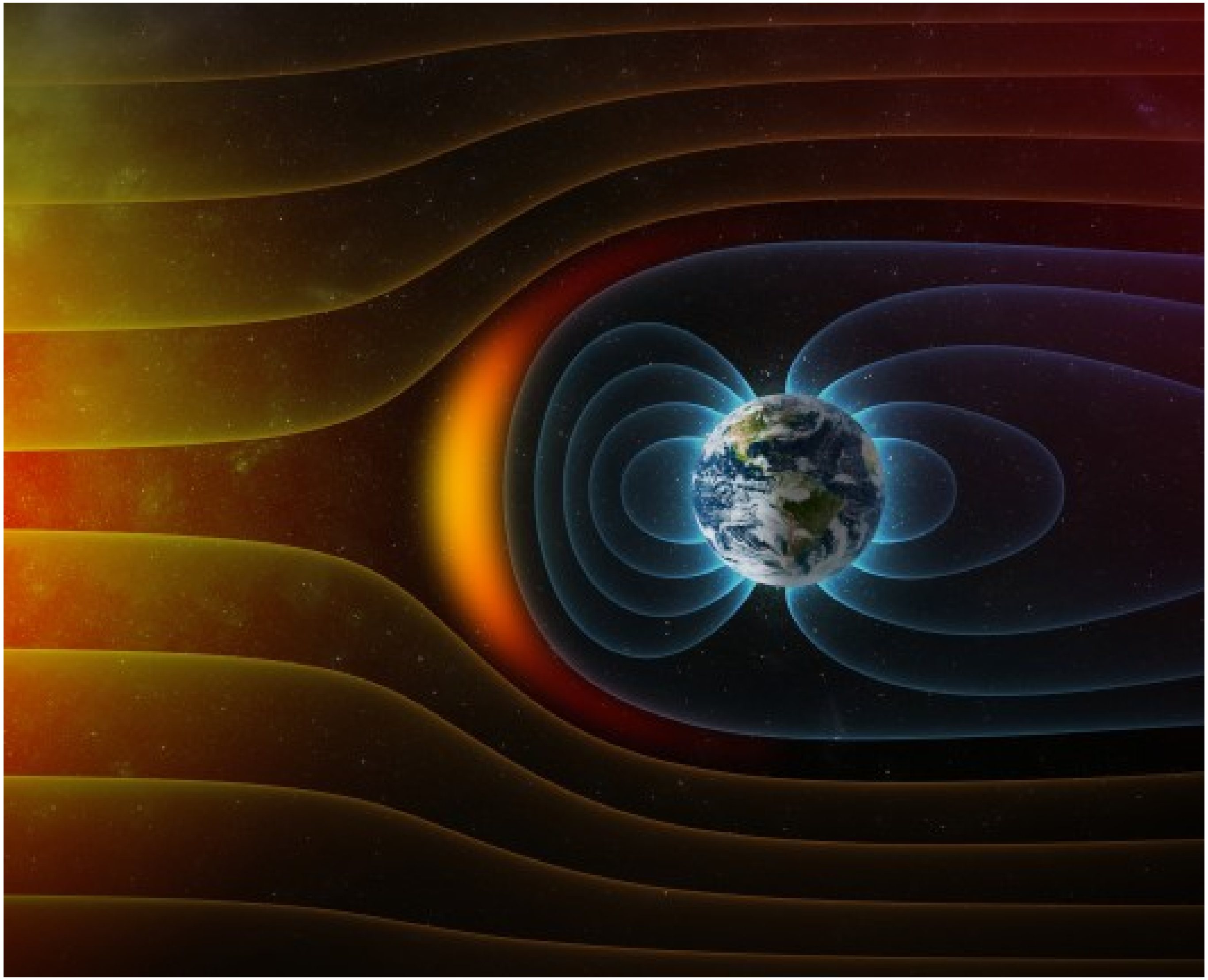


1. Atmospheric shielding.

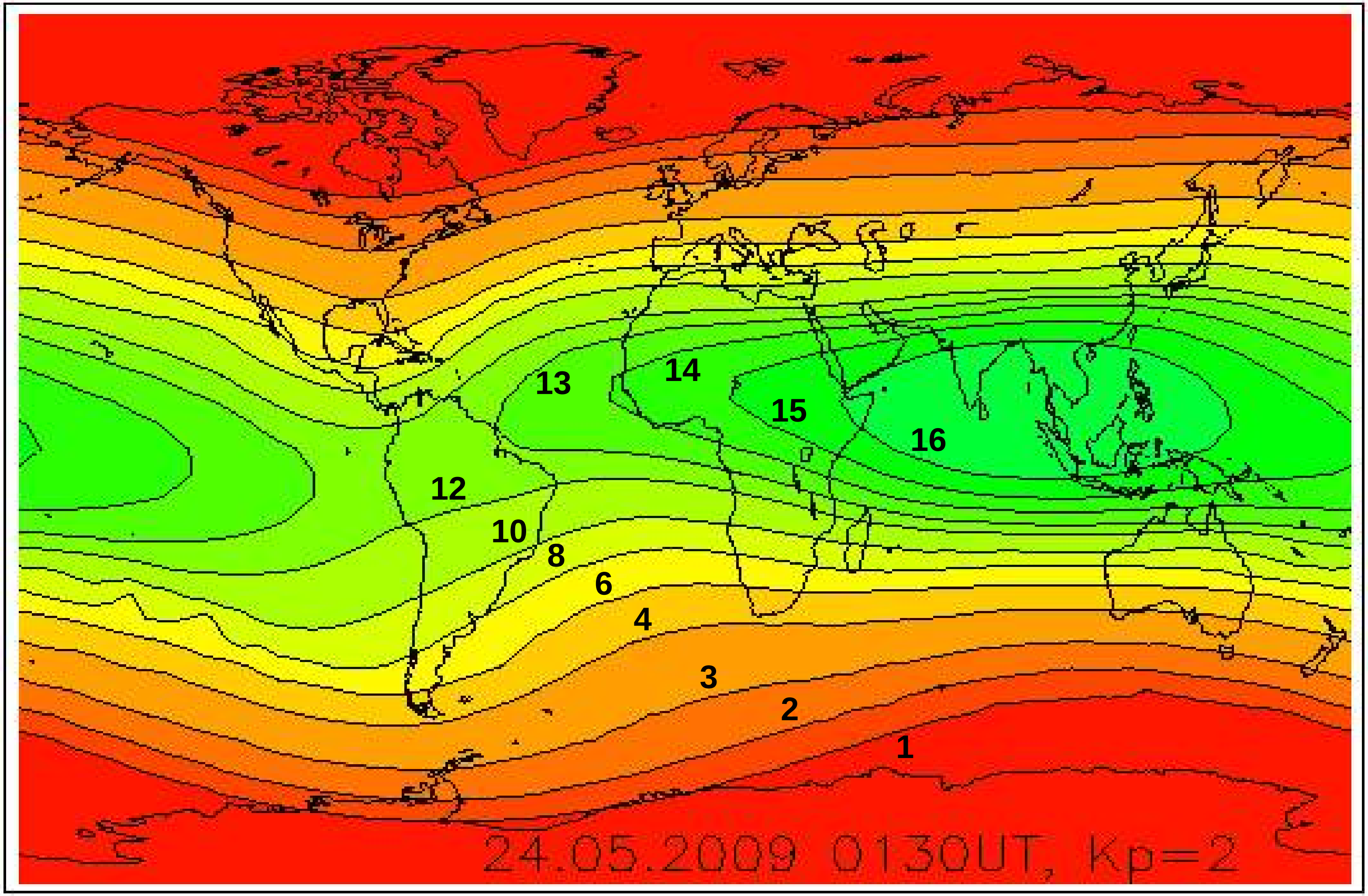
Cosmic Ray flux of neutrons increases sharply with altitude

Cosmic Ray Shielding Effects

2. Magnetic Field deflects particles below a certain energy (Geomagnetic Rigidity)



Geomagnetic Rigidity (GeV)



From: http://www.nmdb.eu/sites/default/files/Bern_cutoff.jpg
See also: Shea and Smart, “The Influence of the Changing Geomagnetic Field on Cosmic Ray Measurements,” J. Geomag. Geoelectr. 42. pp. 1107- 1121, 1990.

Energetics of n + Boron 10 Reaction

^{10}B (n, α) ^{7}Li Reaction

	^{10}B +	n $\rightarrow$	^{7}Li +	^{4}He
Mass (AMU) :	10.01294	1.00870	7.01600	4.00260
Sums:	11.02164		11.01860	

Difference = 0.00304 amu (x 931 MeV/amu) => 2.8 MeV (energy released)

To conserve momentum, this kinetic energy is divided between the products as:
KE(Li) ~ 2.8x4/11 ~ 1.0 MeV, and KE(α) ~ 2.8x7/11 ~ 1.8 MeV.

Note:
mass (^{11}B) = 11.00931 amu < 11.01860 => no spontaneous ^{11}B α decay

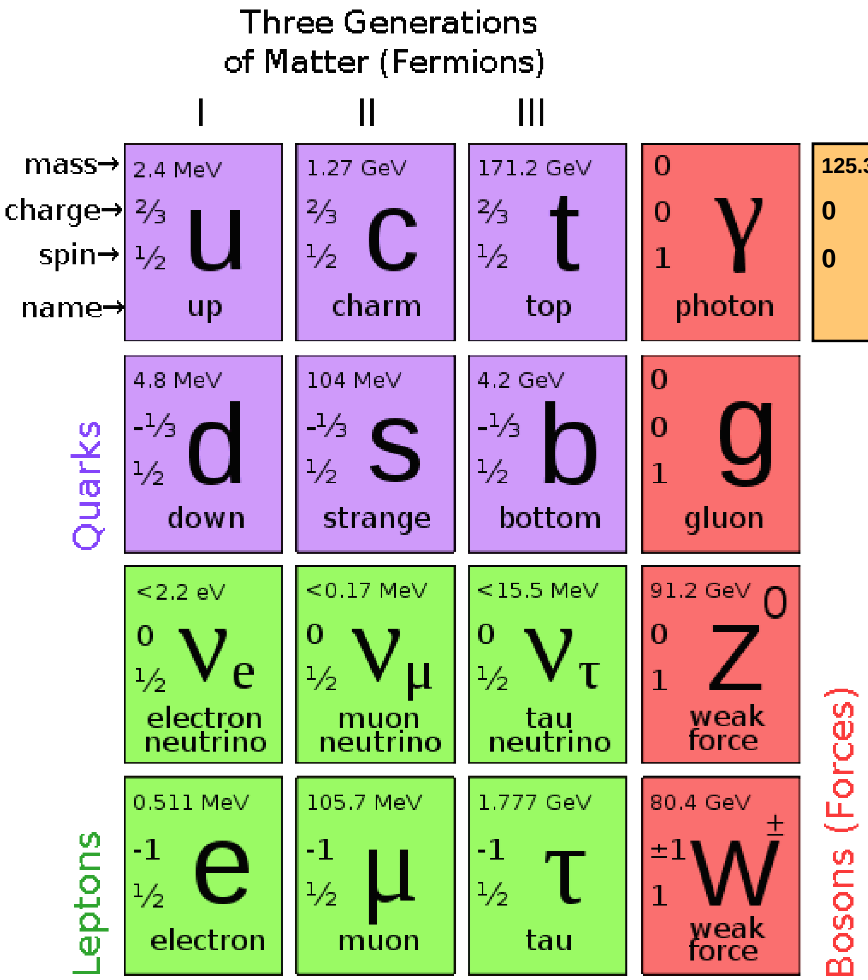
But, when n enters ^{10}B nucleus, the excited $^{11}B^*$ has an excess energy (to ^{11}B) of:
931 MeV x (10.01294 + 1.00870 – 11.00931) = 11.5 MeV
This is sufficient to overcome the barrier to α emission.

History

Jim Ziegler – the Ion Implantion and Cosmic Ray guru at IBM.

- **IEEE Fellow ‘95**
- **IBM Research 1967-2000.**
- **former manager of Material Analysis, Ion Implantation and Radiation Science with IBM**
- ***SRIM "The Stopping and Range of Ions in Matter"***
- ***"Ion Implantation Technology"***

Standard Model



Three Generations of Matter (Fermions)

	I	II	III		
mass→ charge→ spin→ name→	2.4 MeV ⅔ ½ u up	1.27 GeV ⅔ ½ c charm	171.2 GeV ⅔ ½ t top	0 0 1 γ photon	125.3 GeV 0 0 H Higgs field
Quarks	4.8 MeV -⅓ ½ d down	104 MeV -⅓ ½ s strange	4.2 GeV -⅓ ½ b bottom	0 0 1 g gluon	
	<2.2 eV 0 ½ ν_e electron neutrino	<0.17 MeV 0 ½ ν_μ muon neutrino	<15.5 MeV 0 ½ ν_τ tau neutrino	91.2 GeV 0 1 Z^0 weak force	Bosons (Forces)
Leptons	0.511 MeV -1 ½ e electron	105.7 MeV -1 ½ μ muon	1.777 GeV -1 ½ τ tau	80.4 GeV ±1 1 $W^\pm$ weak force	

Most Common Cosmic Shower Hadrons

- **Baryons**
  - **p: uud** **(Nucleons)**
  - **n: udd**
- **Mesons**
  - **π^{+-}: $u\bar{d}$, $\bar{u}d$**
  - **π^0: $(u\bar{u} - d\bar{d})/\sqrt{2}$**
  - **K^{+-}: $u\bar{s}$, $\bar{u}s$**
  - **K^0: $(d\bar{s} + \bar{d}s)/\sqrt{2}$**

(http://en.wikipedia.org/wiki/File:Standard_Model_of_Elementary_Particles.svg)

Boron-10 and the Nazi Atomic Program

The German World War II nuclear program suffered a substantial setback when its inexpensive graphite moderators failed to work. At that time, the German commercial graphite contained too much boron. Since the war-time German program never discovered this problem, they were forced to use heavy water moderators. In the U.S., Leo Szilard, a former chemical engineer, discovered the problem.

To get a chain reaction in natural uranium you need a moderator to slow down the neutrons that are generated from fission. This was widely known. Two moderators were believed to be possible: carbon or heavy water.

Walter Bothe, the leading experimental nuclear physicist in Germany, concluded that carbon in the form of graphite would not work. In America, Enrico Fermi did a similar experiment and concluded that graphite was marginal. He suspected that an impurity in the graphite was responsible for the problem. Leo Szilard, who was working alongside Fermi, remembered that electrodes of boron carbide were commonly used in the manufacture of graphite. It was known that one atom of boron absorbs about as many slow neutrons as 100,000 atoms of carbon. Very small boron impurities would "poison" the graphite for use as a nuclear reaction moderator.

Using pure graphite as the moderator, the American group achieved a chain reaction on December 2, 1942.

The Germans rejected the separation of uranium isotopes as too difficult. They saw the fissionability of plutonium as the key to the entire project. Once you had a chain reaction you could make plutonium, and once you had plutonium, you could make a bomb.

(Hans Bethe, Physics Today Online - July 2000 V. 53, No. 7)