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Space Radiation Transport Results

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Outline

1. Introduction
2. Cross section
3. Boltzmann Transport Equation
4. Pions
5. Minimum in Dose Equivalent vs. Depth
6. Internal environment
7. GCR Sensitivity Analysis
8. Conclusions
9. Summary

INTRODUCTION: SI UNITS

m $\equiv$ meter, s $\equiv$ second, kg $\equiv$ kilogram, N $\equiv$ Newton, J $\equiv$ Joule

- Distance x [m], Time t [s]

- Speed (velocity) $v \equiv \frac{dx}{dt}$ or $v \equiv \frac{\Delta x}{\Delta t}$
  v [m per s $\equiv$ m/s $\equiv$ m s^{-1}]

- Acceleration $a \equiv \frac{dv}{dt} = \frac{d^2x}{dt^2}$ or $a \equiv \frac{\Delta v}{\Delta t}$
  a [m/s^2 $\equiv$ m s^{-2}]

- Force $F = ma$
  m [kg], F [N $\equiv$ kg m s^{-2}]

- Work $W \equiv \int F\, dx$ or $W \equiv F\Delta x$
  W [J $\equiv$ N m]

- Energy $W \equiv \Delta E$ $= \int F\, dx$ (Kinetic Energy, Potential Energy, Mass Energy)
  E [J] or [eV] [eV $\equiv 1.602 \times 10^{-19}$ J]

Introduction: Areal density

- Ordinary thickness doesn't tell you amount of material traversed
  - d = 20 cm Water vs. d = 20 cm Aluminum
  - more material traversed in Al, even though distance d same

- Areal density $x = d\rho$
  - $x \ \ [\mathrm{g/cm^2}]$
  - $d \ \ [\mathrm{cm}]$
  - $\rho \ \ [\mathrm{g/cm^3}]$

- $x = 20 \ \mathrm{g/cm^2}$
  - $\rho_{\mathrm{water}} = 1 \ \mathrm{g/cm^3} \qquad \rho_{\mathrm{Al}} = 2.7 \ \mathrm{g/cm^3}$
  - $d_{\mathrm{water}} = 20 \ \mathrm{cm} \qquad d_{\mathrm{Al}} = 7.4 \ \mathrm{cm}$

- Same amount of material traversed in 20 cm Water and 7.4 cm Al

- $x_{\mathrm{ISS}} \approx 15 \ \mathrm{g/cm^2}, \quad x_{\mathrm{Mars\ Atmosph}} \approx 20 \ \mathrm{g/cm^2}, \ \ x_{\mathrm{Earth\ Atmosph}} \approx 1000 \ \mathrm{g/cm^2}$

- $E = mc^2$

- $E \equiv T + m_0 c^2$
  - $E \equiv$ Total energy
  - $T \equiv$ Kinetic energy, often written E !!!!!!!!!
  - $m_0 \equiv$ Rest mass energy

  - $m \equiv \gamma m_0$, $\Rightarrow E = \gamma m_0 c^2$

  - $\gamma \equiv \frac{1}{\sqrt{1-(v/c)^2}}$, $\beta \equiv v/c \Rightarrow \gamma = \frac{1}{\sqrt{1-\beta^2}}$

- Note: $T = E - m_0 c^2 \neq \frac{1}{2} m v^2$

  $\approx \frac{1}{2} m v^2$ if $v \ll c$

Introduction: MeV / nucleon

Kinetic energy: people write E, but they mean T !!!

- $E = T + m_0 c^2 = mc^2 = \gamma m_0 c^2$

Calculate speed

$$\frac{1}{\sqrt{1-(v/c)^2}} \equiv \gamma = \frac{T}{m_0 c^2} + 1$$

$$\hat{T} \quad [\text{ MeV/n }] \;\Rightarrow\; T = A\hat{T}$$

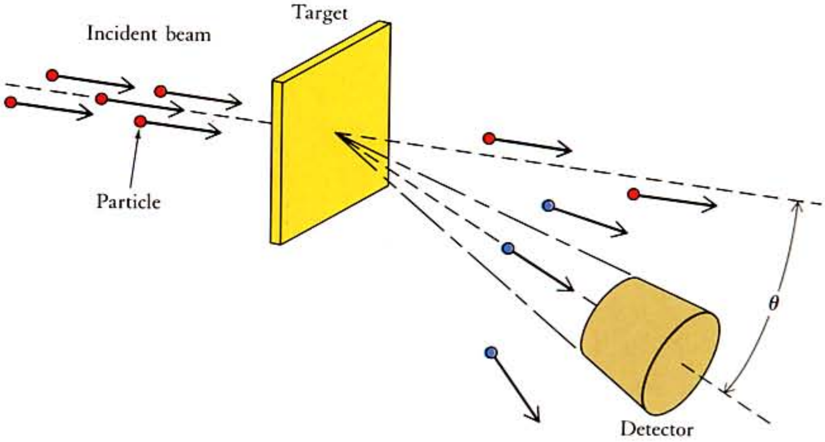
$$m_0 = Am_n \;, \qquad m_n \equiv m_{\text{nucleon}} = 938 \text{ MeV}/c^2$$

$$\gamma = \frac{T}{m_0 c^2} + 1 = \frac{A\hat{T}}{Am_n c^2} + 1 = \frac{\hat{T}}{m_n c^2} + 1$$

E.g. What is speed of 1000 MeV/n ^{56}Fe projectile?

Cross Section

- Typical scattering experiment: beam of particles fired into a target
- Surrounding detectors detect the particles coming out of reaction



[Lederman & Schramm, From quarks to the cosmos, Freeman, New York, 1989]

Cross Section

- Let's say that some protons are detected
- If one just counts the total number N of protons emitted *per unit time* then this is related to the total cross section by

$$N \equiv \mathcal{L}\,\sigma$$

- $\mathcal{L}$ = luminosity of beam
- σ = cross section - related to *probability* that reaction will occur (that a proton will be emitted)
- Above formula: more particles will be detected if reaction probability is large or if we have very intense beam

Cross Section

- Luminosity typically measured in $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
- E.g. Fermilab proton beam (2000) was about $\mathcal{L} = 10^{32}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
- Cross section is measured in units of area namely cm^2
- $N = \mathcal{L}\sigma$ gives units of *counts per second*
- Note that

$$\mathrm{barn} = 10^{-28}\mathrm{m}^2 = 10^{-24}\mathrm{cm}^2$$

  and a *picobarn* (pb) is therefore (pico $\equiv 10^{-12}$)

$$\mathrm{pb} = 10^{-36}\mathrm{cm}^2$$

- Fermilab luminosity can be re-written

$$\mathcal{L} = 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1} = 10^{-4}\mathrm{pb}^{-1}\mathrm{s}^{-1}$$

- Sometimes accelerator administrators use integrated luminosity $\mathcal{L}_{\rm int}$, which is simply luminosity multiplied by time

$$\mathcal{L}_{\rm int} = \mathcal{L}t$$

- E.g. if Fermilab ran continuously over a year, this would correspond to an integrated luminosity of

$$\mathcal{L}_{\rm int}^{\rm 1year} = 10^{-4}{\rm pb}^{-1}{\rm s}^{-1} \times 365\,{\rm days} \;\approx\; 3000\,{\rm pb}^{-1}$$

- If the accelerator only delivered say 1500 pb^{-1} then that would mean it was shut down for half the time
- Integrated luminosity related to integrated number of counts N_{int} (total number of counts, *not* number of counts per unit time) by

$$N_{int} = N\,t$$

where N is number of counts per unit time from before $N = \mathcal{L}\sigma$

CROSS SECTION

- Ice puck collisions:
  - Kinetic energy conserved if surface frictionless
- Particle collisions
  - Often kinetic energy *not* conserved
  - Especially if new particles are created, e.g. p+p $\rightarrow$ p+p+π^0
  - Or particles are lost (absorbed), e.g. p + ^{12}C $\rightarrow$ ^{13}N
- Total energy *E* always conserved (just like momentum & charge)
- Elastic collision $\equiv$ Kinetic energy conserved
  - Does *not* mean that incident KE remains same
  - E.g. Neutron can undergo elastic collision $\Rightarrow$ impart KE to proton
- Inelastic collision $\equiv$ Kinetic energy *not* conserved

CROSS SECTION

- Total cross section - second definition of the word "total"

$$\sigma_{\text{total}} \equiv \sigma_{\text{elastic}} + \sigma_{\text{inelastic}} + \sigma_{\text{absorption}}$$

- Scattering cross section is defined as

$$\begin{aligned} \sigma_{\text{scattering}} &\equiv \sigma_{\text{elastic}} + \sigma_{\text{inelastic}} \\ \Rightarrow \quad \sigma_{\text{total}} &\equiv \sigma_{\text{scattering}} + \sigma_{\text{absorption}} \end{aligned}$$

- Reaction cross section is defined as

$$\begin{aligned} \sigma_{\text{reaction}} &\equiv \sigma_{\text{inelastic}} + \sigma_{\text{absorption}} \\ \Rightarrow \quad \sigma_{\text{total}} &\equiv \sigma_{\text{elastic}} + \sigma_{\text{reaction}} \end{aligned}$$

- Some authors write (including me!)

$$\sigma_{\text{total}} \equiv \sigma_{\text{elastic}} + \sigma_{\text{inelastic}}$$

where $\sigma_{\text{reaction}} \equiv \sigma_{\text{inelastic}}$

[Lamarsh, Nuclear reactor theory, Addison-Wesley, Reading, Massachusetts, 1966]

- Elastic scattering $\Rightarrow$ Kinetic Energy (KE) conserved
  - Nucleus unchanged in isotopic composition or internal energy
  - KE of neutron and nucleus can change (but total KE conserved)
  - Neutron can transfer KE to nucleus
  - Neutron reappears after interaction (n,n)

- Inelastic scattering $\Rightarrow$ KE not conserved
  - Nucleus left in excited state
  - Neutron reappears after interaction (n,n′)

- Neutron scattered elastically (n,n) or inelastically (n,n′)
  - Neutron reappears after interaction

- Absorption reaction $\Rightarrow$ Neutron disappears
  - Examples (n,γ), (n,p), (n,α), fission (by convention)

Notation: (a,b) *means* a + target $\rightarrow$ b + anything

[Lamarsh, Nuclear reactor theory, Addison-Wesley, Reading, Massachusetts, 1966]

- Definitions differ from previous slides, but Lamarsh definitions clearer

$$\begin{aligned}\sigma_{\text{total}} &\equiv \sigma_{\text{elastic(n,n)}} + \sigma_{\text{inelastic(n,n}')} + \sigma_{(\text{n},\gamma)} + \sigma_{(\text{n,p})} + \sigma_{(\text{n,2n})} + \sigma_{(\text{n,3n})} \\ &\quad + \sigma_{(\text{n,pn})} + \sigma_{(\text{n},\alpha)} + \sigma_{(\text{n,fission})} + \cdots\end{aligned}$$

$$\sigma_{\text{total}} \equiv \sigma_{\text{elastic}} + \sigma_{\text{nonelastic}}$$

$$\begin{aligned}\sigma_{\text{nonelastic}} &= \sigma_{\text{inelastic}} + \sigma_{(\text{n},\gamma)} + \sigma_{(\text{n,p})} + \sigma_{(\text{n,2n})} + \sigma_{(\text{n,3n})} \\ &\quad + \sigma_{(\text{n,pn})} + \sigma_{(\text{n},\alpha)} + \sigma_{(\text{n,fission})} + \cdots\end{aligned}$$

$$\sigma_{\text{absorption}} = \sigma_{(\text{n},\gamma)} + \sigma_{(\text{n,p})} + \sigma_{(\text{n},\alpha)} + \sigma_{(\text{n,fission})} + \cdots$$

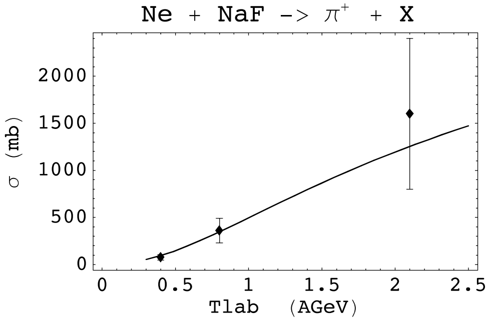
$$\sigma_{\text{nonelastic}} = \sigma_{\text{inelastic}} + \sigma_{\text{absorption}} + \sigma_{(\text{n,2n})} + \sigma_{(\text{n,3n})} + \sigma_{(\text{n,pn})} + \cdots$$

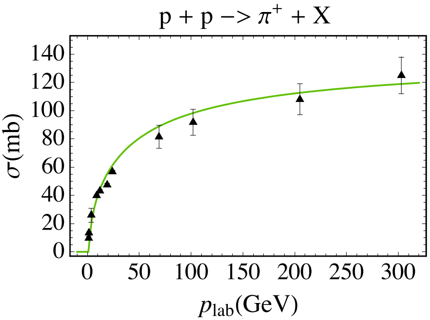
Note: $\sigma_{\text{nonelastic}} \neq \sigma_{\text{inelastic}}$

Total Cross Section

Projectile + Target $\rightarrow$ Detected particles

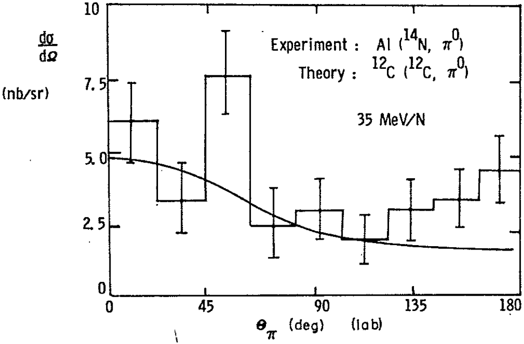
- Count total number of detected particles
  - Total cross section σ
  - Easiest to measure, hardest to calculate (from QFT)





[Norbury, Nucl. Inst. Meth. B 254, 187, 2007], [Norbury, Nucl. Inst. Meth. B 267, 1209, 2009]

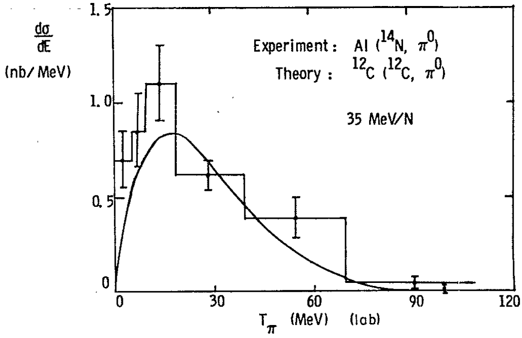
- Count particles at different angles (e.g. $\theta = 0°, 30°, 60°, 90°$)
  - Angular differential cross section $\frac{d\sigma}{d\theta} \equiv \sigma(\theta)$ (Angular distribution)
  - $\sigma = \int_0^{2\pi} \frac{d\sigma}{d\theta}\, d\theta = \int_0^{2\pi} \sigma(\theta)\, d\theta$ $d\Omega = 2\pi \sin\theta d\theta$
  - Harder to measure



[Norbury, Physical Review C 37, 407,1988]

SINGLE DIFFERENTIAL CROSS SECTION

- Count particles of different energies (e.g. E = 5 MeV, 10 MeV, 20 MeV)
  - Energy differential cross section $\frac{d\sigma}{dE} \equiv \sigma(E)$ (Spectral distribution)
  - Energy = $E \equiv$ *Kinetic* Energy!!
  - $\sigma = \int_0^{E_{\max}} \frac{d\sigma}{dE}\, dE = \int_0^{E_{\max}} \sigma(E)\, dE$



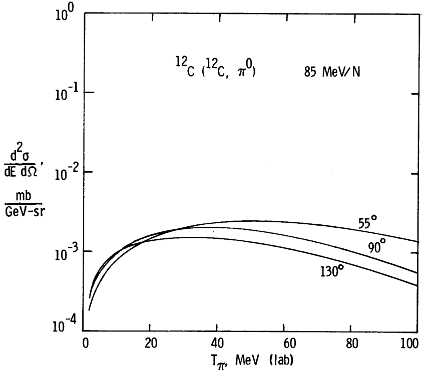
[Norbury, Physical Review C 37, 407,1988]

Double Differential Cross Section

- Count particles of different energies and at different angles

  e.g. ($\theta = 30^\circ$ for E = 5 MeV, 10 MeV) and ($\theta = 60^\circ$ for E = 5 MeV, 10 MeV)

  - Double differential cross section $\frac{d^2\sigma}{dEd\theta} \equiv \sigma(E,\theta)$
  - $\sigma = \int \frac{d^2\sigma}{dEd\theta}\, dEd\theta = \int \sigma(E,\theta)\, dEd\theta$
  - $\frac{d\sigma}{d\theta} = \int \frac{d^2\sigma}{dEd\theta}\, dE = \int \sigma(E,\theta)\, dE$, - $\frac{d\sigma}{dE} = \int \frac{d^2\sigma}{dEd\theta}\, d\theta = \int \sigma(E,\theta)\, d\theta$
  - Hardest to measure, Easiest to calculate (from QFT)



[Norbury et al., NASA Technical Paper 2600, 1986]

Total Cross Section - Two uses of word "total"

- Total $\equiv$ Elastic + Inelastic (or Total $\equiv$ Elastic + Inelastic + Absorption)

  Example: $\sigma_{\text{total}} \equiv \sigma_{\text{elastic}} + \sigma_{\text{inelastic}}$

  Example: $\frac{d\sigma_{\text{total}}}{d\theta} \equiv \frac{d\sigma_{\text{elastic}}}{d\theta} + \frac{d\sigma_{\text{inelastic}}}{d\theta}$

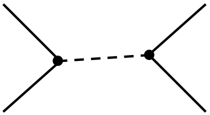
- Total $\equiv$ Non-differential

  $$\sigma \equiv \int \frac{d\sigma}{d\theta}\, d\theta = \int \frac{d\sigma}{dE}\, dE = \int \frac{d^2\sigma}{dE d\theta}\, dE d\theta = \int \sigma(E, \theta)\, dE d\theta$$

  Example: $\sigma_{\text{inelastic}} = \int \frac{d\sigma_{\text{inelastic}}}{d\theta}\, d\theta$

- σ "total - total" $\sigma_{\text{total}} = \int \frac{d\sigma_{\text{total}}}{d\theta}\, d\theta = \int \frac{d\sigma_{\text{elastic}}}{d\theta} + \int \frac{d\sigma_{\text{inelastic}}}{d\theta}$

Recap: Double Differential Cross Section



$$\Rightarrow \quad \sigma(E,\theta) \qquad \equiv \frac{d^2\sigma}{dEd\theta}$$

$\equiv \sigma(E, E', \theta, \theta')$ later in BTE

- Often called 3-dimensional (3d)
- Very precise information
- Function of both energy & angle
- Ultimate test of nuclear theory
- Needed for 3d transport

$$\sigma(E) = \int d\theta \; \sigma(E, \theta) \qquad \frac{d\sigma}{dE} = \int d\theta \; \frac{d^2\sigma}{dE d\theta}$$

$\equiv \sigma(E, E')$ later in BTE

$$\sigma(\theta) = \int dE \; \sigma(E, \theta) \qquad \frac{d\sigma}{d\theta} = \int dE \; \frac{d^2\sigma}{dE d\theta}$$

- Less precise information
- Function of energy OR angle

$$\sigma = \int dE\, \sigma(E) = \int d\theta\, \sigma(\theta) = \int dEd\theta\, \sigma(E,\theta)$$

$\equiv \sigma(E)$ later in BTE

- Very crude
- No angle or energy dependence
- Just total number of counts

Cross Section: Exclusive vs. Inclusive

EXCLUSIVE: $A + B \rightarrow C + D + E + F$

- Ultimate theoretical test
- Hard to measure

INCLUSIVE: $A + B \rightarrow C + anything$

- Very crude theoretical test
- Easy to measure

BETHE - BLOCH EQUATION

[RMP1260, NCRP153-62, Jackson628, Alpen369, NASARP1257-34,40,73, RPP]

BETHE - BLOCH EQUATION

$\hbar\omega$ = MEAN EXCITATION ENERGY

$$\frac{dE}{dx} = 4\pi N_T Z_T \frac{Z_P^2 e^4}{mc^2 \beta^2} \left[\ln\left(\frac{2\gamma^2 \beta^2 mc^2}{\hbar\omega} \right) - \beta^2 + \text{corrections} \right]$$

Boltzmann Transport Equation

1-dimensional Transport Equation

$$\left[\frac{\partial}{\partial x} - \frac{\partial}{\partial E} S_i(E) + \tilde{\sigma}_i(E)\right] \phi_i(x, E) = \sum_j \int_E^\infty dE' \, \tilde{\sigma}_{ij}(E, E') \, \phi_j(x, E')$$

Solve for
$\phi_i(x, E)$ = differential fluence of isotope i at position x with energy E

$\tilde{\sigma}_i(E) \equiv \tilde{\sigma}_{\text{total}}$ = isotopic total cross sect. for isotope i with energy E
$\sigma_{\text{total}} = \sigma_{\text{elastic}} + \sigma_{\text{nonelastic}} = \sigma_{\text{elastic}} + \sigma_{\text{inelastic}} + \sigma_{\text{absorption}} + \sigma_{\text{other}}$

$\tilde{\sigma}_{ij}(E, E')$ = inclusive isotopic energy (single) differential cross section for producing isotope i with energy E from isotope j with energy E'

Different materials: $\tilde{\sigma}$ are cross sections for specific target material

Note: $\frac{\partial}{\partial E} S_i(E)\phi_i(x, E) \equiv \frac{\partial}{\partial E}[S_i(E)\phi_i(x, E)]$

Boltzmann Transport Equation - Units

1-dimensional Transport Equation

$$\left[\frac{\partial}{\partial x} - \frac{\partial}{\partial E} S_i(E) + \tilde{\sigma}_i(E)\right] \phi_i(x,E) = \sum_j \int_E^\infty dE' \, \tilde{\sigma}_{ij}(E,E') \, \phi_j(x,E')$$

- $\phi \sim$ [anything], $\quad x \sim$ [g/cm^2] $\;\Rightarrow\;$ $\tilde{\sigma}_i(E) \sim$ [cm^2/g]
- 12 g of ^{12}C contains $\mathrm{N_A}$ molecules, where $\mathrm{N_A} = 6.02 \times 10^{23}$
  ^{12}C: number density $\equiv$ number per gram = $\tilde{\rho}$ [#/g] = $\mathrm{N_A}/12$ [g^{-1}]
  In general, $\tilde{\rho}$ [#/g] $\equiv \mathrm{N_A}/\mathrm{A}$ [g^{-1}]
- $\tilde{\rho} = \frac{n}{\rho}$, $\quad n$ = # atoms /cm^3 (number density), $\quad \rho$ = "normal" mass density [g/cm^3]
- Thus, $\tilde{\sigma} = \tilde{\rho}\sigma \quad \sim$ [cm^2/g] = [g^{-1} cm^2]
- $S_i(E) = \frac{dE}{dx} \Rightarrow \frac{\partial}{\partial E} S_i(E) = \frac{\partial}{\partial E}\frac{dE}{dx}$ same units as $\frac{\partial}{\partial x}$. $\quad$ Note: $L = \frac{dE}{dx}$ $[\frac{\mathrm{MeV}}{\mathrm{cm}}]$, but $\frac{L}{\rho}$ $[\frac{\mathrm{MeV}}{\mathrm{g/cm^2}}]$
- $\tilde{\sigma}_{ij}(E,E') \equiv \frac{d\tilde{\sigma}_{ij}(E')}{dE} \quad \sim$ [g^{-1} cm^2 E^{-1}]
- Let differential fluence $\phi_i(x,E) \sim$ [# cm^{-2} E^{-1}]
- E $\sim$ [anything], because cancel everywhere, Typically E $\sim$ [A MeV]

3-DIMENSIONAL TRANSPORT EQUATION

$$\left[\boldsymbol{\Omega}\cdot\boldsymbol{\nabla} - \frac{\partial}{\partial E}S_i(E) + \tilde{\sigma}_i(E)\right]\phi_i(\mathbf{r},\boldsymbol{\Omega},E) = \sum_j \int dE'\,d\boldsymbol{\Omega}'\,\tilde{\sigma}_{ij}(\boldsymbol{\Omega},\boldsymbol{\Omega}',E,E')\phi_j(\mathbf{r},\boldsymbol{\Omega}',E')$$

Solve for $\phi_i(\mathbf{r},\boldsymbol{\Omega},E)$ = differential fluence of isotope i at $\mathbf{r}$ moving in direction $\boldsymbol{\Omega}$ with energy E

$\tilde{\sigma}_i(E)$ = isotopic total absorption cross sect. of isotope i with energy E

$\equiv \sigma$ before

$\tilde{\sigma}_{ij}(\boldsymbol{\Omega},\boldsymbol{\Omega}',E,E')$ = inclusive isotopic double differential cross section for producing isotope i moving in direction $\boldsymbol{\Omega}$ with energy E from isotope j moving in direction $\boldsymbol{\Omega}'$ with energy E'

$\equiv \sigma(\Omega, E)$ before

DOSE

- Absorbed dose [ICRU93] $D \equiv \frac{d\epsilon}{dm}$
  - Units [Gy $\equiv$ J kg^{-1}]
  - $d\epsilon$ = mean energy deposited in mass dm
- Dose deposited at position x obtained by $\sum$ over all particles j

DOSE CALCULATED WITH DIFFERENTIAL FLUENCE ϕ

$$D(x) = \sum_j \int_0^\infty dE\, S_j(E)\, \phi_j(x,E) \qquad [\,\mathrm{Gy} \equiv \mathrm{J\,kg}^{-1}\,]$$

- $S_j(E)$ = stopping power as function of particle kinetic energy E
- $\phi_j(x,E)$ = differential particle fluence at position x
- $dE\, S_j(E)\, \phi_j(x,E) \sim [\mathrm{MeV}]\,[\frac{\mathrm{MeV}}{\mathrm{g/cm^2}}]\,[\frac{\#}{\mathrm{cm^2 MeV}}] \sim [\frac{\mathrm{MeV}}{\mathrm{g}}]$

DOSE

- $\phi_j(x, E)$ = differential particle fluence at position x $\quad [\ \frac{\#}{\mathrm{cm^2\,MeV}}\ ]$
- Φ_j = particle fluence (integrated) $\quad [\ \frac{\#}{\mathrm{cm^2}}\ ]$ (Borak, Nelson lectures)

good for a beam of fixed Z, fixed E, then LET fixed

DOSE CALCULATED WITH INTEGRAL FLUENCE Φ

If L has units $[\ \frac{\mathrm{MeV}}{\mathrm{g/cm^2}}\ ]$:

$$D = L\Phi \qquad [\frac{\mathrm{MeV}}{\mathrm{g/cm^2}}][\frac{\#}{\mathrm{cm^2}}] = [\frac{\mathrm{MeV}}{\mathrm{g}}] \sim [\frac{\mathrm{J}}{\mathrm{kg}}]$$

If L has units $[\ \frac{\mathrm{MeV}}{\mathrm{cm}}\ ]$:

$$D = \frac{L}{\rho}\Phi \qquad [\frac{\mathrm{MeV/cm}}{\mathrm{g/cm^3}}][\frac{\#}{\mathrm{cm^2}}] = [\frac{\mathrm{MeV}}{\mathrm{g}}] \sim [\frac{\mathrm{J}}{\mathrm{kg}}] \qquad \text{(Borak, Nelson)}$$

Dose - Unit conversion factor

Assume L has units [$\frac{\text{keV}}{\mu\text{m}}$] (Borak, Nelson)

$$
\begin{aligned}
D &= \frac{L}{\rho}\Phi \\
&\sim \frac{\text{keV}/\mu\text{m}}{\text{g}/\text{cm}^3}\,\text{cm}^{-2} = \frac{\text{keV}}{\text{g}}\,\frac{\text{cm}}{\mu\text{m}} \\
&= \frac{10^3\text{eV}}{10^{-3}\text{kg}}\,\frac{10^{-2}\text{m}}{10^{-6}\text{m}} = 10^{10}\,\frac{\text{eV}}{\text{kg}} = 10^{10}\,\frac{1.602\times10^{-19}\,\text{J}}{\text{kg}} \\
&= 1.602\times10^{-9}\,\frac{\text{J}}{\text{kg}} \\
&= 1.602\times10^{-9}\,\text{Gy} \quad = 1.602\times10^{-7}\,\text{cGy}
\end{aligned}
$$

Dose conversion factor

$D = \frac{L}{\rho}\Phi = 1.602\times10^{-9}\,\text{Gy}$ with $L \sim [\,\frac{\text{keV}}{\mu\text{m}}\,]$, $\Phi \sim [\text{cm}^{-2}]$, $\rho \sim [\frac{\text{g}}{\text{cm}^3}]$

Dose Equivalent

- Stopping power $\approx$ LET, $L \equiv dE/dx$
  - Units [$\mathrm{keV}/\mu\mathrm{m}$]
- Dose at a point becomes

$$D(x) = \sum_j \int_0^\infty dE\, L_j(E)\phi_j(x, E)$$

Dose equivalent calculated with differential fluence ϕ

$$H(x) \equiv \sum_j \int_0^\infty dE\; Q(L_j)\, L_j(E)\, \phi_j(x, E) \qquad [\,\mathrm{Sv}\,]$$

$Q(L_j)$ = quality factor, function of LET, which is function of E

$$\Rightarrow \quad Q(L_j) \equiv Q(L_j(E))$$

Dose Equivalent

Previous equation gives $dD/dE = L_j(E)\phi_j(x,E)$, so that

$$H(x) = \sum_j \int_0^\infty dD\, Q(L_j)$$

Defining [ICRU93, p.5]

$$D_L \equiv \frac{dD}{dL}$$

with units of m kg^{-1}, gives

$$H(x) = \sum_j \int_0^\infty dL\, D_L\, Q(L_j)$$

Note that it is *incorrect* to write

$$H(x) \neq \sum_j \int_0^\infty dL\, D(L)\, Q(L_j)$$

Effective Dose

- Different tissues have different radiosensitivity

Effective Dose

$$E \equiv \sum_T w_T \, H_T \qquad\qquad [\,\mathrm{Sv}\,]$$

Summary

Cross Sections σ_i , σ_{ij} PHYSICS (NUCFRG, QMSFRG)

Boltzmann TRANSPORT Eqn $\Rightarrow$ FLUENCE ϕ_i $[\#/cm^2/MeV]$ (HZETRN)

$$\left[\frac{\partial}{\partial x} - \frac{\partial}{\partial E} S_i(E) + \sigma_i(E)\right] \phi_i(x,E) = \sum_j \int_E^\infty dE' \, \sigma_{ij}(E,E') \, \phi_j(x,E')$$

$$\text{Dose} \quad D(x) = \sum_i \int_0^\infty dE \, S_i(E) \, \phi_i(x,E) \qquad [\mathrm{Gy} = \mathrm{J/kg}]$$

$$\text{Dose Equivalent} \quad H(x) = \sum_i \int_0^\infty dE \, Q(L_i(E)) \, L_i(E) \, \phi_i(x,E) \qquad [\mathrm{Sv}]$$

$$\text{Effective Dose} \quad E = \sum_T w_T \, H_T \qquad [\mathrm{Sv}] \qquad \Rightarrow \text{Risk}$$

BIOLOGY $Q(L_i), w_T$

$$L_i \equiv \frac{dE}{dx} \approx S_i(E)$$

Pions

Leptons spin =1/2

Flavor		Mass GeV/c^2	Electric charge
ν_L	lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e	electron	0.000511	–1
ν_M	middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ	muon	0.106	–1
ν_H	heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ	tau	1.777	–1

Quarks spin =1/2

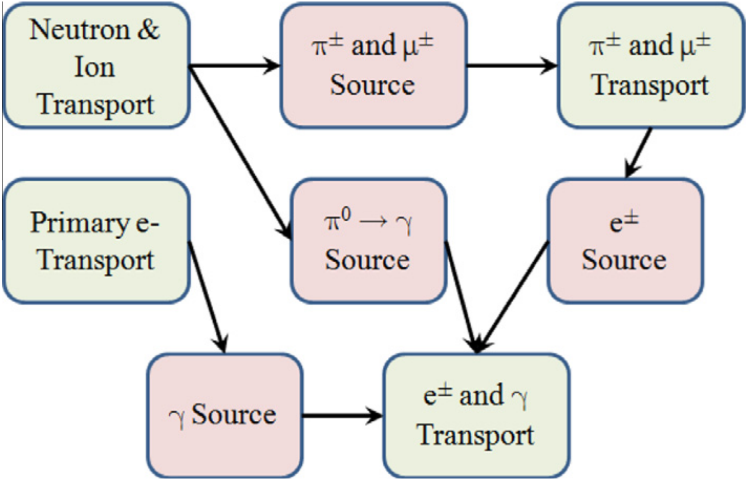
Flavor		Approx. Mass GeV/c^2	Electric charge
u	up	0.002	2/3
d	down	0.005	–1/3
c	charm	1.3	2/3
s	strange	0.1	–1/3
t	top	173	2/3
b	bottom	4.2	–1/3

Neutron, Proton = 3 quarks Pion = 2 quarks

[http://education.web.cern.ch, 2014]

PIONS

[Slaba, Blattnig, Reddell, Bahadori, Norman, Badavi, Advances Space Research 52, 62, 2013]



Flowchart of HZE-π/EM transport model

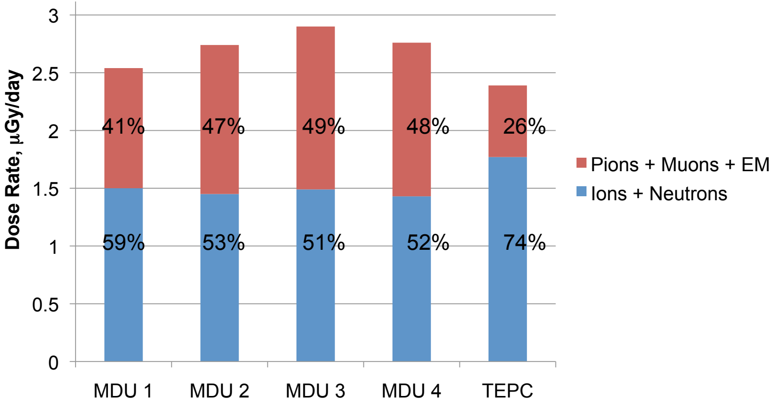
Pions make large contributions to Dose

[Slaba, Mertens, Blattnig, NASA TP-2013-217983]

[Norman, Blattnig, De Angelis, Badavi, Norbury: Advances Space Research 50, 146, 2012]

[Slaba, Blattnig, Reddell, Bahadori, Norman, Badavi: Advances Space Research 52, 62, 2013]

[Aghara, Blattnig, Norbury, Singleterry: Nucl. Inst. Meth. B 267, 1115, 2009]



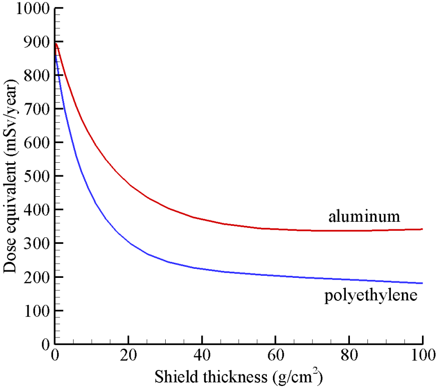
MDU=Mobile Dosimetry Unit (ISS)

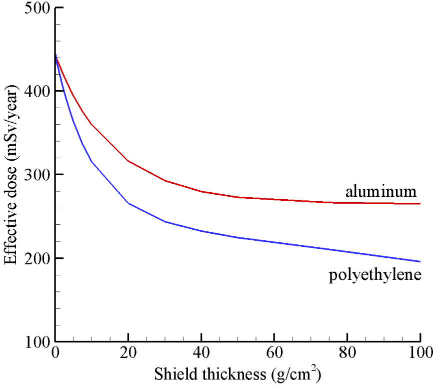
- Important discovery in space radiation

Minimum in Dose Equivalent vs. Depth

[Blattnig, Slaba, Bahadori, Norman, Clowdsley, Space Radiation Investigators' Workshop, Galveston, TX, 2014]

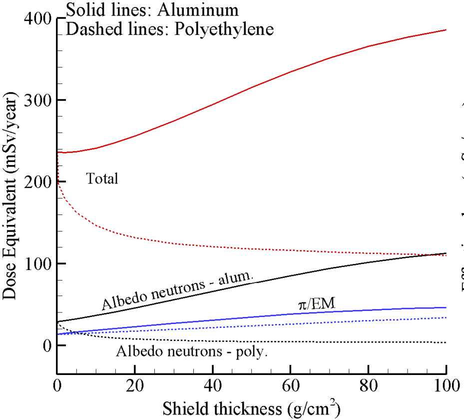
- Previous design paradigm
  - Exposures from GCR show little variation past 40 g/cm^2
  - Increased shielding slightly decreases exposures
  - Transport performed with HZETRN (straight ahead transport with no pions)





BON2010 used to generate Oct 1976 GCR environment.

Minimum in Dose Equivalent vs. Depth



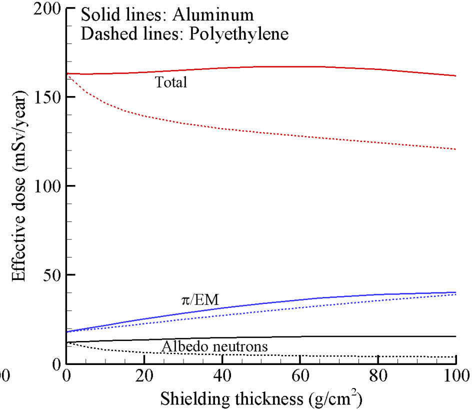


Figure 3. Dose equivalent (left pane) and effective dose (right pane) as a function of shield thickness on the Martian surface.

MINIMUM IN DOSE EQUIVALENT VS. DEPTH

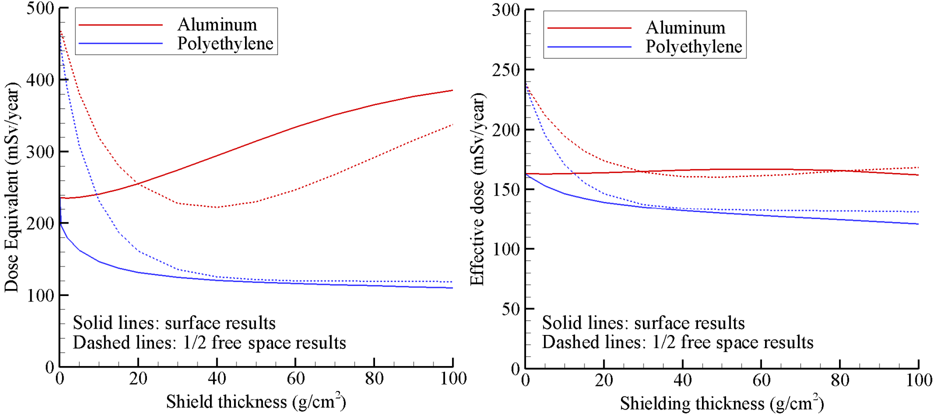
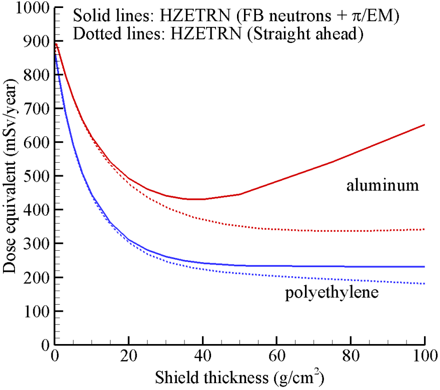


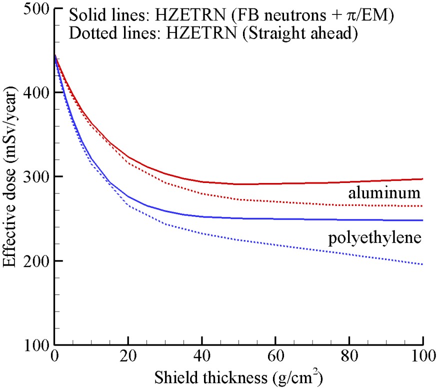
Figure 4. Comparison of surface exposure to ½ free space exposure as a function of shield thickness.

MINIMUM IN DOSE EQUIVALENT VS. DEPTH

[Blattnig, Slaba, Bahadori, Norman, Clowdsley, Space Radiation Investigators' Workshop, Galveston, TX, 2014]

- New design paradigm
- If forward/backward (FB) neutron transport and pions turned ON
  - Minimum in dose equivalent vs. depth near 40 g/cm^2
  - Increased shielding increases exposure
  - Material optimization more important than previously thought



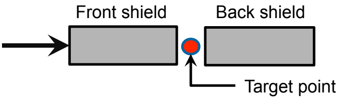


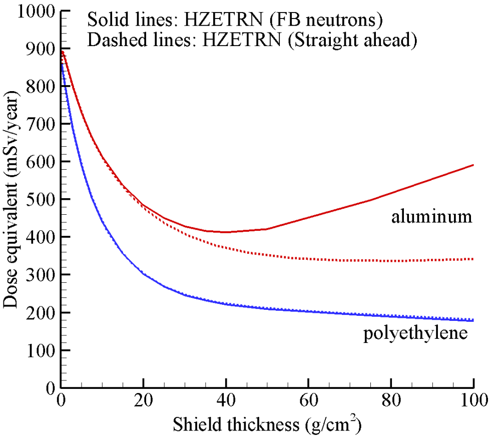
BON2010 used to generate Oct 1976 GCR environment.

Minimum in Dose Equivalent vs. Depth

[Blattnig, Slaba, Bahadori, Norman, Clowdsley, Space Radiation Investigators' Workshop, Galveston, TX, 2014]

- Dose equiv in Al is result of neutron production & back-scatter in shielding behind target point
  - Back scattered neutrons produce high LET target fragments with short ranges

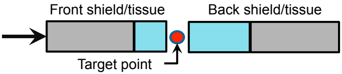


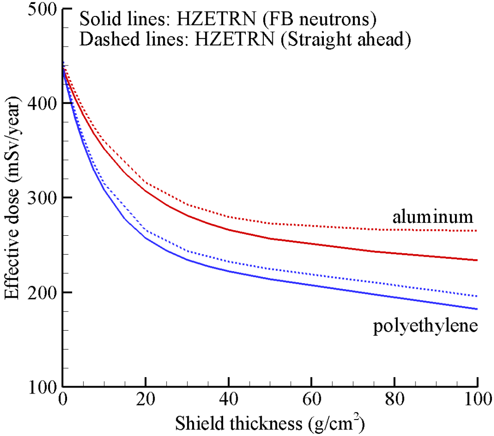


Minimum in Dose Equivalent vs. Depth

[Blattnig, Slaba, Bahadori, Norman, Clowdsley, Space Radiation Investigators' Workshop, Galveston, TX, 2014]

- Effective dose - body self shielding moderates neutron field & reduces impact of backward component
  - FB neutron transport accounts for multiple elastic collisions (moderation)

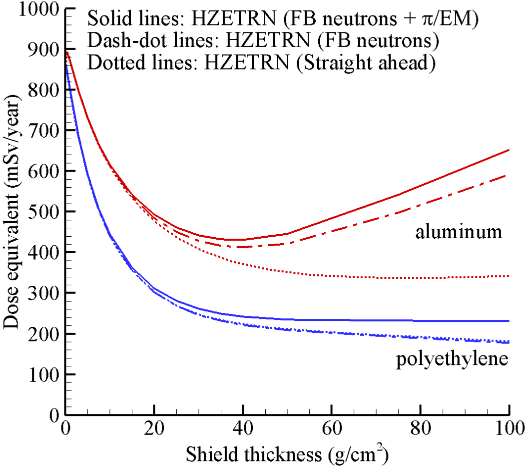




Minimum in Dose Equivalent vs. Depth

[Blattnig, Slaba, Bahadori, Norman, Clowdsley, Space Radiation Investigators' Workshop, Galveston, TX, 2014]

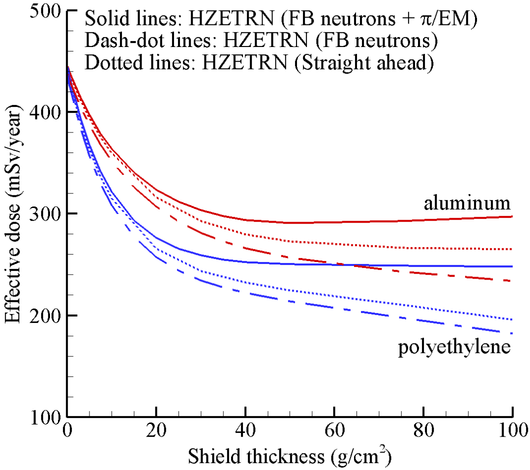
- Pion/EM contribution to dose equivalent smaller than contribution from neutrons, but still noticeable
  - Neutron contribution mainly from high LET target fragments (avg Q $\sim$ 20)
  - Pion/EM avg Q $\sim$ 1



MINIMUM IN DOSE EQUIVALENT VS. DEPTH

[Blattnig, Slaba, Bahadori, Norman, Clowdsley, Space Radiation Investigators' Workshop, Galveston, TX, 2014]

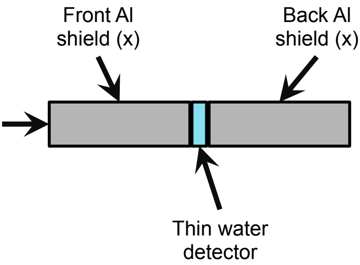
- Pion/EM contribution to effective dose more noticeable because tissue moderates/attenuates contribution from neutron field

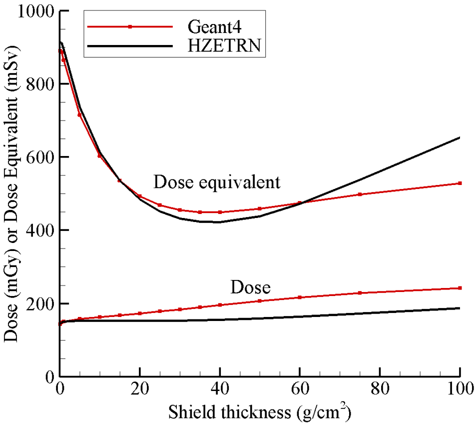


Minimum in Dose Equivalent vs. Depth

[Blattnig, Slaba, Bahadori, Norman, Clowdsley, Space Radiation Investigators' Workshop, Galveston, TX, 2014]

- Verification
  - Preliminary comparison to Geant4





BON2010 used to generate solar minimum GCR environment (ϕ = 475 MV).

Minimum in Dose Equivalent vs. Depth

[Blattnig, Slaba, Bahadori, Norman, Clowdsley, Space Radiation Investigators' Workshop, Galveston, TX, 2014]

- Summary & Conclusions

- New improvements to transport codes indicate potentially significantly different exposure vs. depth behavior in the region of 30-100 g/cm^2
- Significant work has been done to confirm these findings but more is needed including:
  - More extensive benchmarking with Monte Carlo codes
  - Thick target experiments
- Vehicle and system designs may need to adapt to these new results including:
  - Renewed emphasis on materials optimization
  - Changes in configurations to avoid thicknesses where exposures are maximal

- NASA space radiation has focused on heavy ions (Fe)

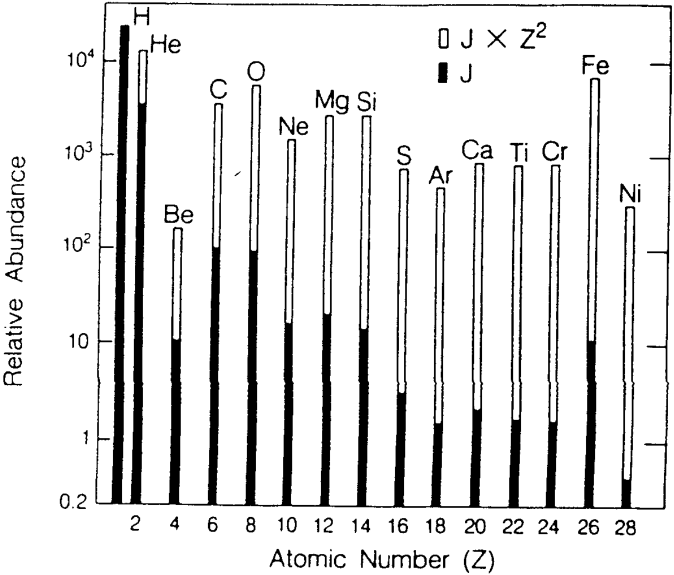
  - Biology: majority of experiments at NSRL

  - Nuclear Physics: QMSFRG based on Eikonal approx

  - Transport: 1d HZETRN based on Straight-Ahead approx

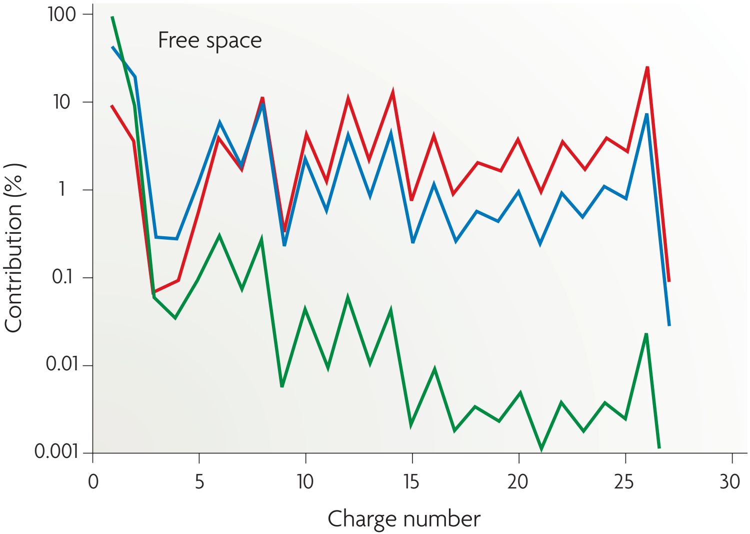
  - Reason $\rightarrow$

INTERNAL ENVIRONMENT (FREE SPACE)

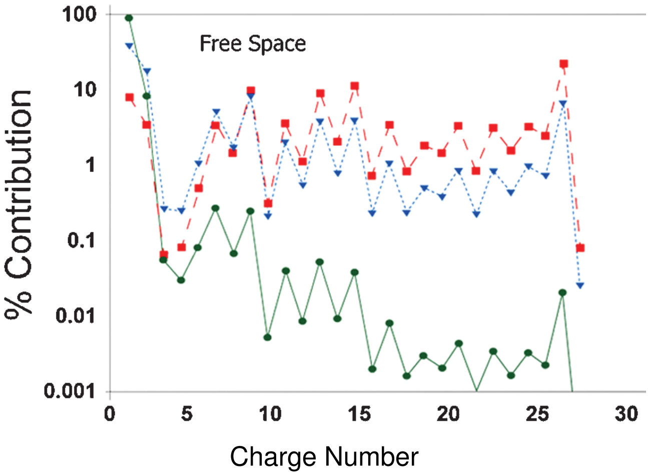


[NCRP Report No. 98]

[Durante & Cucinotta, Nature Reviews Cancer 8, 465, 2008]



GCR environment. Fluence, Dose, Dose equivalent.



Relative contribution in fluence, dose and dose equivalent of different elements in the GCR spectrum. Calculation is an average over 1 year in solar minimum behind 5 g/cm^2 Al shielding.

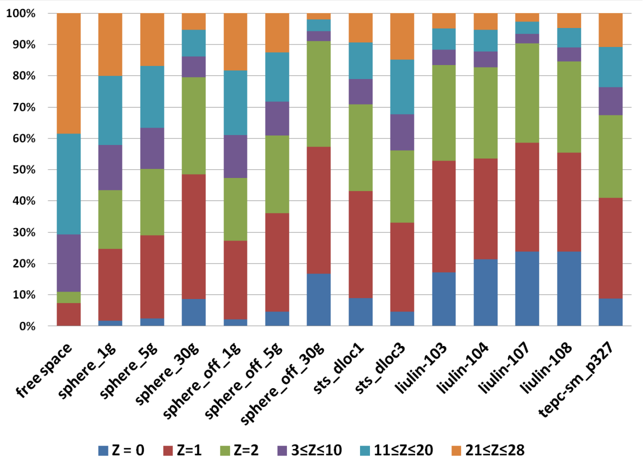
[Durante & Cucinotta, Rev. Mod. Phys. 83, 1245, 2011]

BUT we don't have naked astronauts in free space . . .

... and usually not thinly shielded

Internal Environment

[Walker, Townsend, Norbury, Advances in Space Research 51, 1792, 2013]



Percent contribution to BFO dose equivalent by charge group.

Light ions & neutrons dominate!

Internal Environment

- NASA space radiation has focused on heavy ions (Fe)
  - OK for naked astronaut or thin shielding
  - Biology: more neutron, light ion experiments at NSRL
  - Not saying Heavy ions not important: need both heavy + light

- Neutrons & Light ions deflected at large angles
  - Nuclear Physics: QMSFRG based on Eikonal approx
  - Transport: 1d HZETRN based on Straight-Ahead approx
  - Both not adequate for neutrons, light ions

- Langley: 3d nuclear physics & 3d transport for neutrons, light ions

- Neutrons large Q, light ions highly penetrating
  - Accurate description $\rightarrow$ lower risk

GCR Sensitivity Analysis: External Environment

- Heavy Ions in external environment
  - Produce the light ions and neutrons in the internal environment

GCR Sensitivity Analysis

- ACE = Advanced Composition Explorer
  - Earth-Sun L1 (1.5 million km from Earth)
  - CRIS Cosmic Ray Isotope Spectrometer

- AMS = Alpha Magnetic Spectrometer (on board ISS)
  - Search for dark matter, antimatter etc.
  - Also cosmic rays

- NSRL = NASA Space Radiation Lab
  - Brookhaven National Lab on Long Island
  - p - Fe 50 MeV/n - 1 GeV/n
  - up to Au 165 MeV/n

- FAIR = Facility for Antiproton and Ion Research
  - GSI Gesellschaft fur Schwerionenforschung (Darmstadt)
  - Ne 45 GeV/n, U 35 GeV/n

GCR Sensitivity Analysis - 20 g/cm^2

[Slaba & Blattnig, Space Weather, in press, 2014]

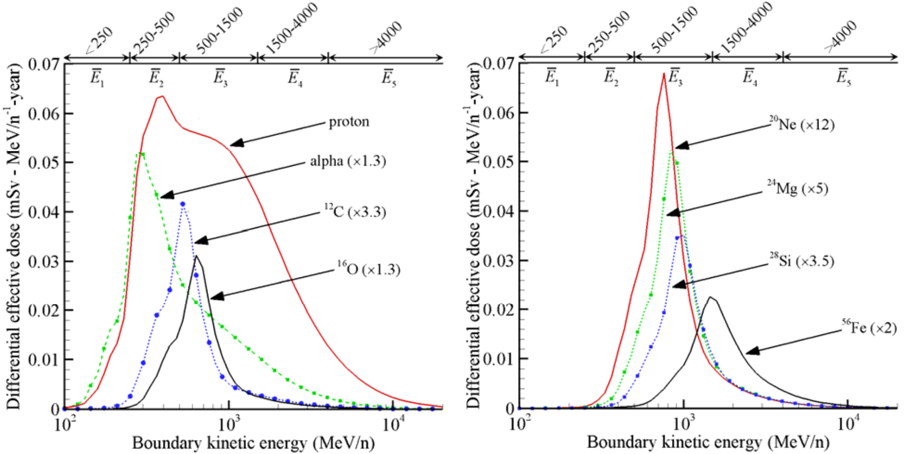


Figure 2. Differential effective dose rate as a function of boundary kinetic energy behind 20 g/cm^2 of aluminum exposed to solar minimum conditions described by BON2010 model. Results for specific ions have been scaled to improve plot clarity. The location of the peak distribution values along the horizontal axis indicates which boundary energies are most important to effective dose behind shielding.

GCR spectrum 90% effective dose > 500 MeV/n (ACE not helpful)

GCR Sensitivity Analysis - 0 g/cm^2

Energy	Range	Satellite	Accelerator
E_1	$< 250\ MeV/n$	ACE, AMS	NSRL
E_2	$250 - 500\ MeV/n$	ACE, AMS	NSRL
E_3	$500 - 1500\ MeV/n$	AMS	NSRL, FAIR
E_4	$1500 - 4000\ MeV/n$	AMS	FAIR
E_5	$> 4000\ MeV/n$	AMS	FAIR

[Slaba & Blattnig, Space Weather, in press, 2014]

Table 1. Relative contribution (×100) of GCR boundary energy and charge groups to effective dose with no shielding. A value of 0.0 indicates that the relative contribution is less than 0.1%. The BON2010 GCR model was used for these results during solar minimum conditions.

	$\bar{E}_1$	$\bar{E}_2$	$\bar{E}_3$	$\bar{E}_4$	$\bar{E}_5$	Total
$Z = 1$	2.1	3.7	11.6	10.5	7.7	35.6
$Z = 2$	2.1	1.4	2.5	1.6	0.9	8.4
$Z =$ 3-10	4.1	5.5	2.6	1.0	0.6	13.8
$Z =$ 11-20	1.4	6.0	7.7	2.7	1.5	19.3
$Z =$ 21-28	0.4	3.0	11.1	5.5	3.0	22.9
Totals	10.0	19.5	35.6	21.3	13.6	100.0

$\mathrm{E_3 + E_4 + E_5 = 70\%}$ $\mathrm{E_4 + E_5 = 35\%}$

GCR Sensitivity Analysis - 20 g/cm^2

Energy	Range	Satellite	Accelerator
E_1	$< 250\ MeV/n$	ACE, AMS	NSRL
E_2	$250 - 500\ MeV/n$	ACE, AMS	NSRL
E_3	$500 - 1500\ MeV/n$	AMS	NSRL, FAIR
E_4	$1500 - 4000\ MeV/n$	AMS	FAIR
E_5	$> 4000\ MeV/n$	AMS	FAIR

[Slaba & Blattnig, Space Weather, in press, 2014]

Table 2. Relative contribution (×100) of GCR boundary energy and charge groups to effective dose with 20 g/cm^2 aluminum shielding. A value of 0.0 indicates that the relative contribution is less than 0.1%. The BON2010 GCR model was used for these results during solar minimum conditions.

	$\bar{E}_1$	$\bar{E}_2$	$\bar{E}_3$	$\bar{E}_4$	$\bar{E}_5$	Total
$Z = 1$	1.2	5.4	18.2	18.4	14.8	58.1
$Z = 2$	1.2	2.2	4.1	2.9	1.7	12.2
$Z = 3\text{-}10$	0.0	3.3	3.8	1.3	0.8	9.1
$Z = 11\text{-}20$	0.0	0.2	6.6	2.0	1.1	10.0
$Z = 21\text{-}28$	0.0	0.0	4.7	3.8	2.1	10.6
Totals	2.5	11.1	37.4	28.4	20.5	100.0

$E_3 + E_4 + E_5 = 86\%$ $E_4 + E_5 = 49\%$

GCR Sensitivity Analysis - 40 g/cm^2

Energy	Range	Satellite	Accelerator
E_1	$< 250\ MeV/n$	ACE, AMS	NSRL
E_2	$250 - 500\ MeV/n$	ACE, AMS	NSRL
E_3	$500 - 1500\ MeV/n$	AMS	NSRL, FAIR
E_4	$1500 - 4000\ MeV/n$	AMS	FAIR
E_5	$> 4000\ MeV/n$	AMS	FAIR

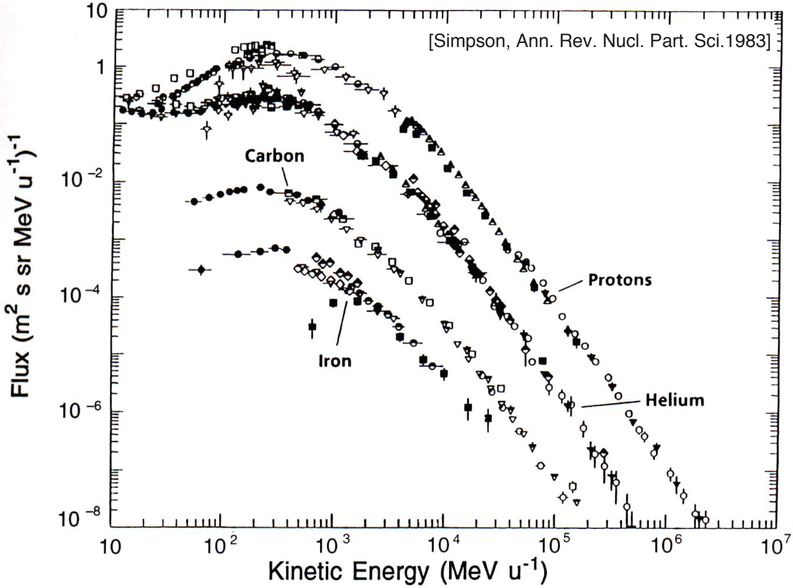
[Slaba & Blattnig, Space Weather, in press, 2014]

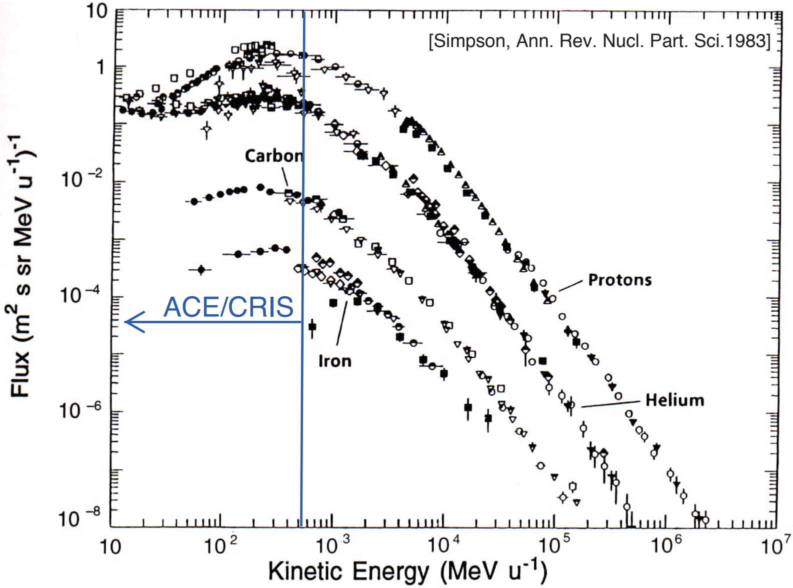
Table 3. Relative contribution (×100) of GCR boundary energy and charge groups to effective dose with 40 g/cm^2 aluminum shielding. A value of 0.0 indicates that the relative contribution is less than 0.1%. The BON2010 GCR model was used for these results during solar minimum conditions.

	$\bar{E}_1$	$\bar{E}_2$	$\bar{E}_3$	$\bar{E}_4$	$\bar{E}_5$	Total
$Z = 1$	0.2	5.4	20.9	23.0	20.0	69.6
$Z = 2$	0.1	2.5	4.9	3.9	2.5	14.0
$Z = 3\text{-}10$	0.0	0.5	3.9	1.4	0.9	6.7
$Z = 11\text{-}20$	0.0	0.0	2.9	1.4	0.8	5.1
$Z = 21\text{-}28$	0.0	0.0	1.1	2.3	1.2	4.6
Totals	0.3	8.5	33.8	32.0	25.4	100.0

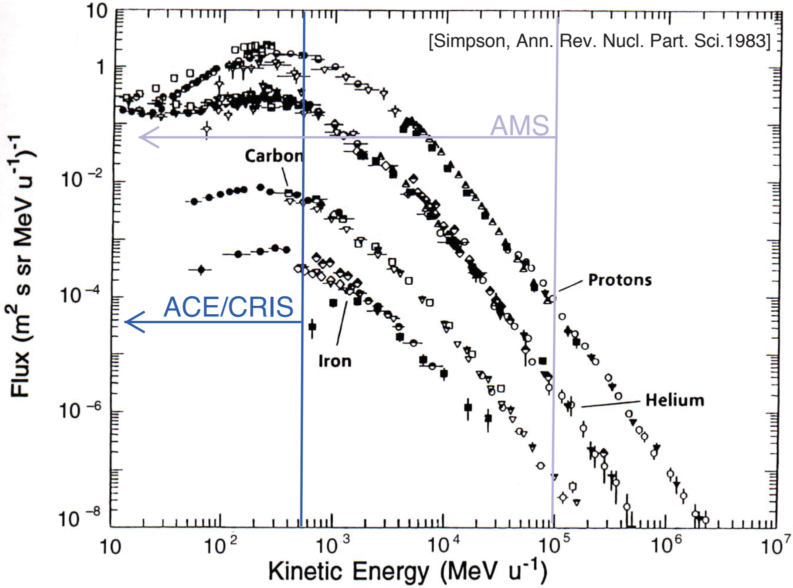
$\mathrm{E}_3 + \mathrm{E}_4 + \mathrm{E}_5 = 91\%$ $\quad$ $\mathrm{E}_4 + \mathrm{E}_5 = 57\%$

GCR Sensitivity Analysis

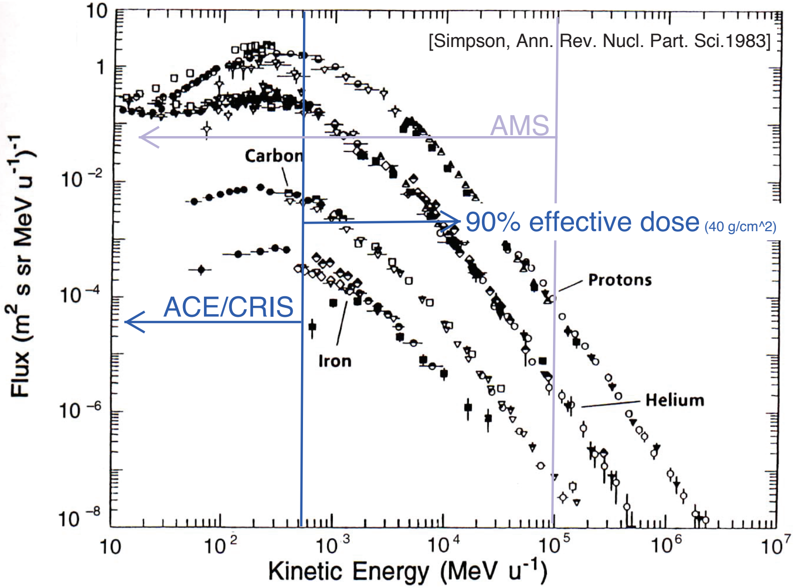



[Simpson, Ann. Rev. Nucl. Part. Sci.1983]
Flux (m2 s sr MeV u-1)-1
Kinetic Energy (MeV u-1)
10
1
10 -2
10 -4
10 -6
10 -8
10
10 2
10 3
10 4
10 5
10 6
10 7
Carbon
Iron
Protons
Helium
ACE/CRIS

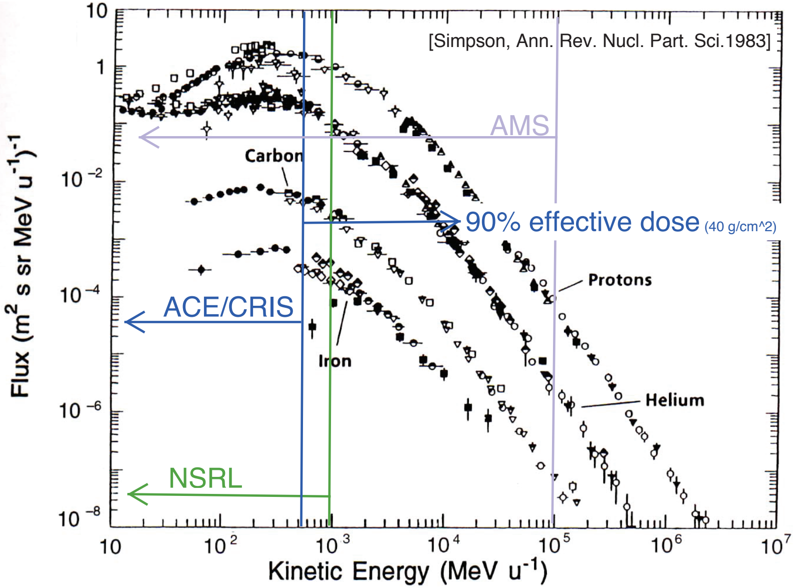
GCR Sensitivity Analysis



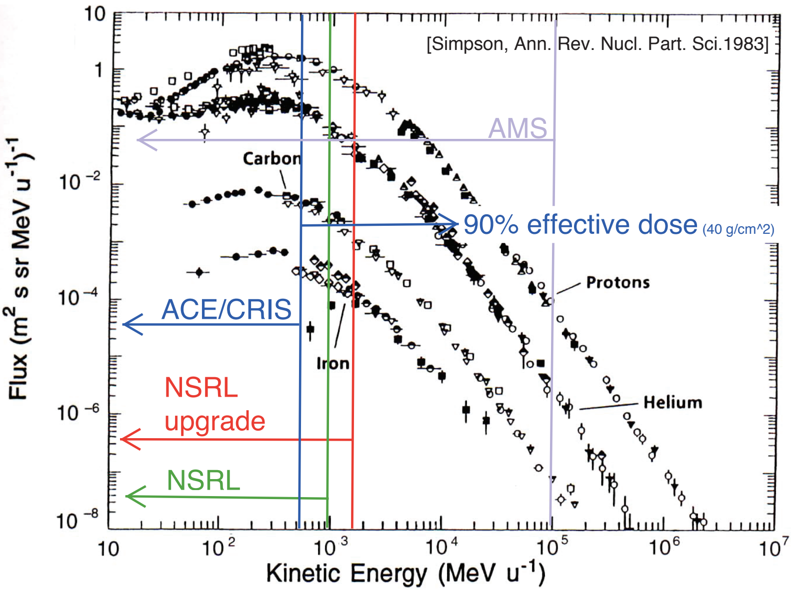
GCR Sensitivity Analysis



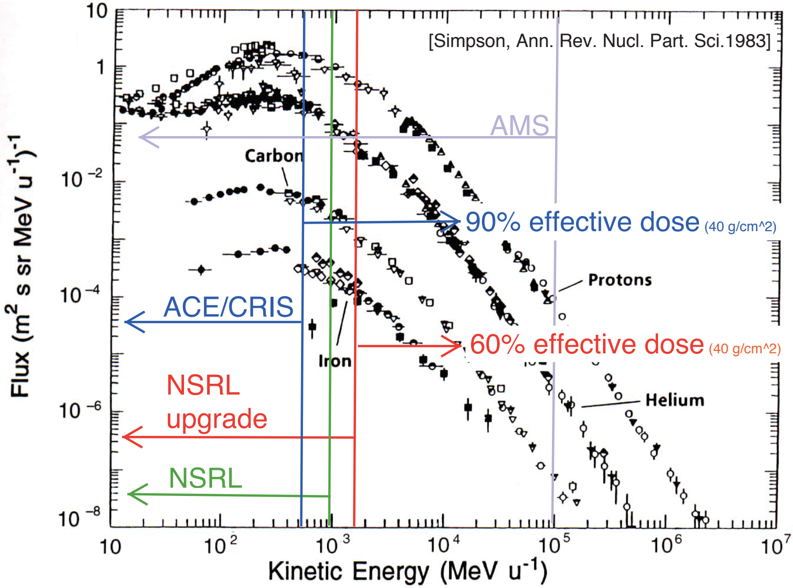
GCR SENSITIVITY ANALYSIS



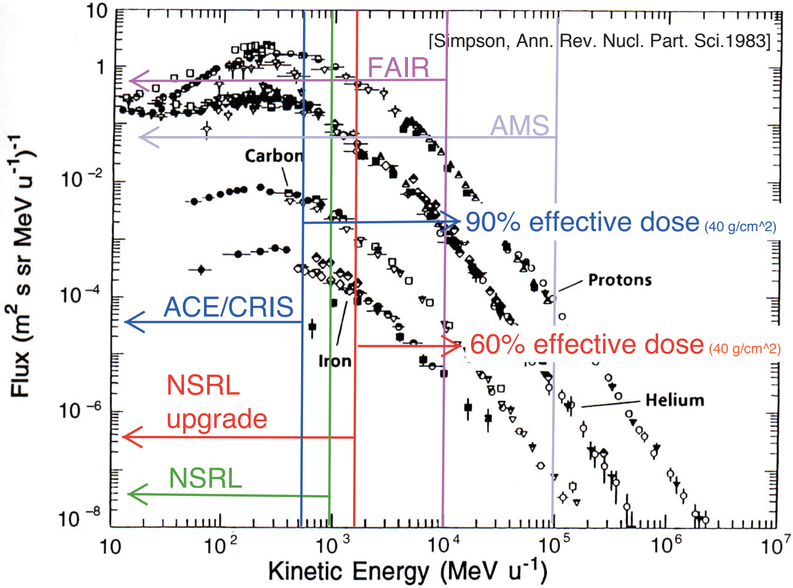
GCR Sensitivity Analysis



GCR Sensitivity Analysis



GCR Sensitivity Analysis



- No shielding (naked astronaut)

  Satellites: ACE helpful, AMS much better
  Accelerators: NSRL very useful, FAIR very useful

- Moderate shielding (20 $\mathrm{g/cm^2}$)

  Satellites: ACE inadequate, AMS very useful
  Accelerators: NSRL useful for low Z, FAIR useful for high Z

- Thicker shielding (40 $\mathrm{g/cm^2}$)

  Satellites: ACE useless, AMS very useful
  Accelerators: NSRL inadequate, FAIR very useful

NASA Space Radiation Lab (NSRL):

- Wrong Ions (Z)?
  - Internal spectrum neutrons & light ions
- Wrong Flux (dose rate)?
  - Hormesis, Bystander, Fractionation, Countermeasures
- Wrong Energy (E)?
  - 60% effective dose $>$ 1.5 GeV/n $(40\,\mathrm{g/cm^2})$

SUMMARY

- E = 1 GeV/n, really means T = 1 GeV/n
- Cross Section
  - Total, Differential, Angular, Spectral, Double Differential
- Transport
  - Flux, Fluence, Dose, Dose Equivalent
- Pions make significant contributions to dose
- Possible minimum in Dose equivalent vs. Depth curve
- ACE not sufficient - AMS needed
- NSRL not sufficient - FAIR needed

THE END

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