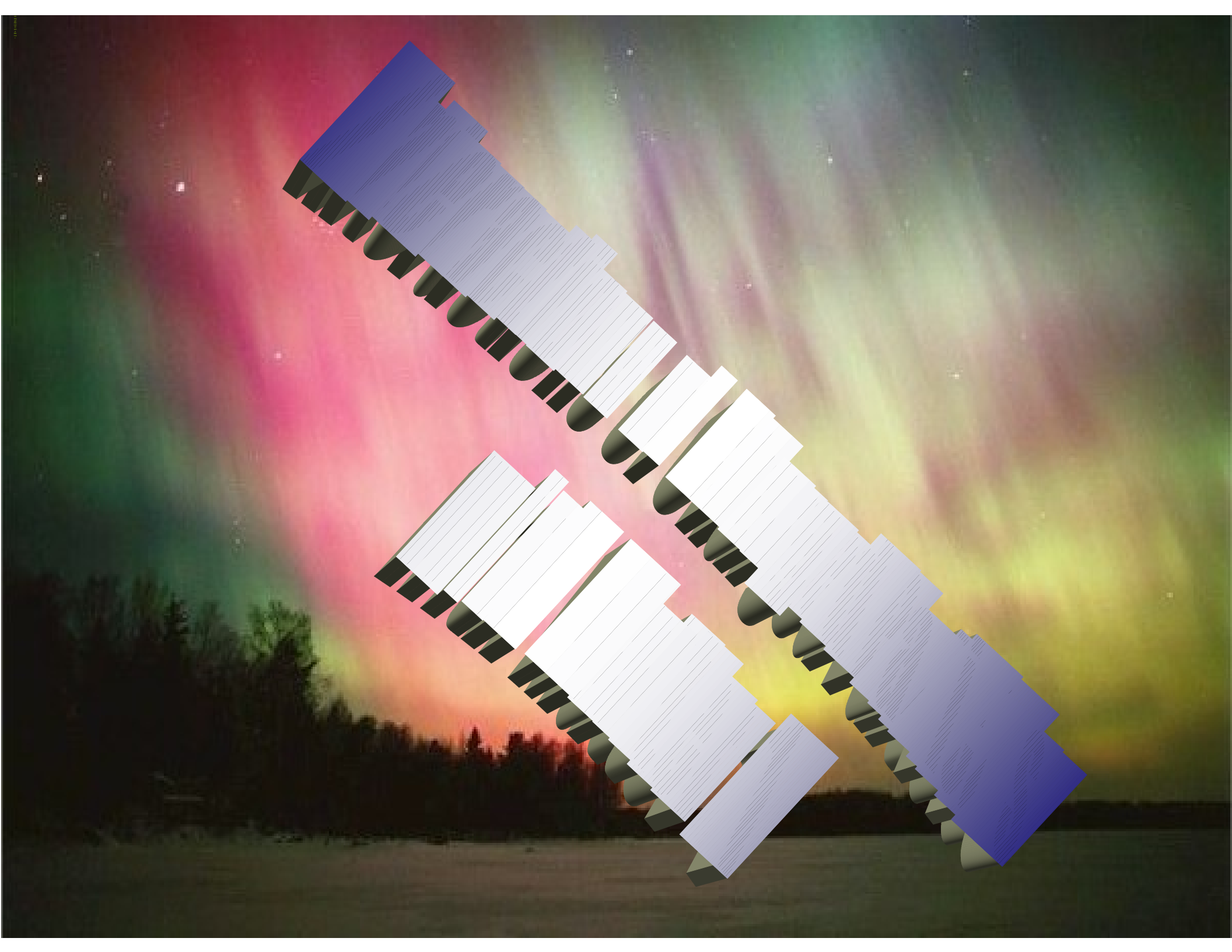
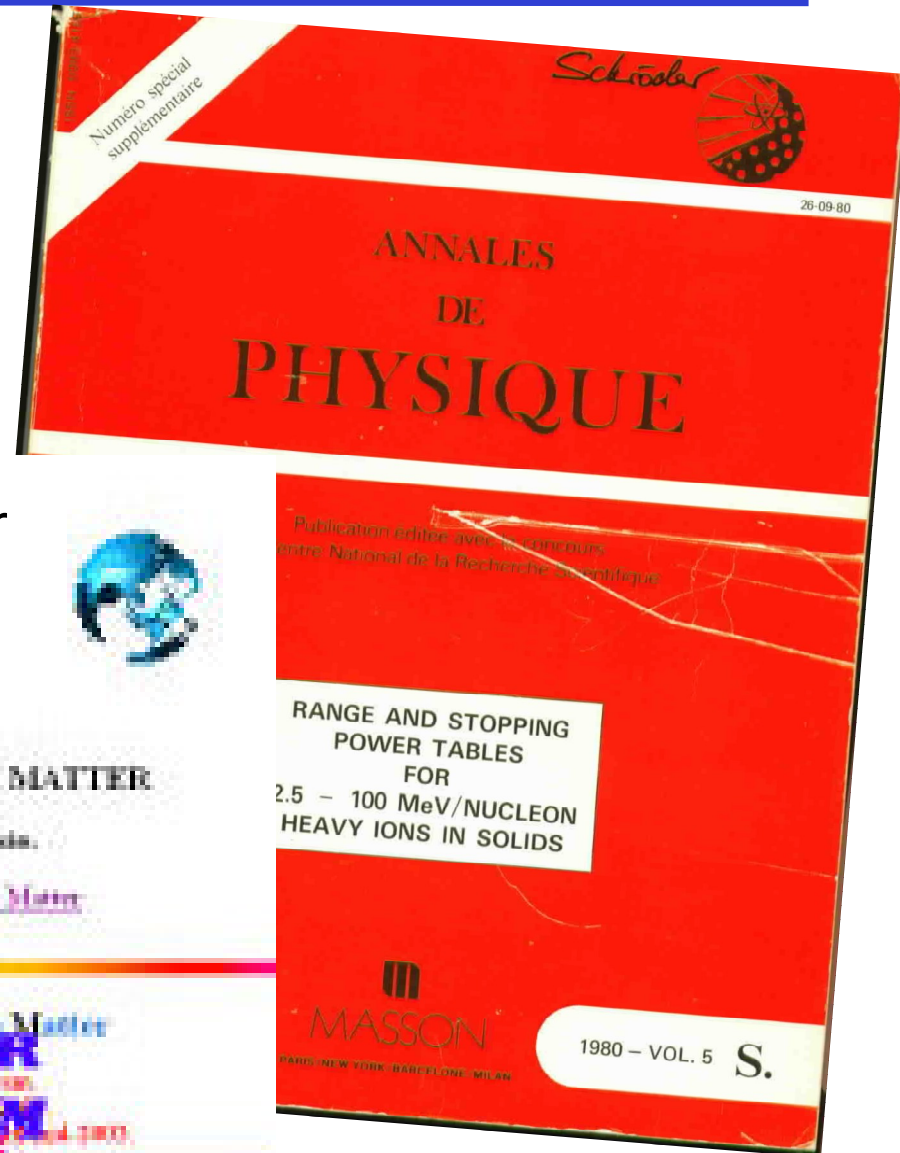
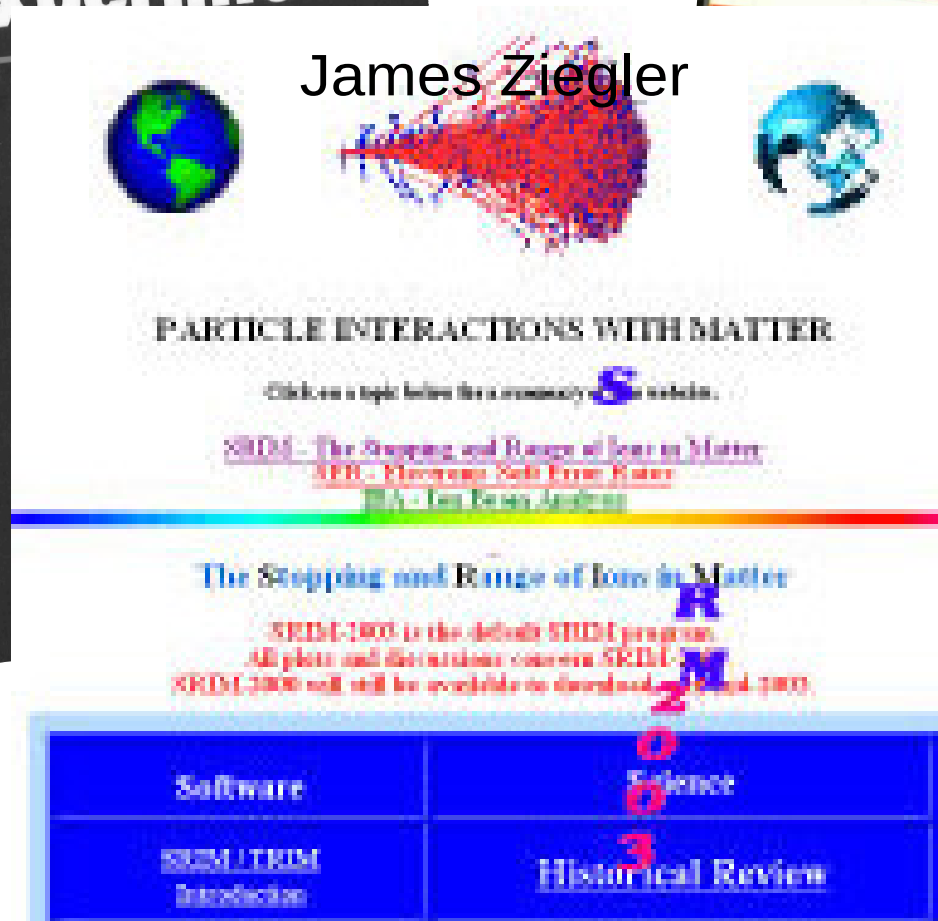
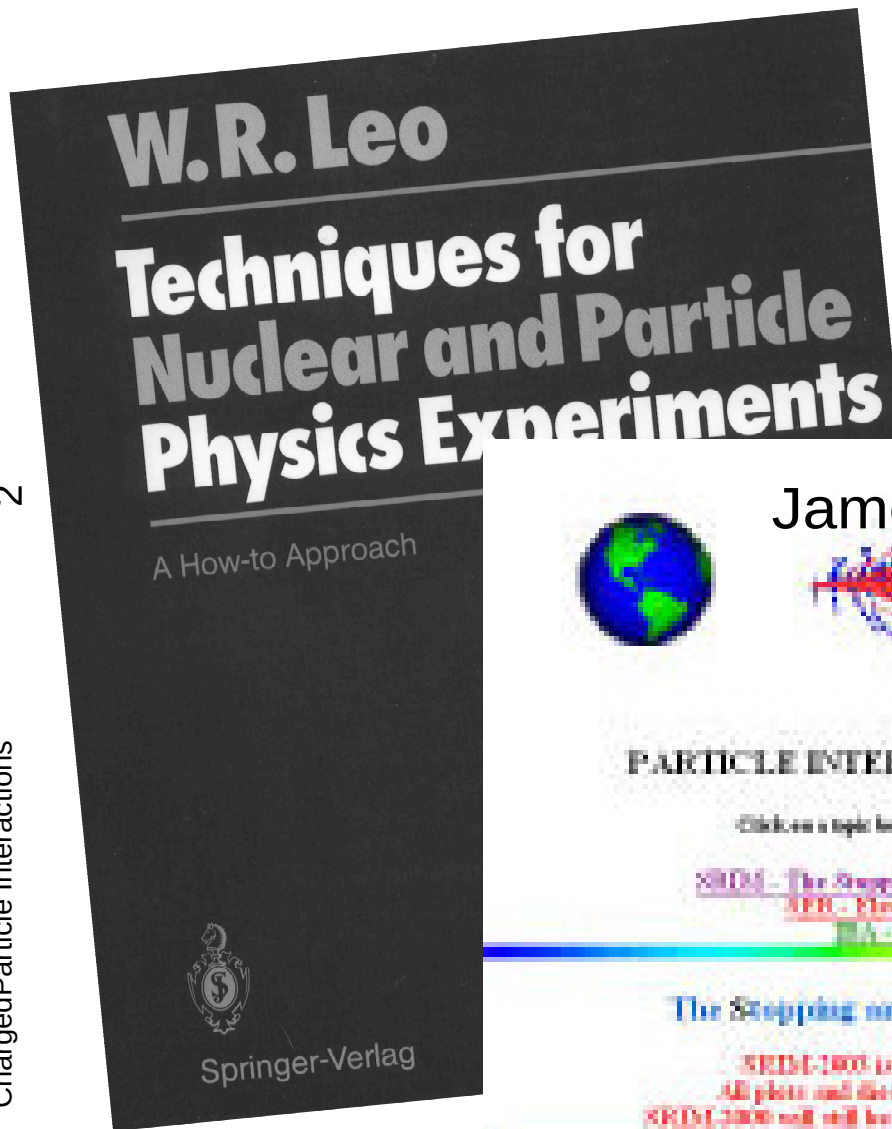




Literature/ Tutorials

2

Charged Particle Interactions



Stopping and Range Tables for Charged Particles

J.F. Ziegler (IBM&J.P. Biersack (HMI))

<http://www.srim.org>

Ion Stopping & Range Tables

Ion **Target**

Symbol Name Atomic Number Mass (amu) Ion Energy Range (keV) Lowest Highest

? **Ion** **PT** Tc Technetium 43 97 10 10000

Target Description: Technetium in Bismuth

Add Element Compound Dictionary

Delete Element Symbol Name Atomic Number Weight

X **PT** Bi Bismuth 83 208

Stopping Power Units: MeV / (mg/cm²)

Compound Correction: 0 Stopping Power Version: SRIM - 2000

TRIM Input

TRIM (Monte Carlo Ranges)

TRIM Demo ? Restore Last TRIM Data ?

Type of TRIM Calculation: DAMAGE Ion Distribution and Quick Calculation of Damage ?

Basic Plots: Ion Distribution with Recoils projected on Y-Plane ?

Symbol Name of Element Atomic Number Mass (amu) Energy (keV) Angle of Incidence

? **ION DATA** **PT** H Hydrogen 1 1.008 10 ? 0

? **TARGET DATA**

Elements in Layer 1

Add New Layer Add New Element to Layer Compound Dictionary

Layer Name	Width	Density (g/cm ³)	Compound Corr	Gas	Symbol	Name	Atomic Number	Weight (amu)	Atom Stoich or %	Damage (eV) Disp Latt Surf
X Layer 1	10000	An	0	0	X PT		0	1	100	20 3 2

Special Parameters

Name of Calculation: H (10) into Layer 1 Stopping Power Version: SRIM-2000 ?

AutoSave at Ion #: 10000 Total Number of Ions: 99999 Random Number Seed: Plotting Window Depths: Min: 0 Max: 10000

Output Disk Files

? ☐ Ion Ranges ? ☐ Backscattered Ions ? ☐ Transmitted Ions ? ☐ Sputtered Atoms ? ☐ Collision Details

? ☐ Resume saved TRIM calc. ? ☐ Use TRIM-96 (DOS)

Save Input & Run TRIM **Calculate Quick Range Table** **Main Menu** **Quit**

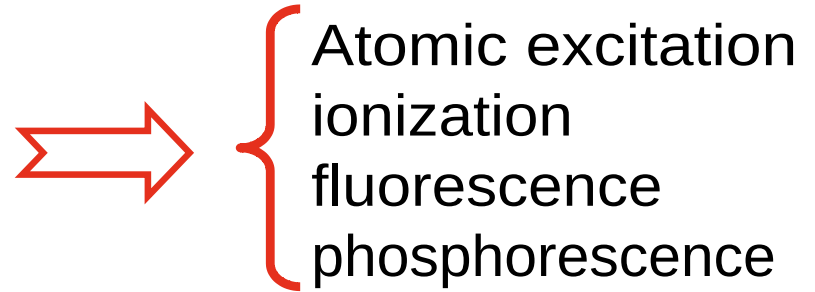
Problem Solving **Clear All**

Older Literature: Hubert et al., Ann. De Physique Suppl.5, 1 (1980)

W. Udo Schröder, 2003

Main Interactions of Charged Particles

Dominant type of interaction:
inelastic collisions with electrons



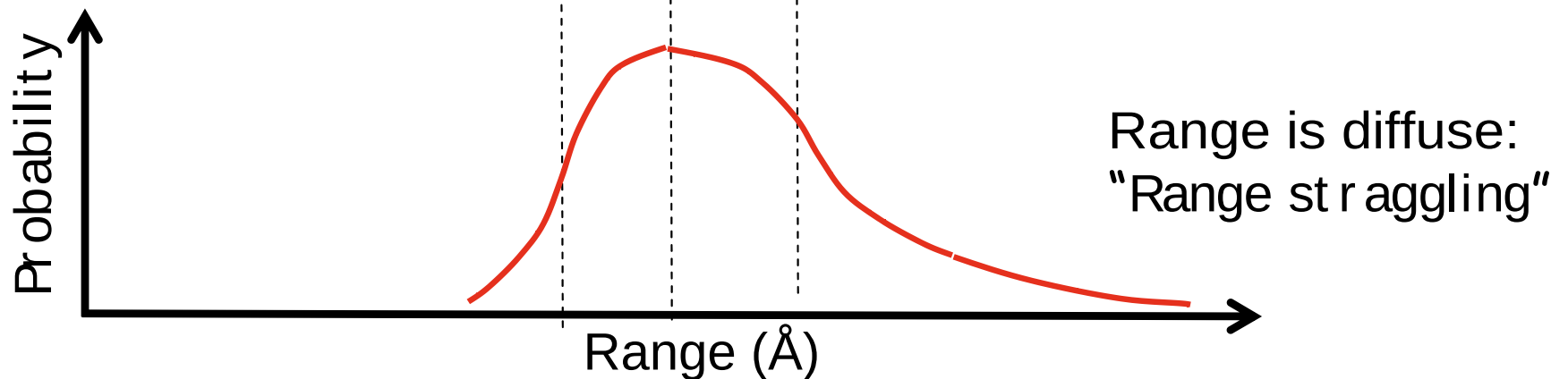
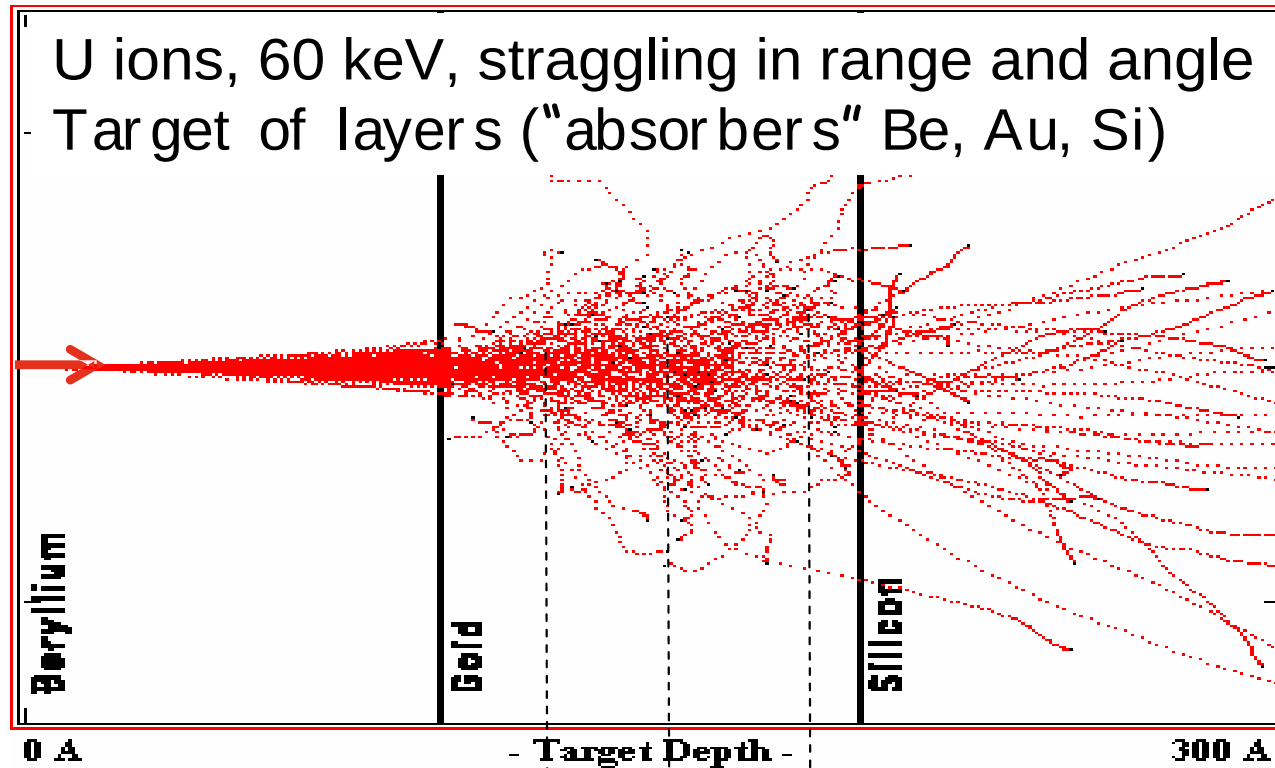
Collisions with nuclei :

$$\frac{\sigma_{nucl}}{\sigma_{atom}} \sim \frac{\pi R_{nucl}^2}{\pi a_Z^2} \sim \frac{Z^2 \cdot 10^{-26} \text{ cm}^2}{10^{-16} \text{ cm}^2} \sim Z^2 \cdot 10^{-10} \sim 10^{-6}$$

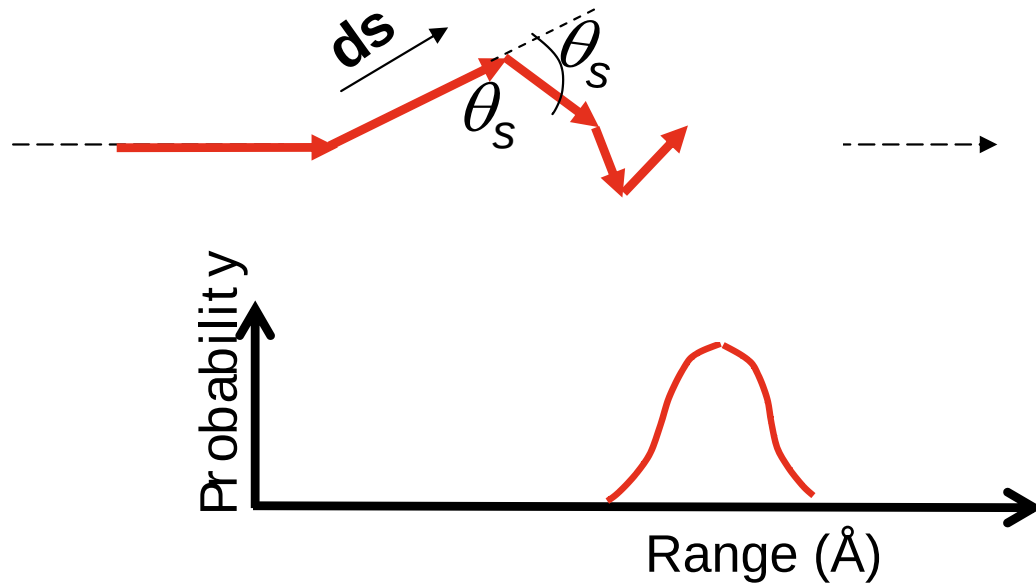
Most interactions of charged particles with material components occur with atomic electrons.

Nuclear collisions are noticeable only at low kinetic energies.

Multiple Scattering and Straggling



Range and Stopping Power



Scattering angle θ_s path variable s

Stochastic multiple scattering process produces straggling in range, energy loss, angle

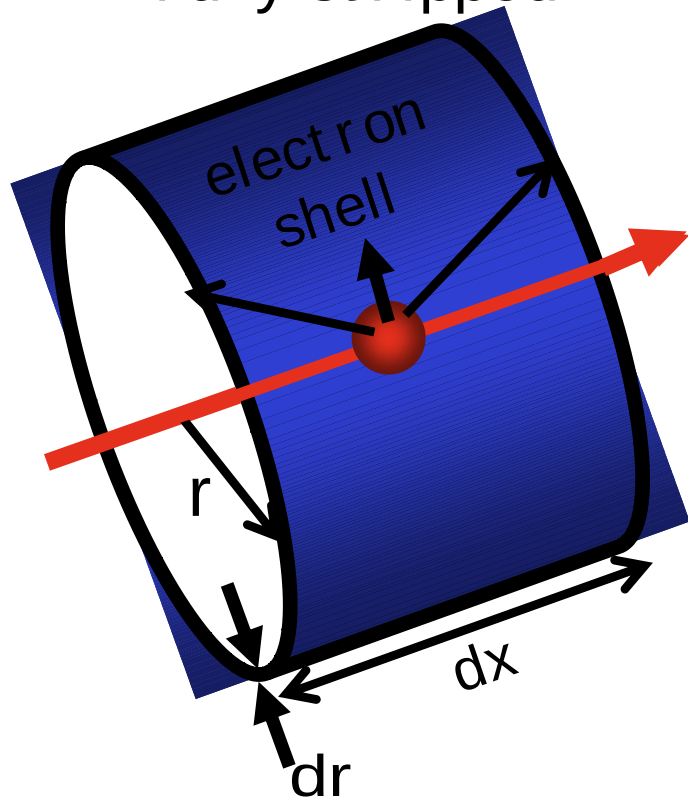
$$R(E) = \int ds \langle \cos \theta_s \rangle = \int_0^E dE' \left[\frac{dE'}{ds} \right]^{-1} \cdot \langle \cos \theta_s \rangle \quad \text{Range}$$

$$\left[\frac{dE}{ds} \right] \quad \text{Stopping power}$$

$$S(E) = \int ds \geq R(E) \quad \text{Path length of trajectory}$$

Phenomenological Model Of Energy Loss in Matter

Bethe et al. (1930-1953), Lindhardt's electron theory
Describes energy loss through ionization, incoming ions are fully stripped



Estimate of trends/ Order of magnitude

E = particle kinetic energy, $e^- \approx$ at rest

$$\Delta p_e = F_{Coul} \cdot \Delta t_{coll} \approx \left(\frac{e^2 Z_p}{r^2} \right) \cdot \left(\frac{2r}{v} \right)$$

$$-dE(r, x) \sim [2\pi r dr dx N_e] \cdot \left[\frac{(\Delta p_e)^2}{2m_e} \right]$$

$$-\frac{dE(r, x)}{dr dx} \sim \left[\frac{4\pi e^4 Z_p^2}{m_e v^2} N_e \right] \cdot \frac{1}{r}$$

Phenomenological Model Of Energy Loss in Matter

Integrate over radial coordinate:

$$\frac{dE(x)}{dx} = \int_{r_{min}}^{r_{max}} dr \frac{dE(r, x)}{dr dx}$$

$$-\frac{dE(x)}{dx} \sim \left[\frac{4\pi e^4 Z_p^2}{m_e v^2} N_e \right] \cdot \ln \left(\frac{r_{max}}{r_{min}} \right)$$

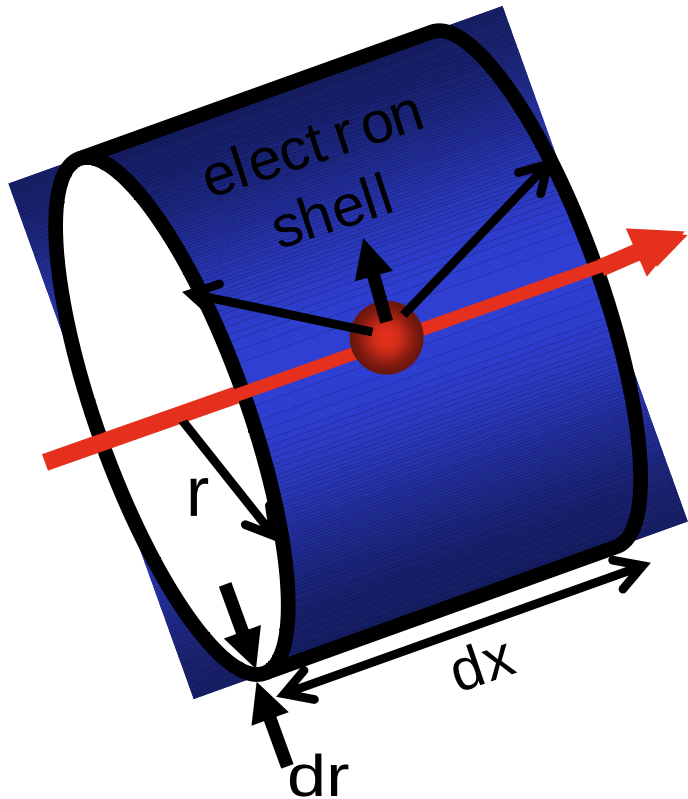
Estimate of radial limits: $N_e = e^-$ density
 $\lambda_e =$ electronic wavelength,
 $I E =$ ionization energy

$$r_{min} \geq \lambda_e = h / p_e = h \sqrt{1 - \beta^2} / m_e v$$

non-adiabatic motion

$$r_{max} / v \leq \Delta t_{coll} = T_e / \sqrt{1 - \beta^2} = 1 / \left[\sqrt{1 - \beta^2} \langle \nu_e \rangle \right]$$

$$\langle \nu_e \rangle = I E / h = \text{average } e^- \text{ orbital frequency}$$



Phenomenological Model Of Energy Loss in Matter

Further:
$$-\frac{dE}{dx} \sim \left[\frac{4\pi e^4 Z_p^2}{m_e v^2} N_e \right] \cdot \ln \left(\frac{2m_e v^2}{h \langle v_e \rangle (1 - \beta^2)} \right)$$

Insert: ρ = atomic density, Z_T = atomic number of target

$$N_e = Z_T \cdot \rho$$

$$-\frac{1}{\rho} \frac{dE}{dx} \approx 4\pi \frac{e^4 Z_p^2}{m_e v^2} Z_T \ln \left(\frac{2m_e v^2}{IE (1 - \beta^2)} \right)$$

$$IE = h \langle v_e \rangle \approx \begin{cases} (12 \cdot Z_T + 7) \text{ eV} & \text{for } Z_T < 13 \\ (9.76 \cdot Z_T + 58.8 \cdot Z_T^{-0.19}) \text{ eV} & \text{for } Z_T \geq 13 \end{cases}$$

Bethe-Bloch Equation

Quantum mechanical calculation (for heavy particles $M \gg m_e$):

$$-\frac{1}{\rho} \frac{dE}{dx} \approx 0.1535 \frac{Z_p^2}{\beta^2} \frac{Z_T}{A_T} \left[\ln \left(\frac{2m_e c^2}{IE(1-\beta^2)} \right)^2 - 2\beta^2 \right] \frac{\text{MeV}}{\text{g/cm}^2}$$

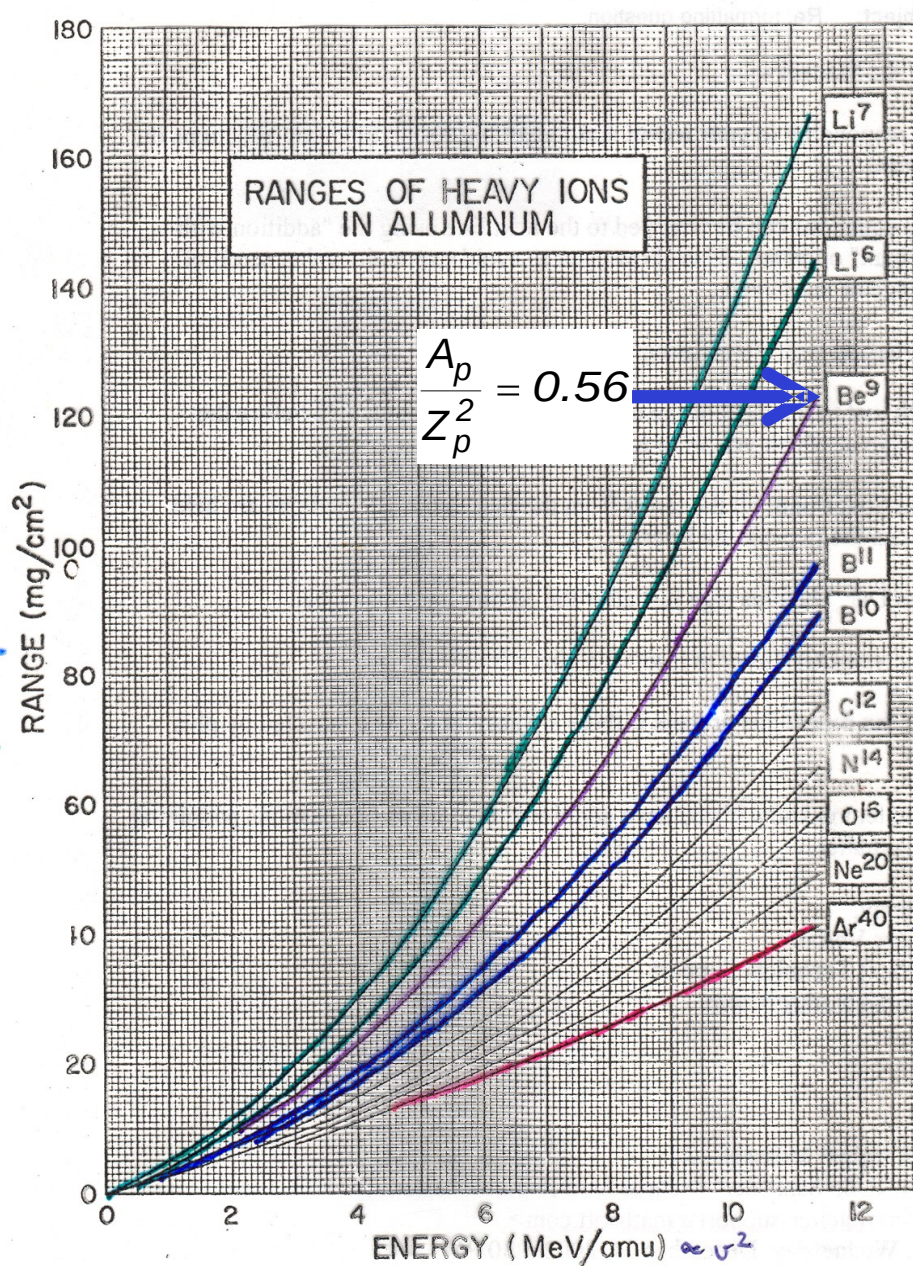
ρ = atomic density

Z_T = atomic number of target

A_T = mass number of target

$$IE = h \langle v_e \rangle \approx \begin{cases} (12 \cdot Z_T + 7) \text{ eV} & \text{for } Z_T < 13 \\ (9.76 \cdot Z_T + 58.8 \cdot Z_T^{-0.19}) \text{ eV} & \text{for } Z_T \geq 13 \end{cases}$$

Stopping Power Isotopic Scaling Laws



$$\frac{dE}{dx} = \frac{d(m_p v^2 / 2)}{dx} = Z_p \cdot f\left(\frac{E}{A_p}\right)$$

$$\frac{dv}{dx} = \left(\frac{Z_p^2}{A_p}\right) \cdot g(v) \rightarrow$$

$$R(v) \approx \int dv \left(\frac{dv}{dx}\right)^{-1} \approx \left(\frac{A_p}{Z_p^2}\right) \cdot h(v)$$

Describes well the difference of R for different isotopes of a given element, but:

$$\frac{A_p}{Z_p^2} = 0.12$$

$$R(\text{Be})/R(\text{Ar}) = 2.97 \text{ expt } 4.67 \text{ theo}$$

$Z_{\text{eff}} \neq Z_p$ effective charge



End of Part 1

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