Week 2: Chap. 2 Interaction of Radiation

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Introduction
-- Goals, roll back the fog
-- General Nomenclature
-- Decay Equations
-- Laboratory Sources

Interaction of Radiation with Matter
-- Charged Particles
--- heavy
--- electrons
--Gamma Rays
-- Neutrons

Vacuum Technology

Chap. 2 Interaction of Radiation with Matter

Classes of Radiation to consider

Mass →

Electromagnetic

Coulombic

Charge ↓

Gamma Rays		Neutrons	(Atoms)
	Electrons +/-	Protons +	Heavy ions (1+)
			Nuclear Ions (q+)

Neutrons are special, only interact with nuclei (save for last). Nuclear

Others interact *primarily* with electrons. The Coulomb interaction is long-ranged so the slowing down of the *charged particles* is most effective and is a continuous process. The electromagnetic interaction requires a “collision” of a photon and electron and leads to a discrete stopping process. Similarly, interactions of neutrons with nuclei are clearly “collisions” and thus are discrete.

E.g, solid Silicon:

Aside on Target Materials

Areal density or surface density, ρ_A: a way to describe very thin foils, literally the mass per unit area of a thin material. The areal density is the mass per unit AREA. The linear "thickness" is simply the Areal-density divided by the mass-density. E.g.,

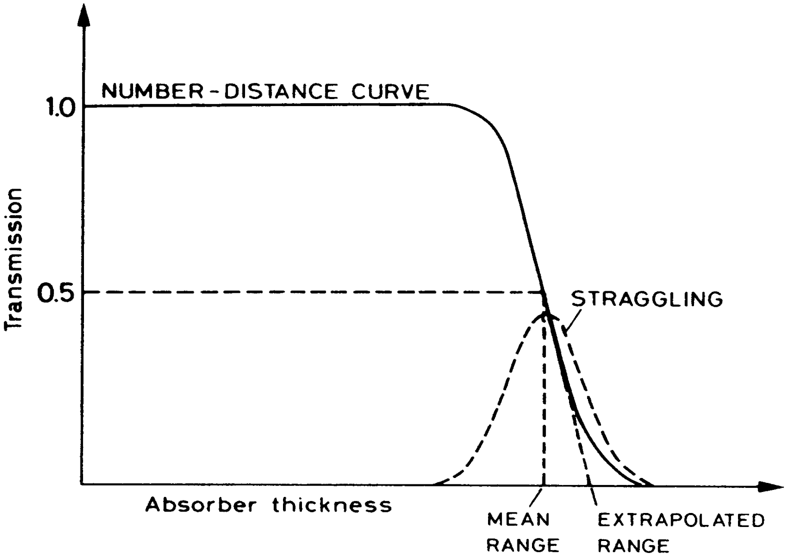
$$`\rho_A' = mass\ /\ area$$

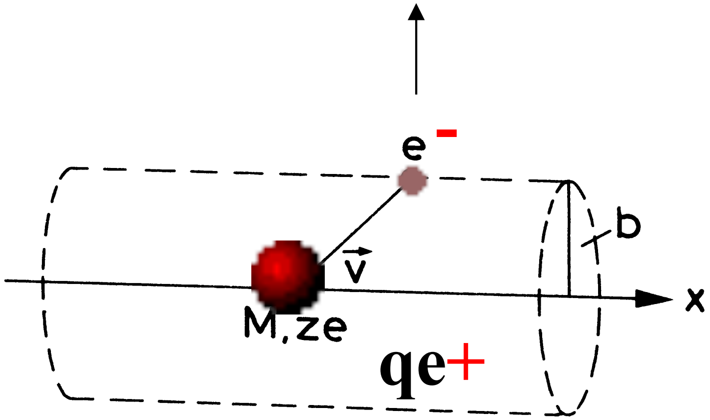
Gold foil:

Element	Atomic Number	Density (g/cm³)	Atomic Mass (g/mol)	ρ_N (N_A/cm^3)	$\rho_e = Z\rho_N$ (N_A/cm^3)
Beryllium	4	1.85	9.0122	0.205	0.821
Aluminum	13	2.70	26.98	0.10	1.3
Silver	47	10.5	107.88	0.0973	4.6
Gold	79	19.3	197.0	0.0980	7.7

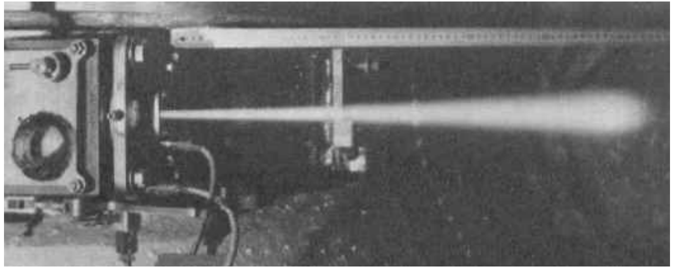
Interaction of massive C.P. with Matter –1–

“Massive” particles moving through material can be expected to interact with the electrons but the very large ratio of masses ($m_p/m_e \sim 1836$) means that the ions will travel on essentially straight lines until the end, continuously slowing down, and finally stop at some point after a huge number of interactions.





[What’s wrong with this picture of collision?]



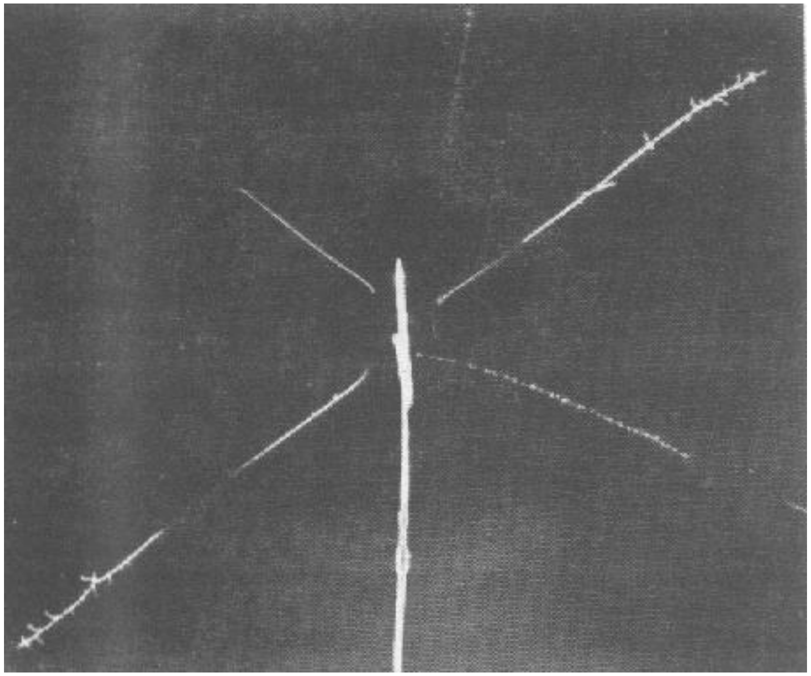
Deuterons in air from:
A.K. Solomon, "Why Smash Atoms?" (1959)

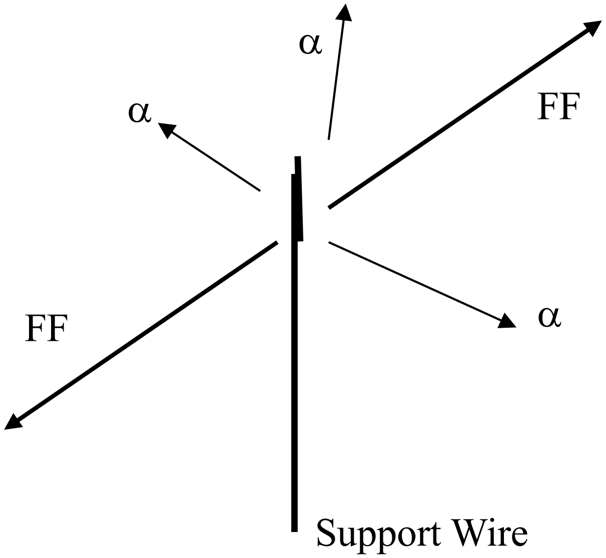
Expect that the ion <u>intensity</u> remains essentially constant with depth until the end of the range when the ions all come to rest. On the other hand the kinetic energy of the ion will drop continuously in tiny increments until it stops. In a single collision the energy lost:

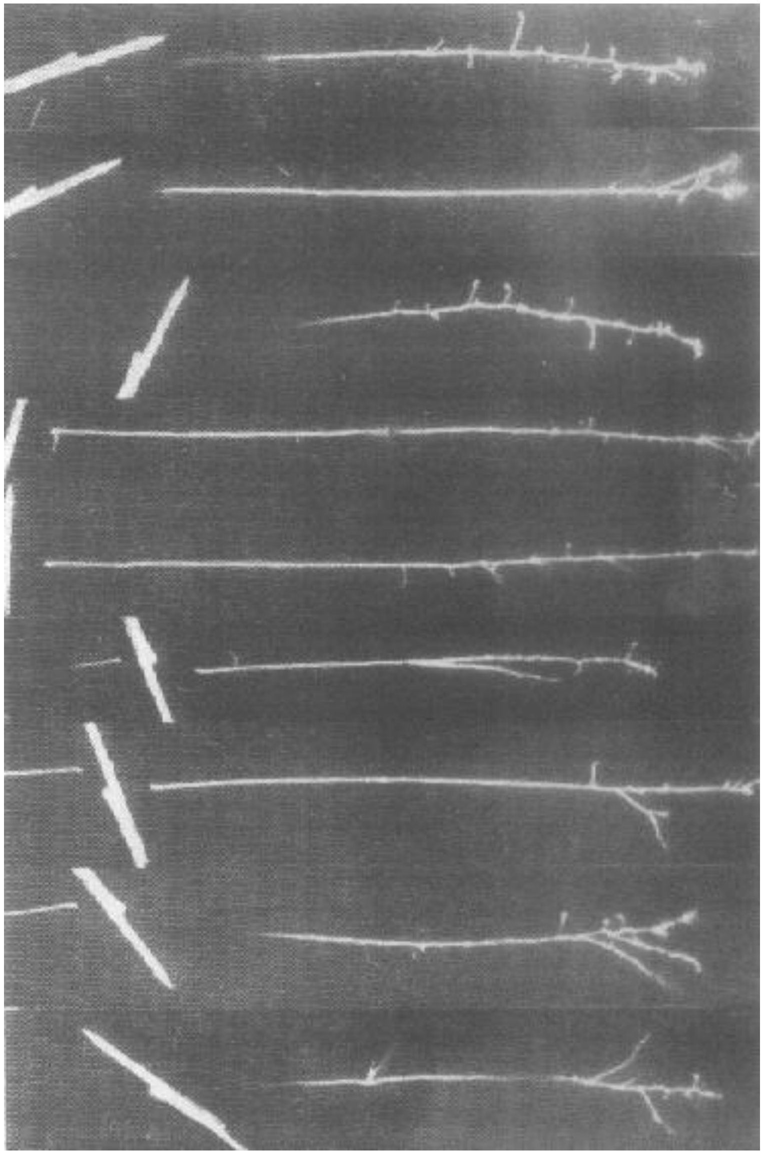
$\Delta E(b) = [\ \text{Impulse}(b)\ ]^2 / m_e$, b impact parameter

Cloud Chamber Images of ^{252}Cf source

Recall this nuclide: 97% alpha emission, 3% spontaneous fission







From: http://www.lateralscience.co.uk/cloud/diff.html

Interaction of massive C.P. with Matter –2–

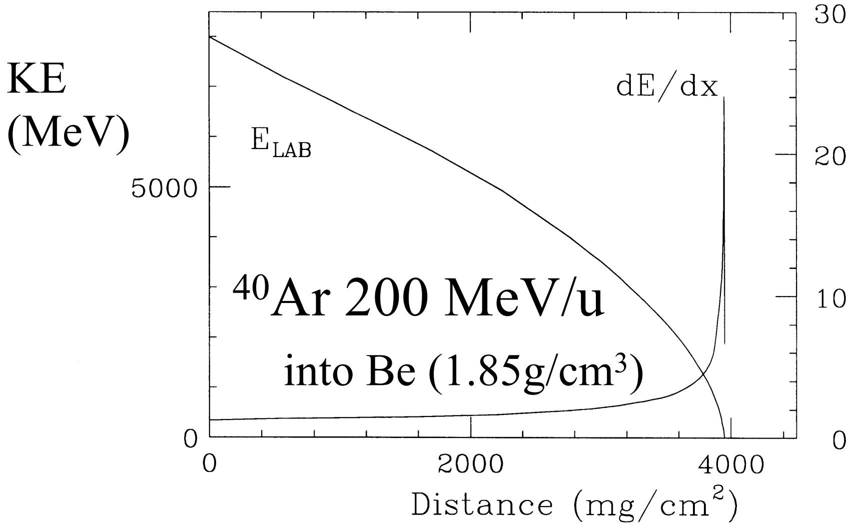
Rate of energy loss, dE/dx, for a heavy charged particle is called the *stopping power* and it is made of three contributions. The electronic stopping is the most important, the nuclear reaction part is generally very small, and the nuclear-atomic part is only important at the end of the range (misnomer in my opinion).

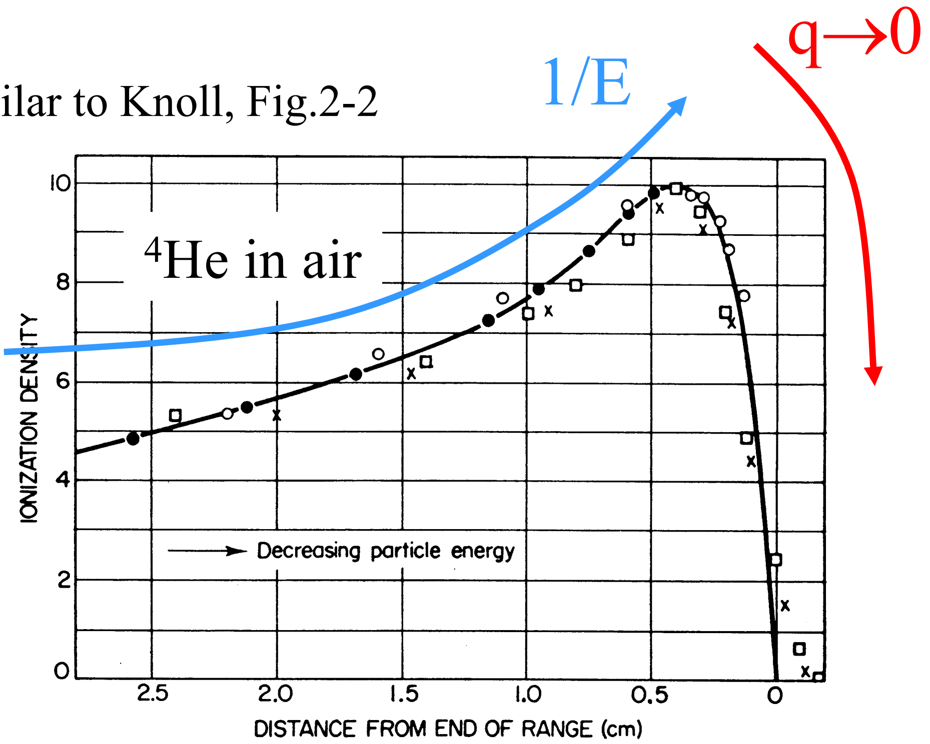
$$\frac{-dE}{dx} = S_{electronic} + S_{\substack{nuclear\\reaction}} + S_{\substack{nuclear\\atomic}}$$

Bethe-Bloch Eq.

$$\frac{-dE}{dx} = \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \frac{4\pi}{m_e}\left(\frac{q^2}{v^2}\right) Z_{Tar}\rho_{Tar}\left(\ln\left[\frac{2m_e c^2\beta^2}{I_{Tar}}\right] - \ln[1-\beta^2] - \beta^2\right)$$

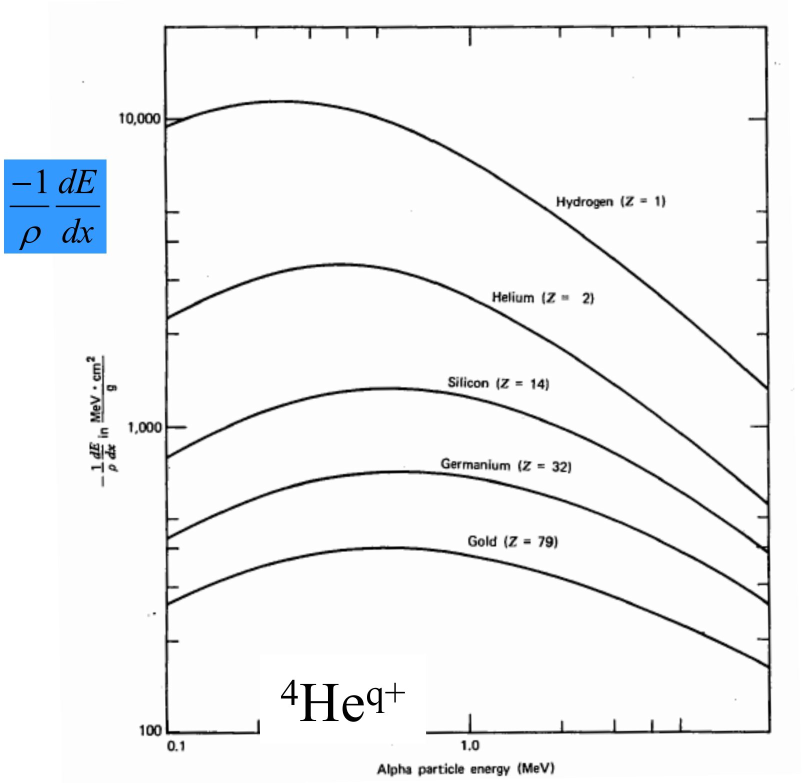
$$\frac{-dE}{dx} \propto K\frac{Aq^2}{KE}$$



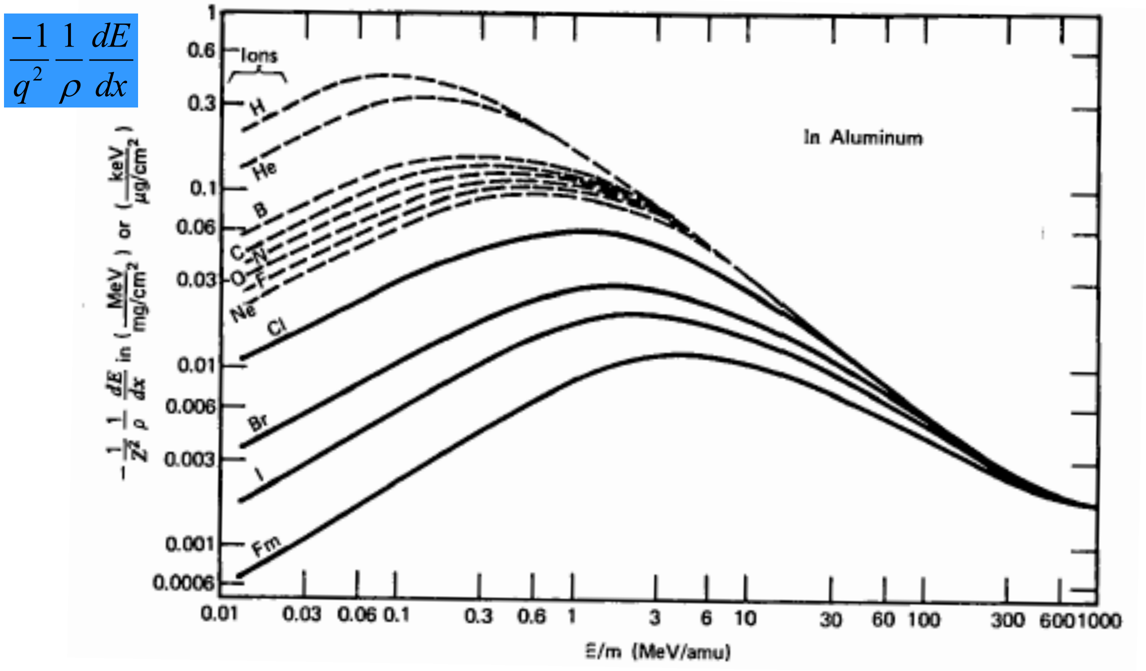

Similar to Knoll, Fig.2-2

Interaction of massive C.P. with Matter –3–

Knoll, Fig.2-10, one ion in various materials



Knoll, Fig.2-11, various ions in one material



There are a large number of sources of dE/dx values for heavy charged particles in the literature and included in computer calculations.

TABULAR: Nucl. Data Tables A7 (1970) 233
Ziegler et al. “The Stopping Power and Ranges of Ions in Matter” Vol. 1, SRIM/ SRT
MONTE CARLO: TRIM, http://www.srim.org/index.htm
ANALYTICAL: ATIMA in LISE++, http://groups.nscl.msu.edu/lise/lise.html

Interaction of massive C.P. with Matter –4–

The charge state of an ion moving through a medium will depend on the kinetic energy of the ion. In the simplest approximation a fully-stripped ion will be able to capture electrons from the medium when the slowing ion's velocity approaches the Bohr velocity for a K-electron (fastest) in that element.

$$v_{Bohr}(n) = \frac{Z e^2}{4\pi\varepsilon_0 \; n\hbar}$$

Where n is the principal Quantum Number

$$\beta_{Bohr}(n) = \frac{Z}{n\alpha} = \frac{Z}{n}\frac{1.439 MeV\ fm}{197.5 MeV\ fm} = \frac{Z}{n}0.0729$$

N.B. non relativistic β

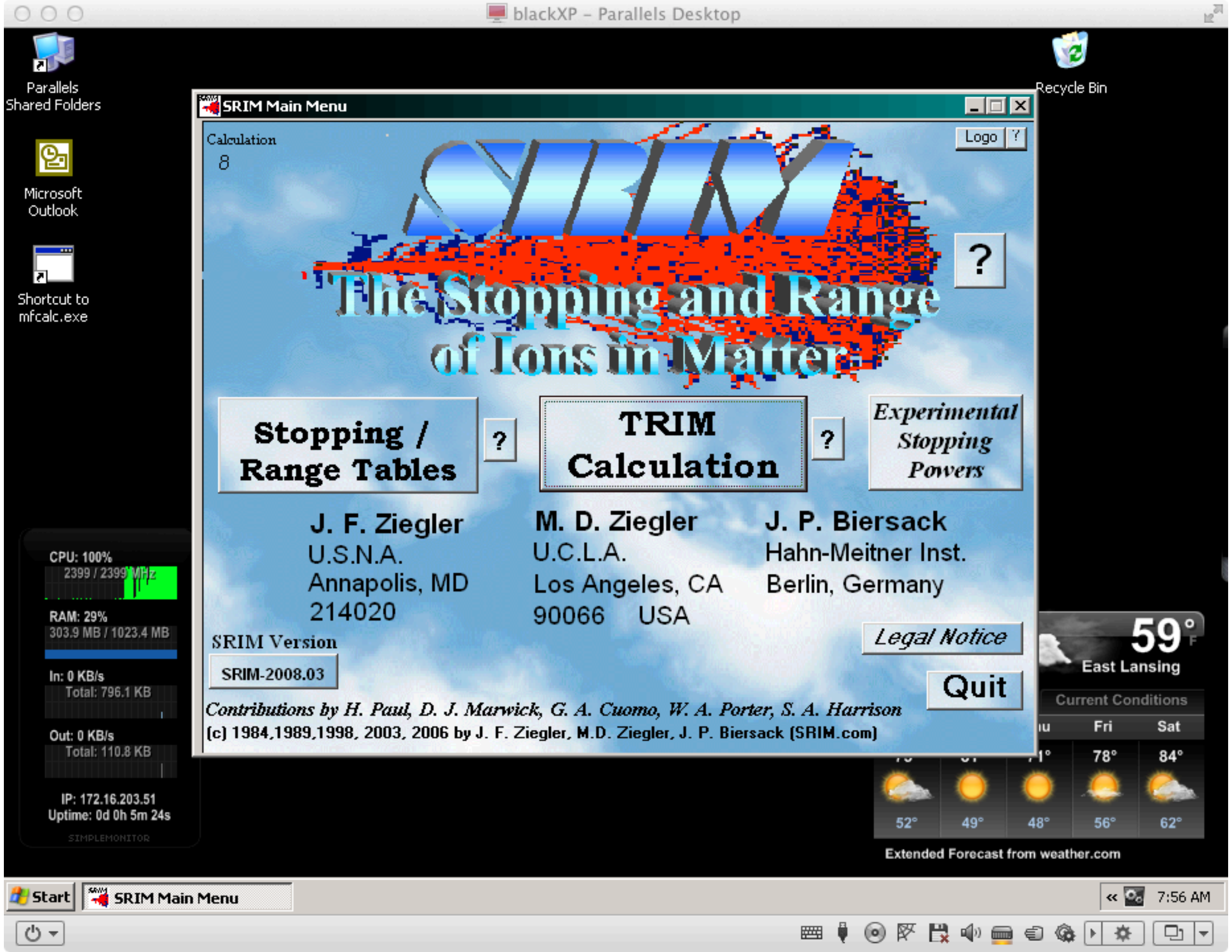
There are empirical expressions for the "equilibrium charge state" of a moving ion based on measurements, e.g.,
Winger, et al. NIM B142 (1998) 441; NIM B70 (1992) 380
Leon, et al. AD&ND Tables 69 (1998) 217
Schiwietz & Grande, NIM B175 (2001) 125

Codes for "high energy ions"
CHARGE – Scheidenberger, et al. NIM B142 (98) 441
GLOBAL – Meyerhof (loc. cit.)
ETACHA – Rozet, et al. NIM B107 (1996) 67

Interaction of massive C.P. with Matter –4a–

Example Calculation: SRIM, http://www.srim.org/index.htm

1) Stopping and Range Tables → SRT
2) Transport of Ions in Material → TRIM



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Contributions by H. Paul, D. J. Marwick, G. A. Cuomo, W. A. Porter, S. A. Harrison
(c) 1984,1989,1998, 2003, 2006 by J. F. Ziegler, M.D. Ziegler, J. P. Biersack (SRIM.com)

Interaction of e' s with Matter –1–

Rate of energy loss, dE/dx, for fast electrons (+ or -) is made of only two terms. The electronic stopping is the most important, the second term is a radiative term due to Bremsstrahlung that is important for high energies and high Z materials. The electronic term is similar to the Bethe-Bloch formula but the experimental situation for e- is complicated due to scattering by identical particles and the fact that the electrons are usually relativistic ($m_e c^2 = 0.511$ MeV).

$$\left(\frac{-dE}{dx}\right)_e = S_{electronic} + S_{radiative}$$

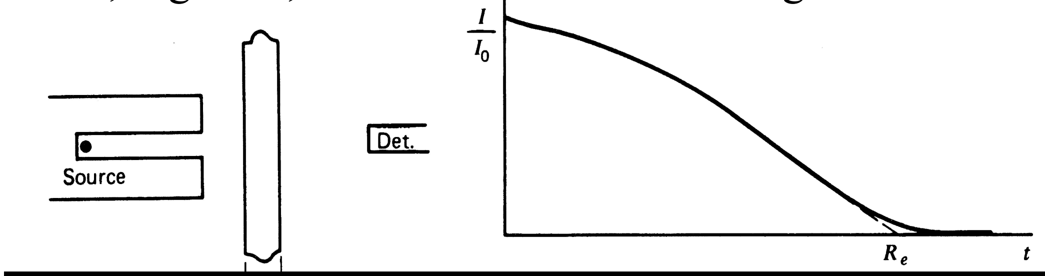
$$\frac{S_{radiative}}{S_{electronic}} \approx \frac{T + m_e c^2}{m_e c^2} \frac{Z}{1600} \rightarrow \frac{3Z}{1600} \; at \; T = 1 \; MeV$$

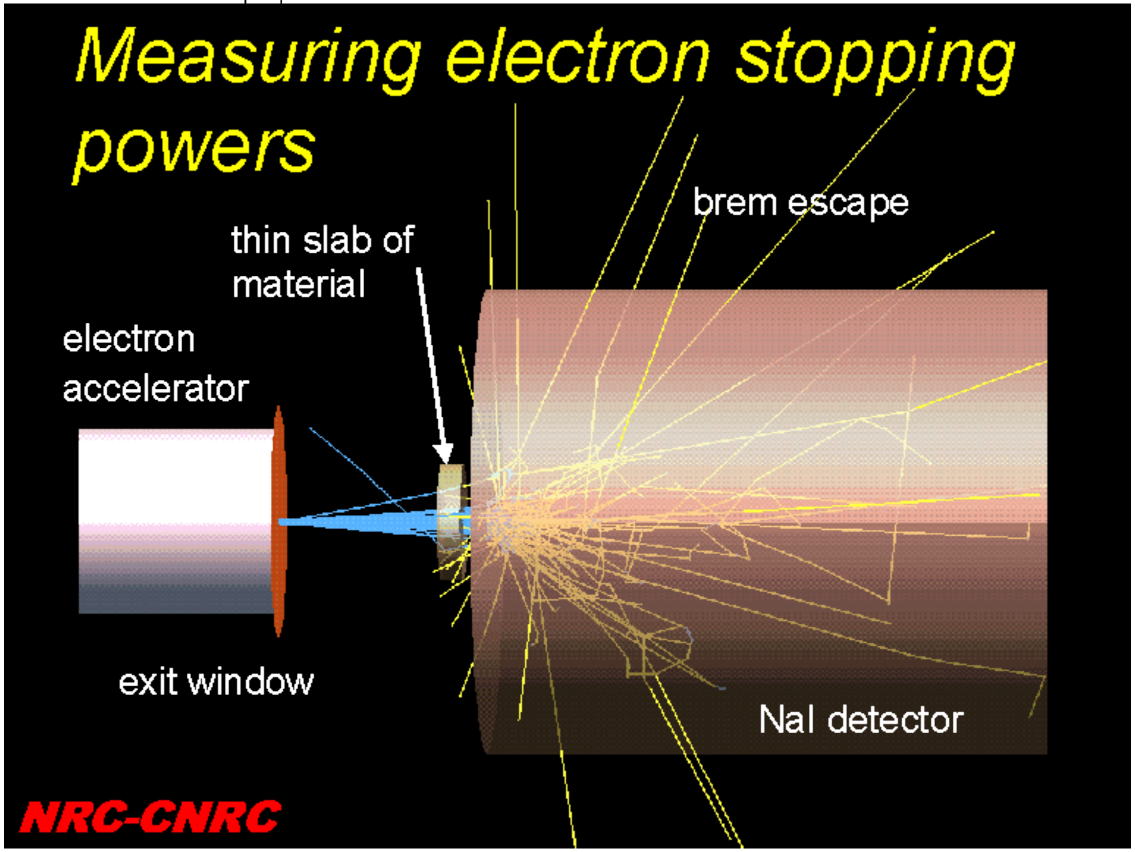
$$\frac{S_{radiative}}{S_{electronic}} \approx \frac{TZ}{700}$$

Interaction of e’ s with Matter –2–

Monoenergetic electrons do not have a sharp range distribution

Knoll, Fig.2-13, transmission of monoenergetic electrons





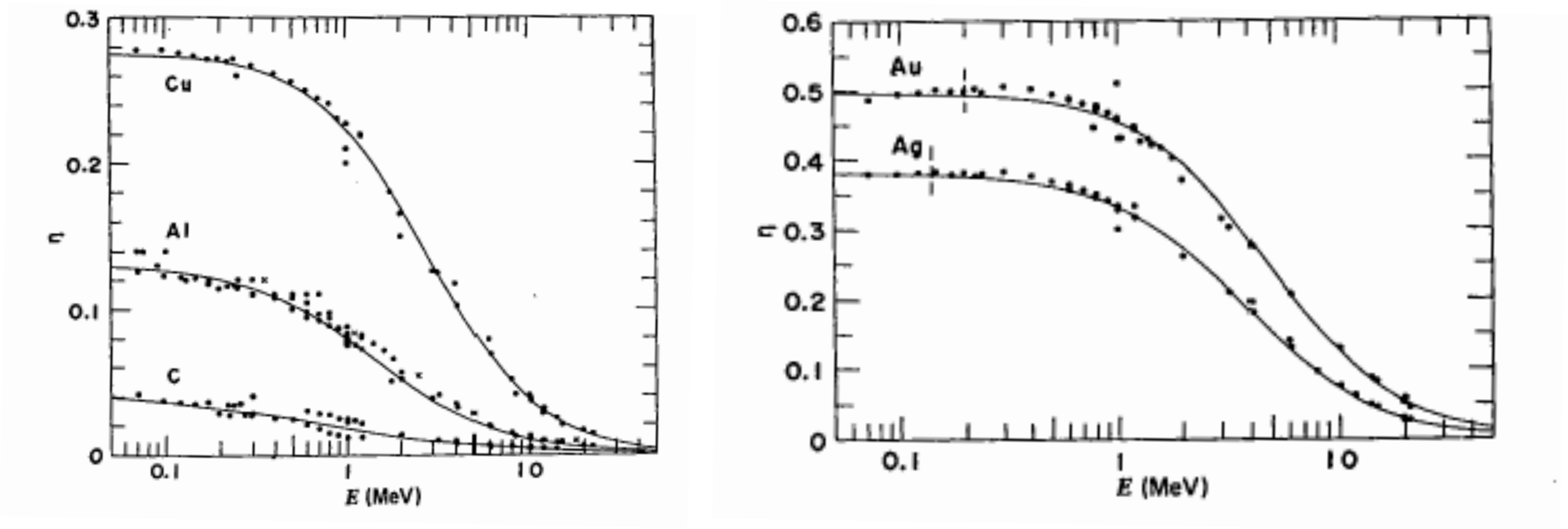
N.B. the range distribution for a beta source will be approximately exponential due to the folding of the Fermi intensity distribution with the range distribution.

The “range distribution” of a monoenegetic electron beam is not simple due to the large angle scattering possible between identical particles.

Rogers et al., Med Phys 22 (1995) 503

Interaction of e' s with Matter –3–

Backscattering: energetic electrons can be scattered to large angles by massive target nuclei due to the high q/m ratio of the electrons.



Knoll, Fig.2-17, fraction of energetic electrons backscattering from a material

Modern calculations of electron "ranges" are performed with Monte Carlo codes such as "EGS" (Electron Gamma Showers) that was started at SLAC and taken over by the NRC in Canada, now called EGSnrc:

http://www.irs.inms.nrc.ca/EGSnrc/EGSnrc.html

http://www.nrc-cnrc.gc.ca/eng/solutions/advisory/egsnrc_index.html

Interaction of Photons with Matter –1–

A beam of photons passes through material until each undergoes a collision, at random, and is removed from the beam. Thus, the intensity of the beam will continuously drop as the beam propagates through the medium but the energy of the photons will remain constant. This degradation of the beam follows the Beer-Lambert exponential attenuation law:

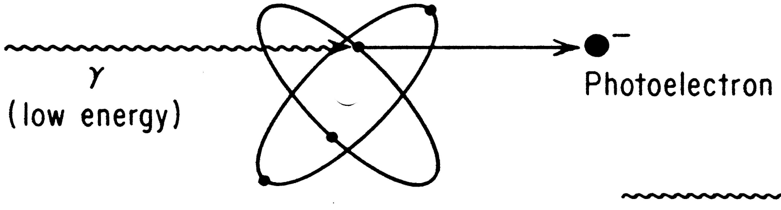
$$I = I_0 \, e^{-\mu x} \qquad \mu = {}^{1}\!/\!_{\lambda}$$

μ attenuation coefficient; λ mean free-path

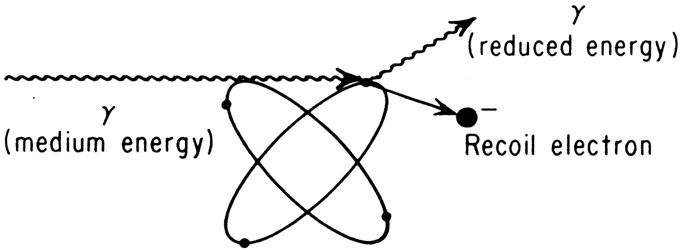
http://physics.nist.gov/PhysRefData/XrayMassCoef/cover.html

Three interaction processes:

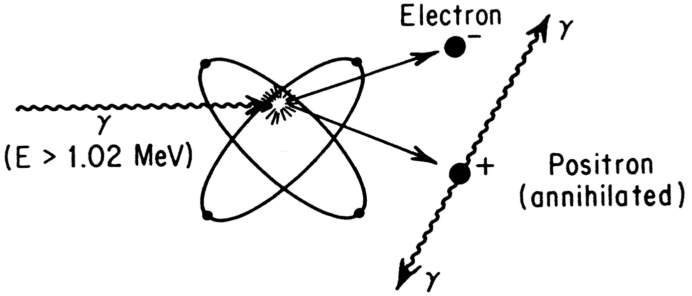
Photoelectric Effect



Compton Scattering



Pair-production

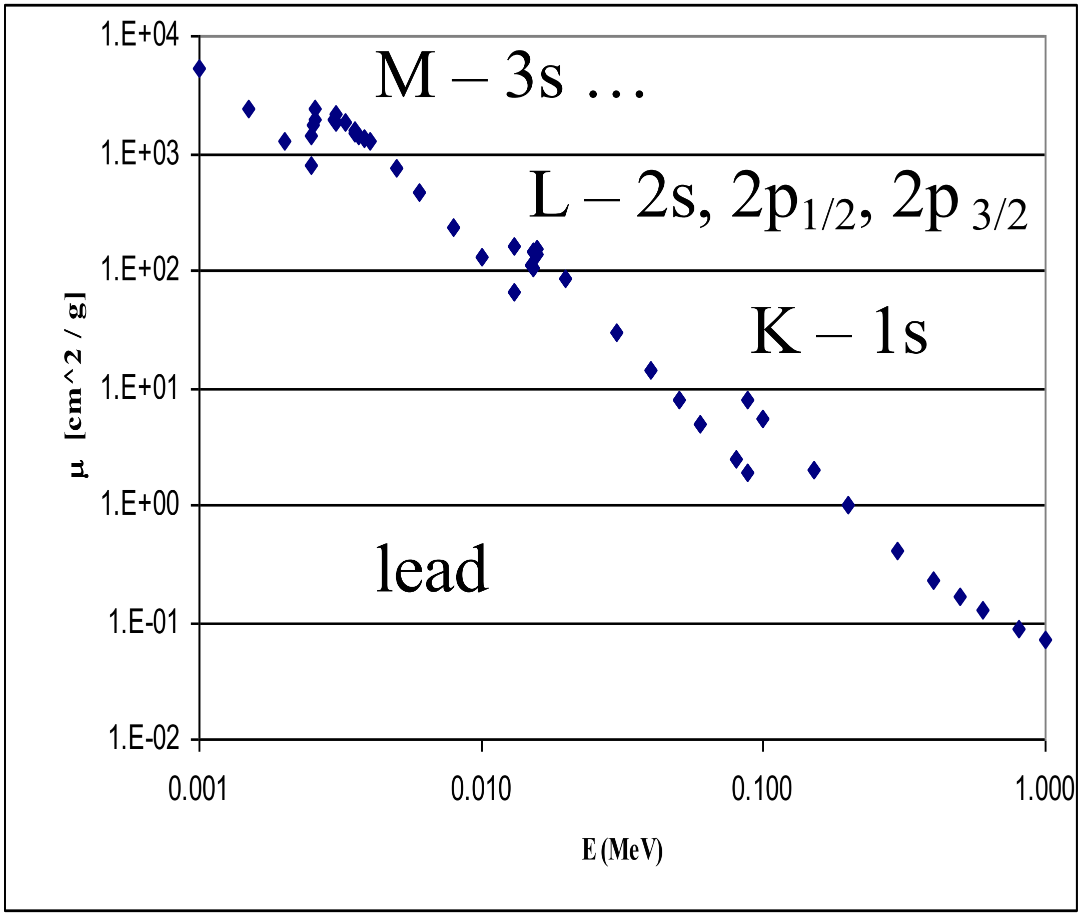


Interaction of Photons with Matter –2–

Photoelectric Effect: process originally described by Einstein, most efficient conversion of photon into a moving electron. [Electron then goes on to ionize the medium as just discussed.] Atomic scale (square angstrom) cross sections that decrease sharply with photon energy with steps at the electron shell energies.

PE effect generates
One electron with:
$E_e = h\nu - BE_e$

"Edges" in data due to a threshold at each electron shell.



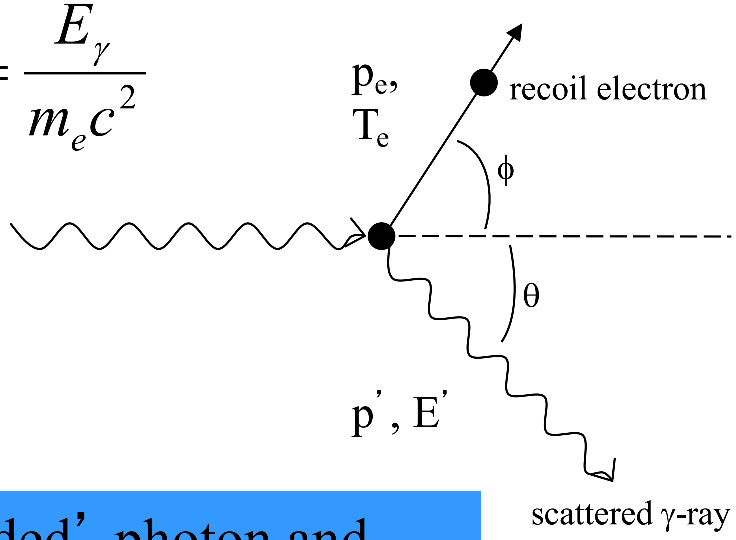
Interaction of Photons with Matter –3–

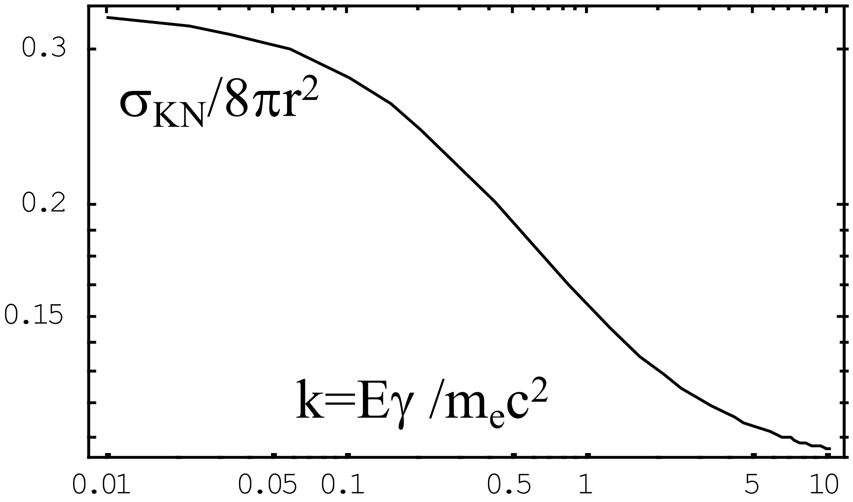
Compton Scattering: scattering of a photon by a (free) electron that leads to a moving electron *and* a lower energy photon. The two-body scattering leads to a correlation between angle and electron kinetic energy. The total cross section for the scattering is given by the Klein-Nisihna formula:

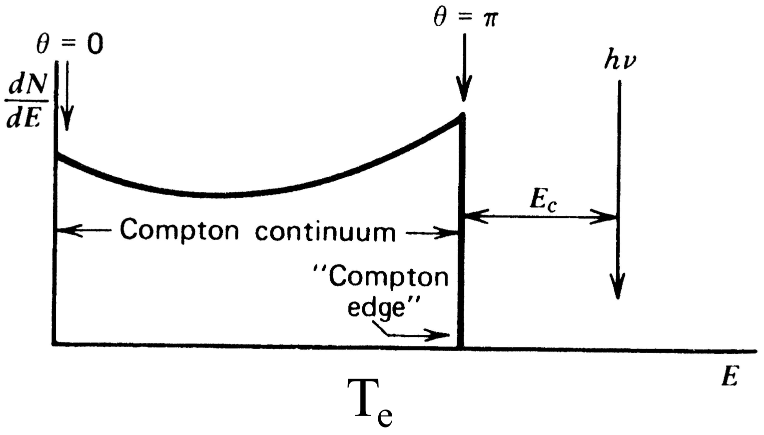
$$\sigma_{KN} \cong 8\pi r_e^2 \frac{1+2k+1.2k^2}{3(1+2k)^2}$$

$$r_e = \frac{e^2}{m_e c^2} = 2.818x10^{-15} m$$

$$k = \frac{E_\gamma}{m_e c^2}$$





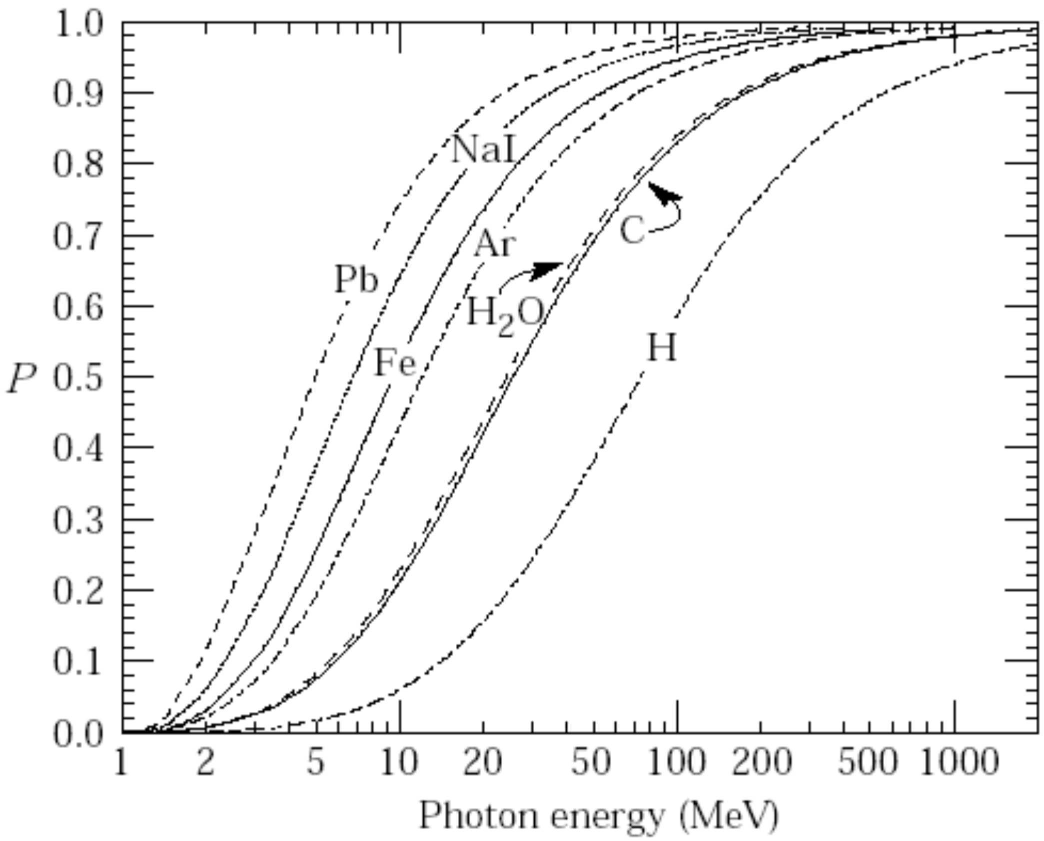


'Degraded' photon and one moving electron.

Interaction of Photons with Matter –4–

Pair production: $E_\gamma > 1.022$ MeV, the conversion of a photon into a matter/antimatter pair of electrons in the presence of a nucleus (or an electron). The process generally depends on the Z^2 of the medium and grows with photon energy. The two moving electrons share the remainder of the initial photon energy. Eventually the positron annihilates at the end of its range giving two 511 keV photons.

Probability of conversion, to be multiplied by a geometric cross section.



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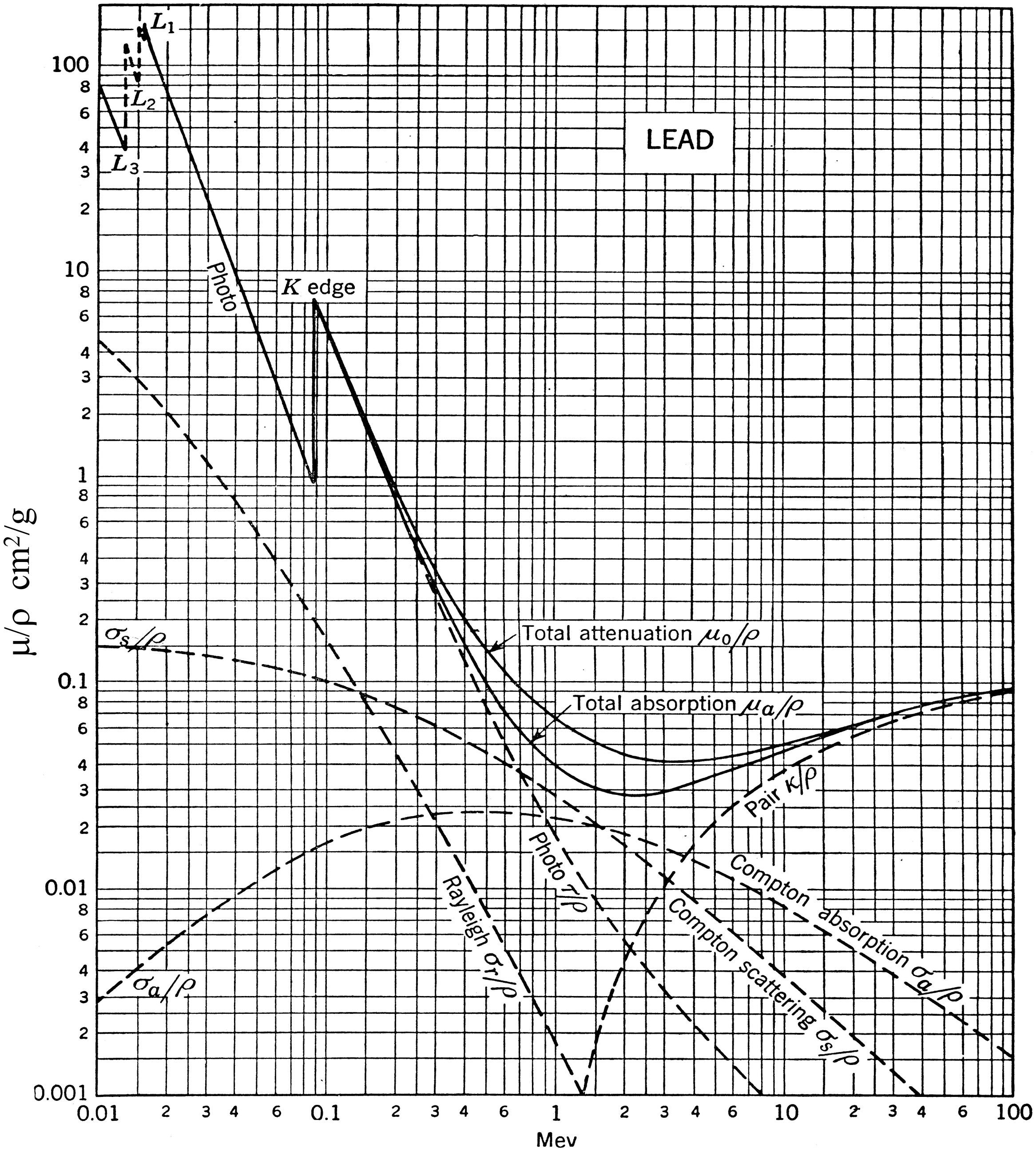
Interaction of Photons with Matter –5–

The full-deal:
μ/ρ mass-attenuation coefficient from <u>*The Atomic Nucleus*</u> by R.Evans

Overall, the photon beam is converted into a variety of fast electrons.



Interaction of Neutrons with Matter –1–

A beam of neutrons passes through material until each undergoes a collision at random and is removed from the beam. In contrast to photons, the neutrons are ‘scattered’ by nuclei and usually only leave a portion of their energy in the medium until they are very slow and then are absorbed by a nucleus. Thus, the intensity of the beam will continuously drop as the beam propagates through the medium and the mean kinetic energy of the neutrons will also generally decrease. The degradation of the beam intensity follows the Beer-Lambert exponential attenuation law and will be characterized by an attenuation coefficient.

$$I = I_0\, e^{-\mu x} \qquad \mu = {}^{1}\!/_{\lambda} = 1 / N_0 \sigma_{Total}$$

Hierarchical List of neutron reactions:

A(n,γ) A+1 – radiative capture
A(n,n) A – elastic scattering
A(n,n’) A* – inelastic scattering
A(n, 2n) A-1 – “nuclear reaction”
A(n,p) A(Z-1)   A(n,np)A-1(Z-1)   etc.
A(n,α)
A(n,f)

Note that the H(n,n)H produces a recoil proton

Interaction of Neutrons with Matter –2–

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Neutron reaction cross sections have a characteristic shape, one or more Breit-Wigner resonances and then a 1/v dependence at the lowest energies. [More on this later!]

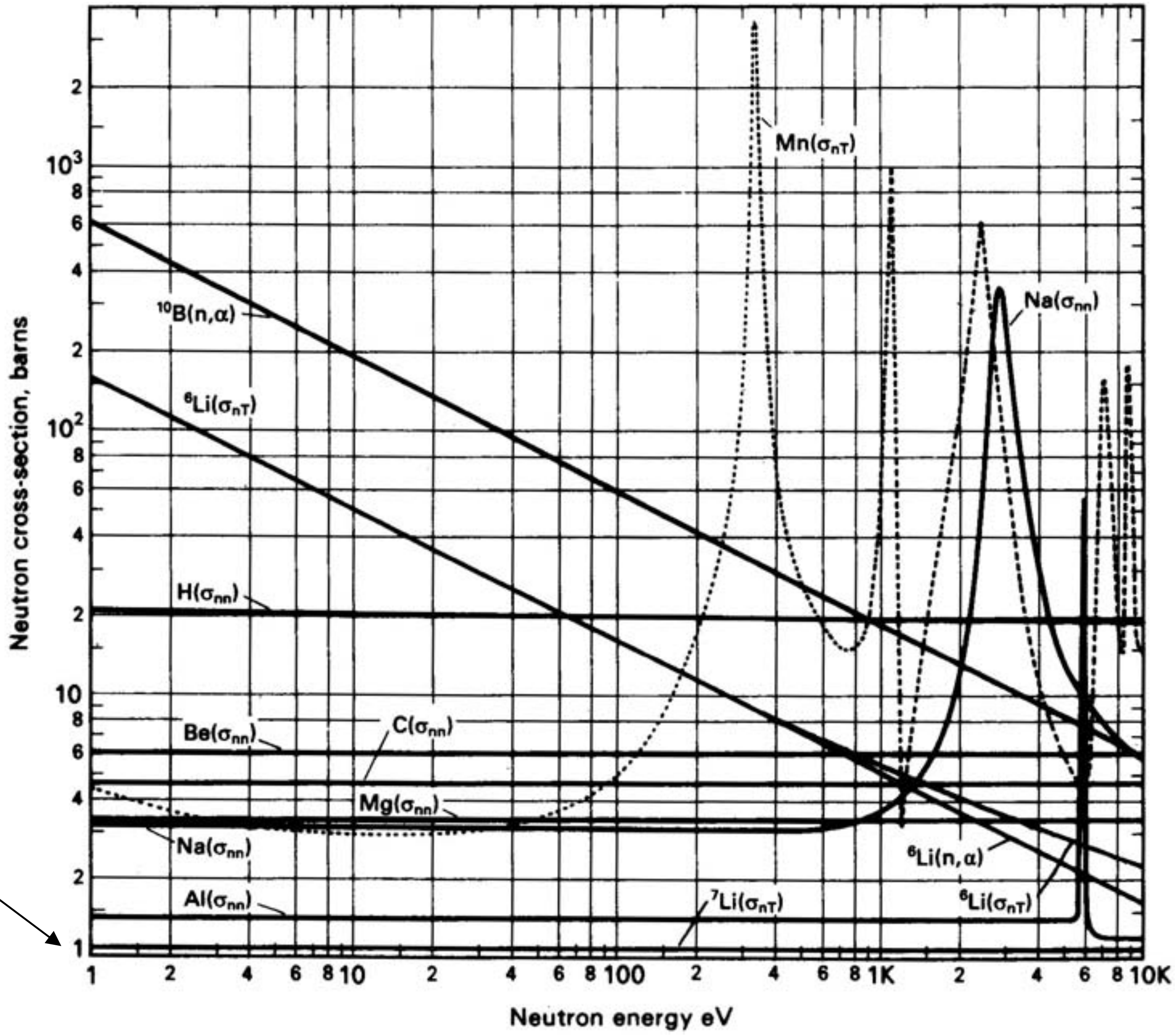
Barn – historical unit
1 barn = 100 fm^2

$\sigma_{geo} = \pi r^2$
$r = r_0 A^{1/3}$ $r_0 \sim 1.3$ fm

$\sigma_{geo} = \pi (1.3 A^{1/3})^2$

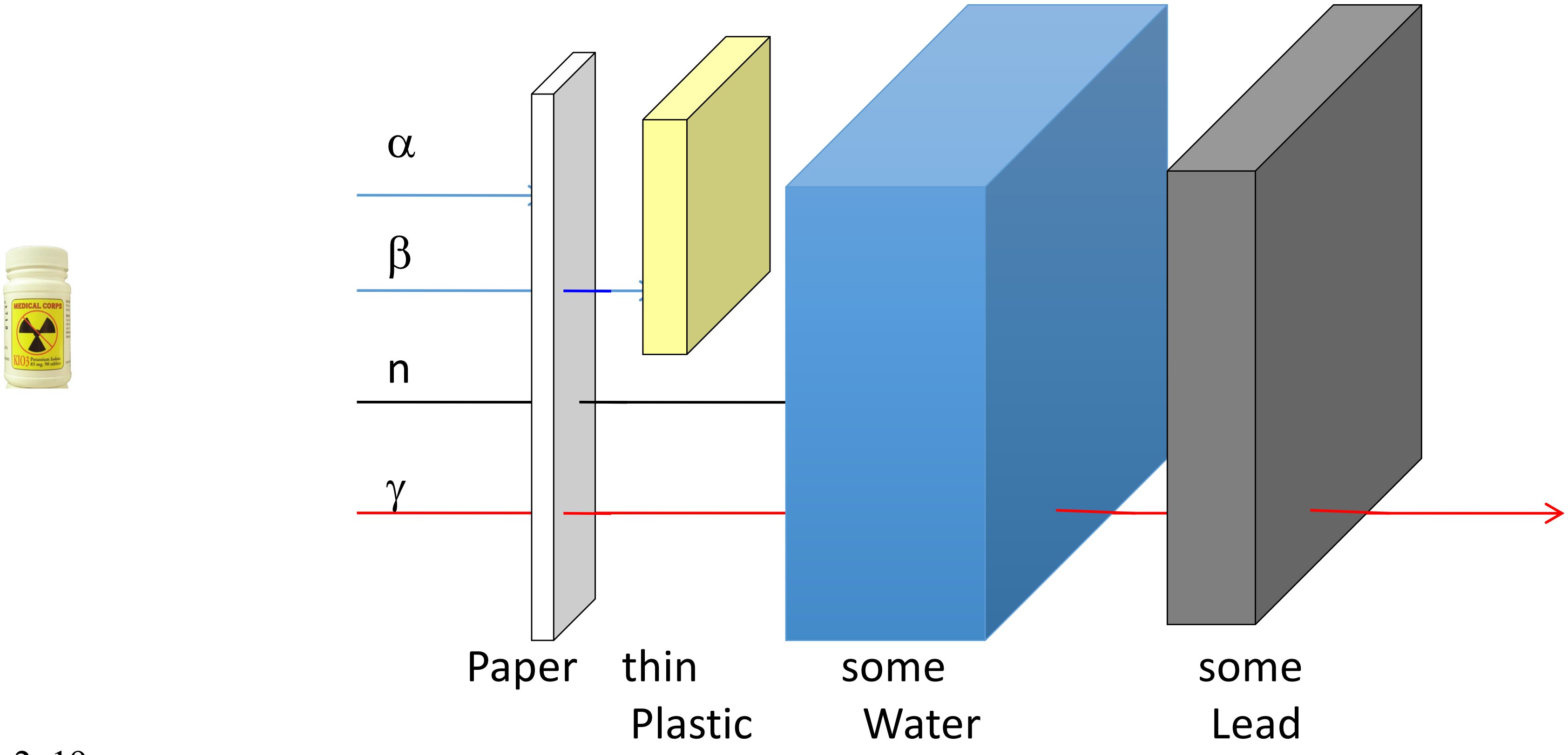
$\sigma_{geo} = 5.3 A^{2/3}$ fm^2

A =80, $\sigma_{geo} = 99$ fm^2



Interaction of Radiation with Matter

Radiation	Primary Scatter-ers	Range	Intensity	Energy
Alpha	Electrons	Definite	Constant	Drops slowly
Beta	Electrons	End-point	Decreases	Drops rapidly
Neutron	Nuclei	Exponential	Exponential	Drops to thermal
Gamma	Electrons	Exponential	Exponential	Constant



Interaction of Radiation with Matter

Classes of Radiation to consider

Electromagnetic

Coulombic

Gamma rays	Neutrons
Electrons +/-	Nuclei & Heavy Charged Particles

Nuclear