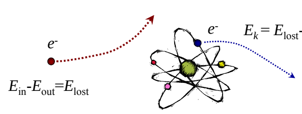
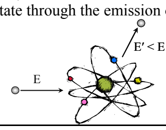
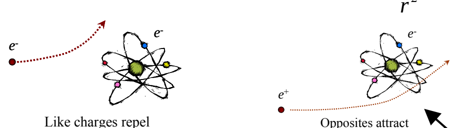
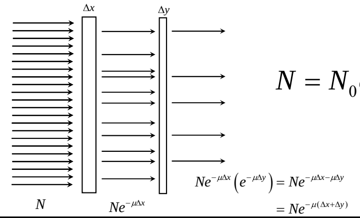
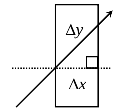
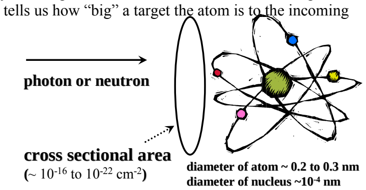
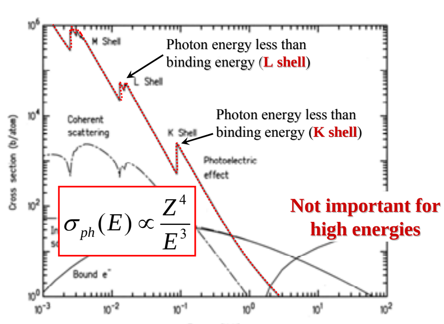
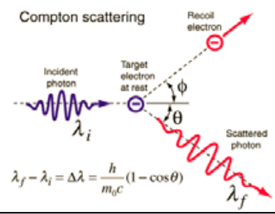
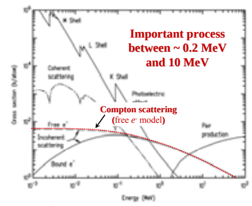
Term	*Definitions*
Ionization	Ionization is a process whereby one or more electrons are liberated from an atom; Atomic number and mass number stays the same; Atom becomes positively charged (because *e-* is removed). Orbital electron is removed from atom… Electron-ion pair is created (~ 10 to 100 eV required)
Excitation	Orbital electron "jump" from a lower to higher orbit.; As electrons jump back to ground state, energy is translated to heat (e.g., vibrational, rotational motion) or photons
Directly Ionizing	*Directly ionizing* (*charged particles*): interactions produce ionization and excitation of the medium (charged particles)…alpha particles, beta particles, fission fragments
Indirectly Ionizing	*Indirectly ionizing* (*photons and neutrons*): interactions produce secondary charged particles that ionize matter… x-rays, gamma-rays, neutrons
Particle Interactions	Interactions of neutral particles with matter are dominated by short-range forces; Neutral particles travel relatively large distances in straight lines and then interact (scatter or absorption); Absorption or scattering of the primary neutral particle may produce secondary charged particles (e^+, e^-, p, α); Interactions of the neutral particle and the second radiations are *stochastic* (probabilistic)--we can predict the average behavior of the radiation but we cannot predict the where and when a specific particle will interact; ***Total relativistic momentum and energy is conserved in all particle interactions!!!*** Atoms are ionized or excited when radiation passes through matter--Net result is that energy is transferred from the ionizing particle to the medium; Interactions occur at discrete sites along the trajectory of the particle..Spatial pattern of energy deposits produced along the trajectory of a particle is often called a *track;* Number and types of interactions are governed by random (stochastic) processes
Scattering	Scattering may be elastic (*kinetic energy conserved*) or inelastic (*kinetic energy not conserved*), and may produce secondary (directly ionizing) radiation
Elastic vs. Inelastic Scattering	Elastic: KE is conserved (i.e. photon to electron)… Inelastic: KE is converted into some other form (i.e. photon absorbed by nucleus and raises it to an excited state. Approximately=elastic… exactly=inelastic Elastic must leave nucleus in ground state.
Elastic Collisions	Elastic collisions with atomic nuclei changes the direction of the electron. No significant energy loss by electron…Kinetic energy and momentum are conserved.
Inelastic Collisions	Inelastic collisions responsible for ionization and excitation… Momentum is conserved, kinetic energy is not. **Inelastic Collision**  ***I is the ionization potential (~ few tens of eV).***
Maximum Energy Loss	Maximum energy that can be lost by an electron in an inelastic collision is ½ the kinetic energy of the incident (colliding) electron.
Bremstrahlung Radiation	When a charged particle is accelerated (changes direction), electromagnetic radiation is emitted. Every charged particle has a virtual "cloud" of photons surrounding it. When a charged particle changes direction, some of the photons continue on in the original direction
Positron Annihilation	Positrons are the anti-matter equivalent of electrons (Same mass/Opposite charge); Energetic positron interactions are nearly the same as for electrons except…As the kinetic energy of the positron approaches zero, the positron will combine with an electron: All of the energy of the positron and electron is converted into electromagnetic radiation (i.e., photons); Two 0.511 MeV photons are created for each positron-electron annihilation event (0.511 MeV = rest mass energy of electron and positron)
Charged Particle Range	*Range* is the average distance a charged particle (*e-*, *e+*, *p*, a) can travel through some medium; For electrons and protons, range can be approximated an empirical formula: $R = \frac{1}{\rho}10^{a+bx+cx^2}$
Stopping Power (specific ioniz.)	Average rate of energy loss (excitation and ionization) per unit path length (distance) traveled.
Absorption	Absorption: Primary particle is absorbed ("captured") by the atom; Some of the energy may appears as nuclear excitation and some as heat (translational, vibrational and rotational energy of the atom); Ultimate result may be the emission of secondary (particulate) radiation, such as in the photoelectric effect
Neutron Collisions	Neutron interactions are: 1) Elastic if the kinetic energy of the incident neutron equals the sum of the kinetic energies of the neutron and recoil nucleus after the interaction (nucleus is left in ground state); 2) Inelastic if nucleus is left in an excited state. Excited nucleus returns to the ground state through the emission of a gamma-ray. 
Negatively charged particles (e^-)	Electrons lose energy as they approach the orbital electrons. $F = k\frac{q_1 q_2}{r^2}$ 
Positively charged particles	Positively charged particles (e^+, p, α) lose energy because like charges attract each other
Linear Interaction Coefficient	Used to quantify the interaction of photons particles with matter; Concept applies to both neutrons and photons; However for neutrons, the term *macroscopic cross section* (Σ) is often used instead of the term *linear interaction coefficient* (μ); Subscripts are used to denote the type of interaction coefficient; May sub-divided μ_a and μ_s into specific types of interactions (e.g., Compton scattering, coherent scattering) $\mu_t(E) = \sum_i \mu_i(E) = \mu_a(E) + \mu_s(E)$ (**total**; **absorption**; **scattering**) *Example : Water* $\mu = \sigma_H N_H + \sigma_O N_O$ $= (0.209\times10^{-24}\text{cm}^{-2}\cdot6.7\times10^{22}\text{ H cm}^{-3}) +$ $(1.69\times10^{-24}\text{cm}^{-2}\cdot3.35\times10^{22}\text{ O cm}^{-3})$ $= 0.0706\text{ cm}^{-1}$
Collided and Uncollided Radiation	Collided: passes through some region of matter but interacts one or more times; Uncollided: passes through some region of matter without interacting; Total: sum of the uncollided and collided radiation

Exponential Attenuation	 $N = N_0 e^{-\mu\Delta x} = Ne^{-\mu(\Delta x+\Delta y)}$
Angles and Photon Incidence	$\cos\theta = \frac{\Delta x}{\Delta y} \Rightarrow \Delta y = \frac{\Delta x}{\cos\theta}$ $N = N_0 e^{-\mu\Delta y}$ 
Radiation Intensity, I	For beams of radiation incident on slab shields, we often describe the amount of radiation passing through some position in the slab in terms of the radiation intensity *I* $I = \frac{\text{number of particles}}{\text{cross sectional area of shield}} = \frac{N}{A}$ $I^o(x) = I^o(0)e^{-\mu x}$ **Units: particle cm^{-2} or cm^{-2}** **Superscript "o" denotes uncollided radiation**
Mean Free Path (mfp) Length $\bar{x} = \frac{1}{\mu}$	Unit: cm… The average distance *l* a particle will travel before it interacts is often called the mean-free path length… Let *p*(*x*)D*x* be the probability a particle travels distance *x* without interacting and then interacts in x and *x* + D*x*… MFP equals the inverse of the linear interaction coefficient. As the m increases, the average distance traveled before the 1st interaction decreases.
Macroscopic Cross Section $\Sigma = \mu = \frac{1}{\bar{x}}$	Unit: cm^{-1}… Macroscopic cross section is an alternate term for the linear interaction coefficient (used for neutrons)… it's the probability per unit path length traveled that a neutral particle (photon or neutron) will interact. $I^o(x) = I^o(0)e^{-\mu x} \Rightarrow \mu = -\frac{1}{\Delta x}\ln\left[\frac{I^o(\Delta x)}{I^o(0)}\right] = \frac{1}{\Delta x}\ln\left[\frac{I^o(0)}{I^o(\Delta x)}\right]$
Microscopic Cross Section	Chance a particle will interact per unit path length traveled through a slab of material is $\mu \propto \{\text{area per atom}\}\cdot\{\text{atoms per unit volume}\}$; Might expect that the chance a particle interacts to be ∝ the cross sectional area of atom (or nucleus). Conceptually, the microscopic cross section may be interpreted as the effective interaction area per atom. Microscopic cross section (s) tells us how "big" a target the atom is to the incoming radiation $\sigma \equiv \frac{\mu}{\rho\frac{N_a}{A}} \sim \{\text{area per atom}\}$ 
Half-Value Thickness HVL=$\frac{\ln(2)}{\mu} \cong \frac{0.693}{\mu}$	In shielding applications, it is often convenient to employ a concept called the half-thickness; Also called the half-value layer (HVL) and half-layer thickness; The HVL is the thickness of a shield required to reduce the intensity of the incident radiation by a factor of 2; Relationship between m and HVL is similar to the relationship between decay constant l and the half-life *T*1/2.
Shield Thickness (x)	$\mu = \Sigma = \frac{\ln(2)}{\text{HVL}} = 0.693\text{ cm}^{-1}$ $\frac{I^\circ(x)}{I^\circ(0)} = e^{-\mu\cdot x} \Rightarrow x = -\frac{1}{\mu}\ln\left(\frac{I^\circ(x)}{I^\circ(0)}\right)$
Tenth Value Thickness	In addition to the HVL, we can also define a tenth-value thickness (TVL); TVL is the thickness of a shield required to reduce the intensity of the incident radiation by a factor of 10 $\frac{I^\circ(\text{TVL})}{I^\circ(0)} = \frac{1}{10} = e^{-\mu\cdot\text{TVL}} \Rightarrow \text{TVL}=\frac{\ln(10)}{\mu} \cong \frac{2.3}{\mu}$
Mass interaction coefficient (μ/ρ) $\mu/\rho = \sigma\frac{N_a}{A}$	Unit: cm^2/g… The quantity μ/ρ is referred to as the *mass interaction coefficient*, and it is an intrinsic property of the interacting medium. Photon mass interaction coefficients (m/r) for air, water, concrete, iron and lead are tabulated in Appendix C (p. 461-465). Multiply by density to obtain linear interaction coefficient.
Compounds and Mixtures	w_i is the weight fraction of the *i*th component of the compound or mixture, s_i is the microscopic cross section for the *i*th component, and N_i is the atom density of the *i*th component. $\mu = \Sigma = \sum_i \mu_i = \sum_i \sigma_i N_i$ $\left(\frac{\mu}{\rho}\right) = \sum_i w_i\left(\frac{\mu}{\rho}\right)_i$
Fluence Rate (Flux Density)	Will be proportional to: Amount (strength or intensity) of radiation field in the volume of interest; Linear interaction coefficient (m or S)… Estimating the fluence rate is hard because: 1) Need to know location and activity of all radiation sources; 2) Decay scheme for all radiation sources (types and energies of the emitted particles); 3) Need to account for all particle interactions that occur between the source and the location of interest $\text{fluence rate }(\phi) = \frac{\text{sum of all particle track lengths}}{\text{volume} \times \text{time interval}} = vn(\mathbf{r})$ $\sim \frac{\text{cm}}{\text{cm}^3 \times \text{s}} = \text{cm}^{-2}\text{s}^{-1}$
Reaction Rate Density $\dot{R} = \mu\phi$	While fluence rate (flux density) tells us the total distance traveled by all particles in the volume of interest during some time interval…. the interaction rate (or reaction rate density) at location r is the product of the fluence rate times the linear interaction coefficient. Reaction rate density decreases over time in line with exponential decay: $\dot{R}(t) = \dot{R}(0)e^{-\lambda t}$ particle interactions/cm × cm-2 s-1 = interactions cm-3 s-1

Fluence	If the intensity of the radiation field does not change with time, the fluence rate will remain constant. If we multiply the reaction rate by a time interval (integrate with respect to time), we obtain the total number of reactions produced in the unit volume during the time interval. $\Phi \equiv \int_{t_1}^{t_2} dt' \phi(t') \underset{\text{fluence rate constant}}{\rightarrow} \phi \Delta t$
Superposition Principle $\dot{R} = \dot{R}_1 + \dot{R}_2$	Suppose we have two g-ray emitting radiation sources. Source 1 produces a reaction rate of 1012 cm-3 s-1 and source two produces a reaction rate 1015 cm-3 h-1. The total reaction rate is the sum of the reaction rates produced by each source (*superposition principle*)… Superposition principle applies as long as radiation emitted by one source does not interfere with radiation emitted by the other source (this is a very good assumption for almost any imaginable situation)
Point Isotropic Source	Point source: All radiation is emitted at some location (*x*0, *y*0, *z*0), Used to represent sources that are small compared to other problem dimensions; Isotropic: Radiation is emitted in all directions with equal probability; Monoenergetic: Energy of the emitted radiation is the same (e.g., 10 MeV)
Inverse Square Law	Fluence rate in a target with unit cross sectional area decreases as the square of the distance from the source to the target. This result is referred to as the *inverse square law* or *geometric attenuation*. Works for any quantity that is proportional to fluence rate! $\phi_1 = \frac{S_p}{4\pi r_1^2}$ and $\phi_2 = \frac{S_p}{4\pi r_2^2} \Rightarrow \therefore \phi_2 = \phi_1 \left(\frac{r_1}{r_2}\right)^2$ $\dot{R} = \mu\phi \Rightarrow \therefore \dot{R}_2 = \dot{R}_1 \left(\frac{r_1}{r_2}\right)^2$
Material Attenuation	As radiation streams out from the radiation source, some of it interacts before reaching our target located at distance *r*. Once a particle interacts, it cannot contribute to the uncollided fluence rate (once it interacts it is, by definition, scattered radiation). The chance a source particle will travel distance *r* without interacting is *e*-m*r*, so the uncollided fluence rate at distance *r* is $e^{-\mu r}$ $\phi^0 = \frac{S_p}{4\pi r^2} \boxed{e^{-\mu r}}$
Optical Thickness $l = \mu t$	The "optical thickness" *l* is a dimensionless quantity that tells us the combined effectiveness of a one or more radiation shields (not necessarily slabs). For a slab shield of thickness *t*, the optical thickness is *l*… For a multi-layer slab shield, the optical thickness is: $l \equiv \int_0^r ds\ \mu(s) = \mu_1 t_1 + \mu_2 t_2 + \cdots + \mu_{n-1} t_{n-1} + \mu_n t_n$
Count Rate	Unit: Counts per minute, or counts per second. Proportional to uncollided fluence rate $C_2 = C_1 \left(\frac{r_1}{r_2}\right)^2 e^{-l}$ $\qquad C = k\phi^0 = k\frac{S_p}{4\pi r^2} e^{-l}$
Calculating radiation intensity	$\phi^0 = \frac{S_p}{4\pi r^2} e^{-l} \Rightarrow \phi_2 = \phi_1 \left(\frac{r_1}{r_2}\right)^2 e^{-l}$
Collision Stopping Power	Average rate of energy loss per unit path length due to *Coulomb collisions* that result in the ionization and excitation of atoms… For heavy charged particles, the collision stopping power is often called *electronic stopping power*. $\left(-\frac{dE}{ds}\right)_{coll} = \rho \frac{Z}{A} z^2 f(I, \beta)$ **Z over A for medium**; **Speed (*v*/c)**; **Ionization potential (~ 75 eV for water)**; **Particle charge (**1 for electron and proton, 2 for alpha**)**
Radiative stopping power (electrons)	Average rate of energy loss per unit path length due to collisions with atoms and atomic electrons in which *bremsstrahlung* quanta are emitted… Important only for electrons. Radiative stopping power is not important for protons, α particles and other heavy charged particles. $\left(-\frac{dE}{ds}\right)_{rad} = \left(\rho \frac{N_a}{A}\right) \cdot (E + m_e c^2) Z^2 F(E, Z)$ **Kinetic energy of electron**; **rest mass energy (**0.511 MeV**)**; **atom cm³**
Nuclear Stopping Power	Average rate of energy loss per unit path length due to the transfer of energy to recoiling atoms in *elastic collisions*… Important only for heavy charged particles.
Total Stopping Power	For electrons, the sum of the collision and radiative stopping powers… for protons and helium ions, the sum of collision and nuclear
Photoelectric Effect	Photon interacts with the *entire atom;* Photon is *absorbed* and an electron is ejected – usually from the *K* shell (orbit); All of the photon's energy (*E* = *hv*) is transferred to the "recoil" atom or the electron; The vast majority of the energy transferred ends up as the kinetic energy of the electron **Photoelectric effect (σ_{ph})** 

Compton Scattering	Compton interactions are: 1) Inelastic in the sense that some of the photon energy must be transferred to the atom to compensate for the binding of the electron to the nucleus--Sum of the kinetic energies of the particles before and after the interaction is not <u>exactly</u> the same; 2) Elastic in the sense that the binding energy is very small compared to the energy of the photon and the recoil electron--Sum of the kinetic energy before and after the interaction is almost the same (within a few eV) **Compton Scattering (σ_C)**  
Coherent vs. Incoherent Scattering	Incoherent (Compton) scattering occurs when a photon interacts with *one orbital electron;* Coherent (Rayleigh) scattering occurs when the incoming photons *simultaneously interact with all of the orbital electrons;* Coherent scattering *most important* for low energies; However, photoelectric is much more important than coherent or incoherent scattering.
Pair Production	Incident photon interacts with the nucleus and is completely absorbed; A positron (*e*+) and an electron (*e*-) are formed; Interaction can only occur for photon energies greater than 1.02 MeV (= 2×0.511 MeV) because we need at least this much energy to form the electron and positron (photon energy → mass) $E_{e^+} + E_{e^-} = E_\gamma - 2m_e c^2 = E_\gamma - 1.02 \text{ MeV}$

* Chance radiation will "hit" a target (e.g., an atom or cell) *increases* as the size of the target *increases*

* Chance radiation will hit a target tends to *decrease* as the distance between the source and target *increases*

Use symbol Σ for neutrons and μ for photons; these symbols are otherwise identical.

I.R. Type	Photon	Charge	Absorbed Dose	Exposure	Stopping Power	Indirect	Kerma
x-ray	✓		✓	✓		✓	✓
gamma	✓		✓	✓		✓	✓
neutron		0	✓			✓	✓
electron		-1	✓		✓		
positron		+1	✓		✓		
proton		+1	✓		✓		
alpha		+2	✓		✓		

Radiation Weight Factors

Radiation Type	Energy Range	W_R
Photons	all	1
Electrons & muons	all	1
Neutrons	< 10 keV	5
	10 keV - 100 keV	10
	100 keV - 2 MeV	20
	2 MeV - 20 MeV	10
	>20 MeV	5
Protons, other than recoil	>2 MeV	5
Alpha particles, fission fragments, heavy nuclei	all	20

1990 ICRP and 1993 NCRP

SI prefixes		
Factor	Name	Symbol
10^{24}	yotta	Y
10^{21}	zetta	Z
10^{18}	exa	E
10^{15}	peta	P
10^{12}	tera	T
10^{9}	giga	G
10^{6}	***mega***	***M***
10^{3}	***kilo***	***k***
10^{2}	hecto	h
10^{1}	deka	da
0		
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	***milli***	***m***
10^{-6}	***micro***	***μ***
10^{-9}	***nano***	***n***
10^{-12}	***pico***	***p***
10^{-15}	femto	f
10^{-18}	atto	a
10^{-21}	zepto	z
10^{-24}	yocto	y

$$\mu_i = \Sigma_i = \sigma_i N = \sigma_i \frac{\rho N_a}{A}$$

microscopic cross section (b = 10^{-24} cm^{-2}) → σ_i; **density** (g cm^{-3}) → ρ; **Avogadro's constant** → N_a; **mass number** → A; **macroscopic cross section** (cm^{-1}) → μ_i, Σ_i; **Atom density** (atom cm^{-3}) → N

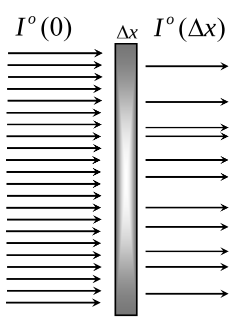
$$\phi^0 = \frac{S_p}{4\pi r^2} e^{-\mu t}$$

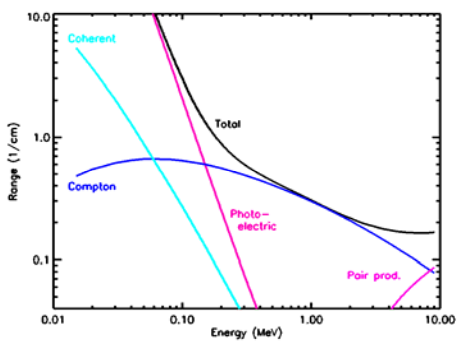
Use thickness of shield here (material attenuation) → t

Use total distance from source to detector (point of interest) here (geometric attenuation) → r

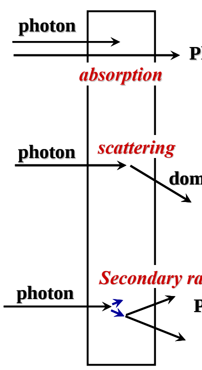
$$\phi^0(E) = \frac{S_p(E)}{4\pi r^2} e^{-l(E)}$$

Particle emission rate (particle of energy *E*) → $S_p(E)$; **Optical thickness** (particle of energy *E*) → $l(E)$; **Uncollided fluence rate for particles with energy *E*** → $\phi^0(E)$





Particle Interactions and Radiation Shielding



Photoelectric dominates (low energies) $\phi \cong \phi^0 = \frac{S_p}{4\pi r^2} e^{-\mu t}$ **good approximation** (shield design ok)

Compton scattering dominates (intermediate energies) $\phi > \phi^0 = \frac{S_p}{4\pi r^2} e^{-\mu t}$ **too low** (not enough shielding)

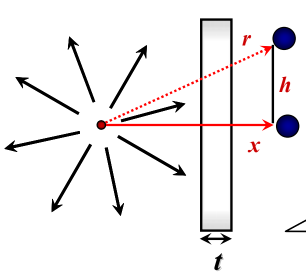
Secondary radiation (e^- and $e^+ \rightarrow 2\gamma$)

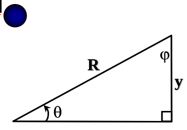
Pair production dominates (high energies) $\phi > \phi^0 = \frac{S_p}{4\pi r^2} e^{-\mu t}$ **too low** (not enough shielding)

Detector response at other locations (angles)

Radiation will have to penetrate through a larger amount of shielding to reach the detector.

$$\cos\theta = \frac{t}{t'} \rightarrow t' = \frac{t}{\cos\theta} \qquad \phi^0 = \frac{S_p}{4\pi r^2} e^{-\mu t'}$$





$\varphi = 90 - \theta$

$$x^2 + y^2 = R^2$$
$$\cos^2\theta + \sin^2\theta = 1$$
$$\cos\theta = \frac{x}{R}$$
$$\sin\theta = \frac{y}{R}$$
$$\tan\theta = \frac{\sin\theta}{\cos\theta} = \frac{y}{x}$$

Photon interaction coefficients

$$\mu/\rho = \sigma \frac{N_a}{A} \xrightarrow{\text{Multiply } \mu/\rho \text{ by } \rho} \mu = \sigma \cdot \left(\rho \frac{N_a}{A}\right)$$

Units: $\frac{\text{cm}^2}{\text{g}}$ Units: cm^{-1}

Neutron interaction coefficients

microscopic cross section (b =10^{-24} cm^2) → σ

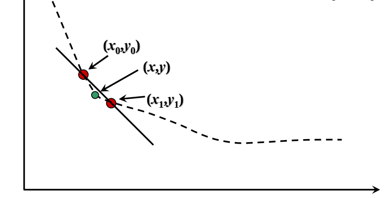
$$\Sigma = \sigma \cdot \left(\rho \frac{N_a}{A}\right)$$

Units: cm^{-1}

Interpolation (linear-linear)

Key equations for linear-linear interpolation:

$$y = m(x - x_0) + y_0 \qquad m = \frac{y_1 - y_0}{x_1 - x_0} = \frac{y_0 - y_1}{x_0 - x_1}$$



Log-log interpolation

$$m = \frac{\ln y_1 - \ln y_0}{\ln x_1 - \ln x_0} = \frac{\ln(y_1/y_0)}{\ln(x_1/x_0)} \qquad y = \exp\{m(\ln x - \ln x_0) + \ln y_0\}$$

Radiation dosimetry (motivation)

- Even if we could measured or calculate fluence or fluence rate, we would be overwhelmed by information in any practical situation

We need quantities that condense information about particle fluence and fluence rate into other biologically meaningful quantities, *preferably ones that can be measured*.

fluence rate (φ) ⟶ **reaction rate (μφ)** ⟶ **energy deposition rate** (∝ μφ) ⟶ **Measurable!**

energy deposition rate (∝ μφ) ⟶ **energy deposition rate per unit mass, i.e., *dose rate* (∝ μφ/*m*)** (*convenient normalization*)

{biological effects} ∝ {energy deposited (and dose)}

{damage to inanimate systems} ∝ {energy deposited (and dose)}