

The Radiological Sciences And Ionizing Radiation

Radiation Therapy



**Linear accelerators
Co-60
brachytherapy**

Diagnostic Imaging



**CT scanner
X-ray machine
Fluoroscopy**

Nuclear Medicine

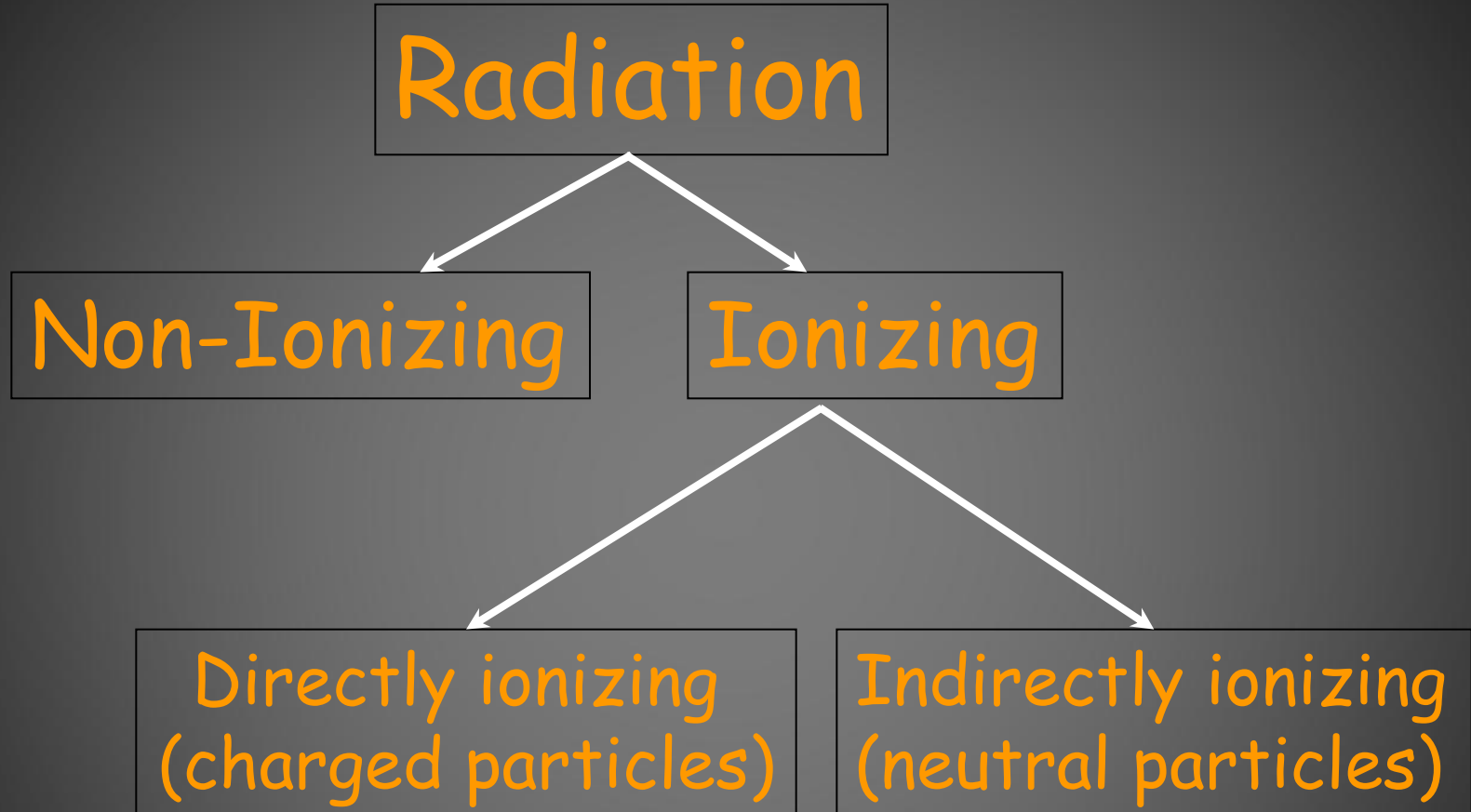


**PET scanner
SPECT camera**

Radiation Biology



**Understand the
Mechanisms for
Radiation interaction
At the cellular and
DNA level.**



Directly ionizing (charged particles)

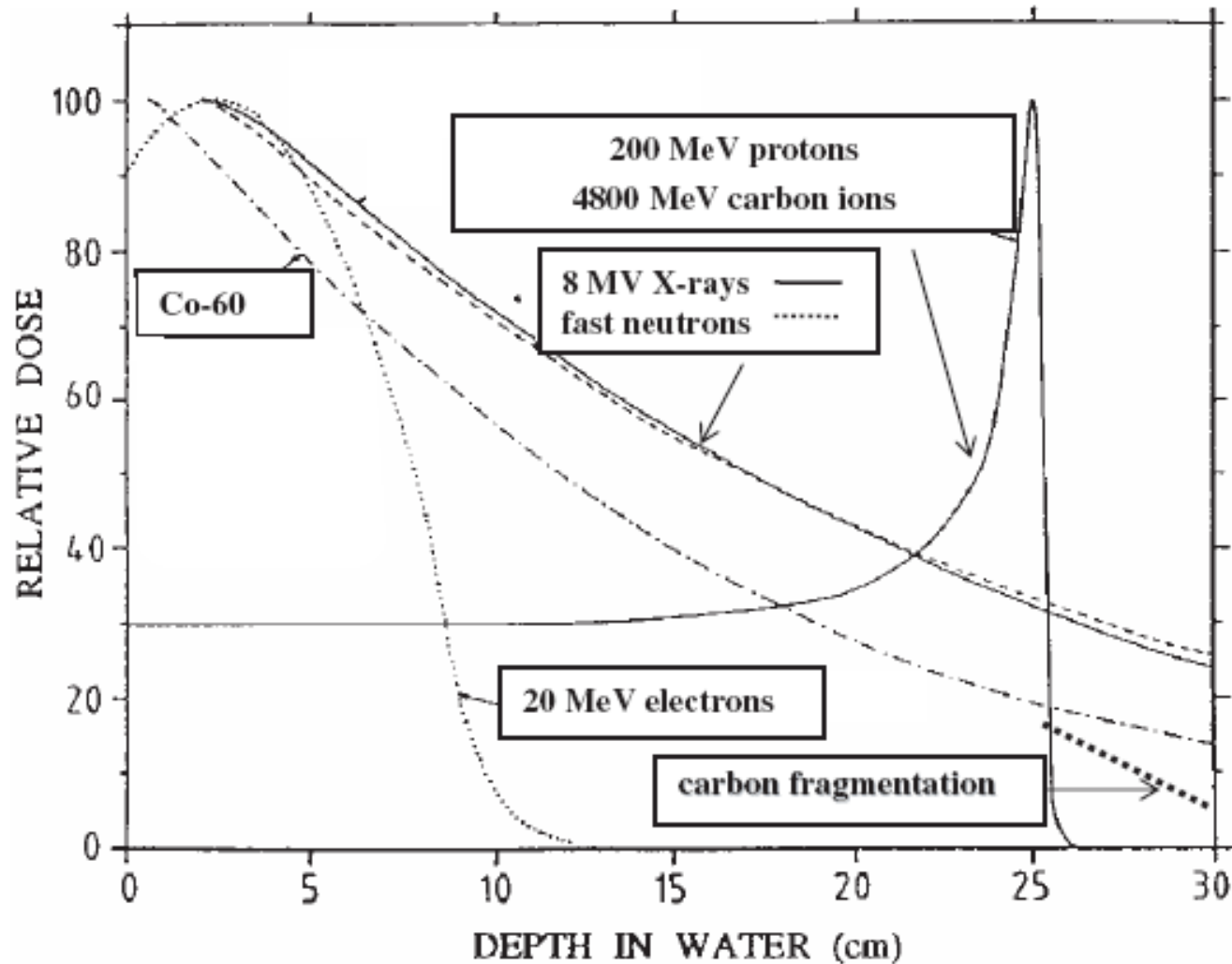
Electrons, protons, heavy ions

- finite "range"
- stopping power, linear energy transfer
- primary charged particle will deposit energy while "slowing-down"
- produce secondary charged particles
- protons and heavy ions can undergo nuclear interactions

Indirectly ionizing (neutral particles)

Photons, neutrons

- infinite "range"
- $e^{-\mu x}$ exponential attenuation
- secondary charged particles responsible for energy deposition
- neutrons and high-energy photons can undergo nuclear interactions



From Amaldi and Kraft, "Radiotherapy with beams of carbon ions, Reports on Progress in Physics, 68, (2005)

Electromagnetic Radiation



$E = 12.4 \text{ meV} - 1.24 \text{ eV}$
 $\lambda = 100 \text{ } \mu\text{m} - 1 \text{ } \mu\text{m}$

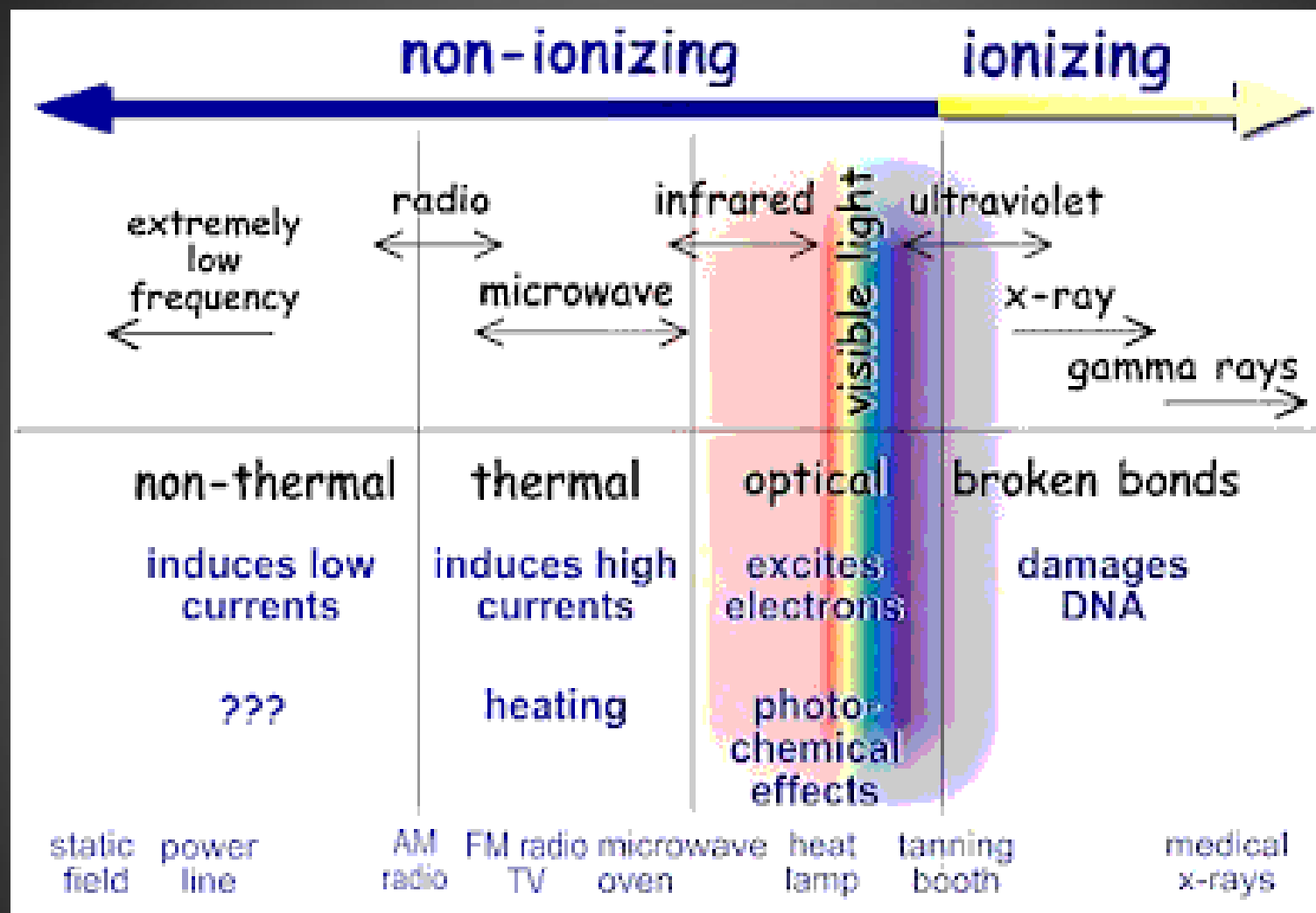
$E = 1.77\text{-}3.1 \text{ eV}$
 $\lambda = 700\text{-}400 \text{ nm}$

$E = 3.1\text{-}124 \text{ eV}$
 $\lambda = 400\text{-}10 \text{ nm}$

$E \approx 1\text{-}120 \text{ keV}$
Diagnostic

$E > 500 \text{ keV}$
Therapy

$$E_{\gamma} = h\nu = \frac{hc}{\lambda} = \frac{1.2398 \text{ keV} \cdot \text{nm}}{\lambda}$$





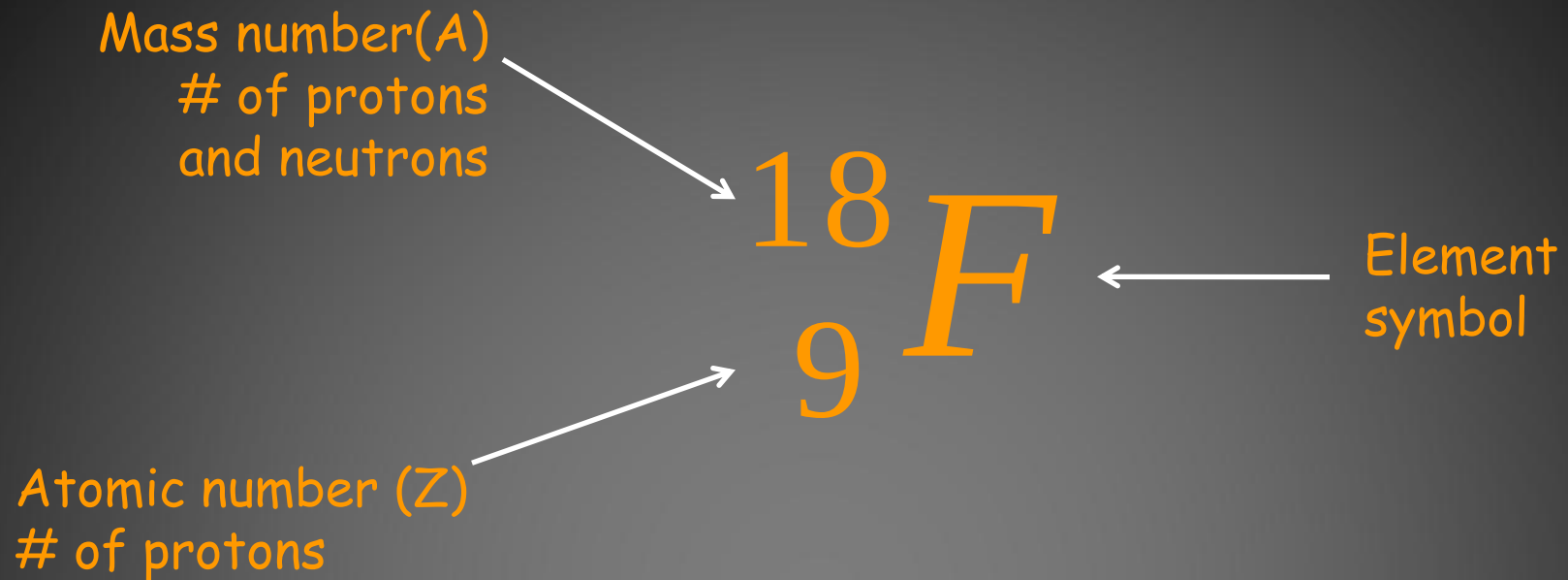
$$E = mc^2$$

Kinetic
energy

Rest mass
energy

$$E = T + m_0 c^2$$

Electron	e-	0.511 MeV
Positron	e+	0.511 MeV
neutron	n	939.6 MeV
proton	p	938.3 MeV
pion		139.6 MeV
Alpha	He-4	3727.4 MeV

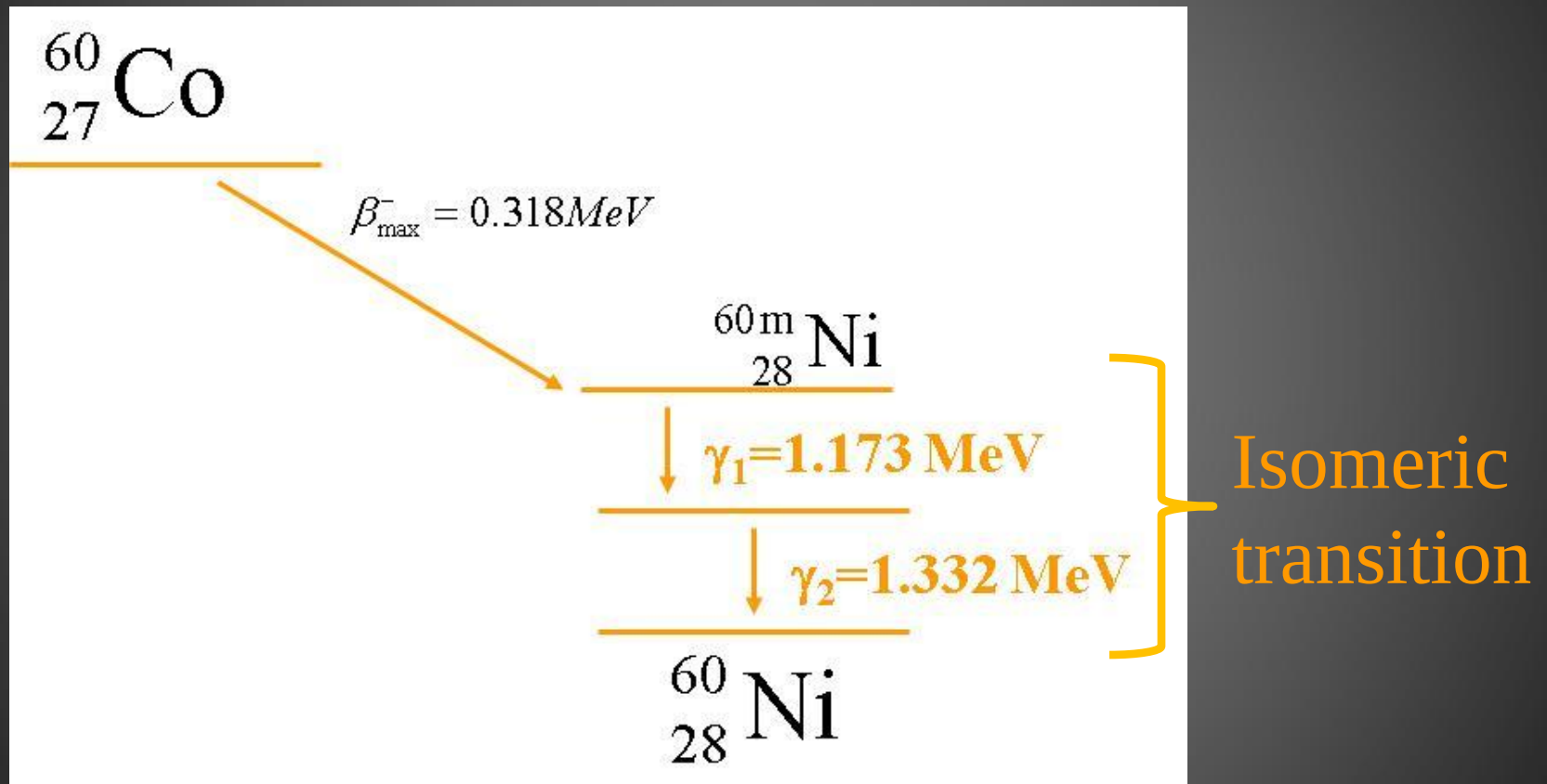


Isotopes - atoms having nuclei with the same number of protons but different number of neutrons.

Isotones - atoms having nuclei with the same number of neutrons but different number of protons.

Isobars - atoms having nuclei with the same number of nucleons but different number of protons.

Isomers - identical nuclei (same number of protons and neutrons) but differ only in their nuclear energy state.

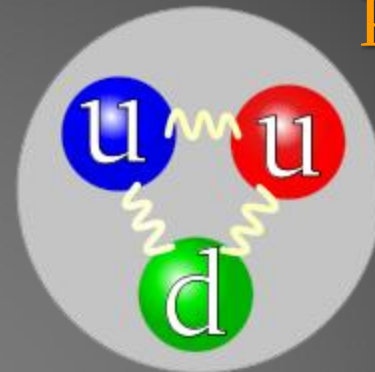


Three Generations of Matter (Fermions)

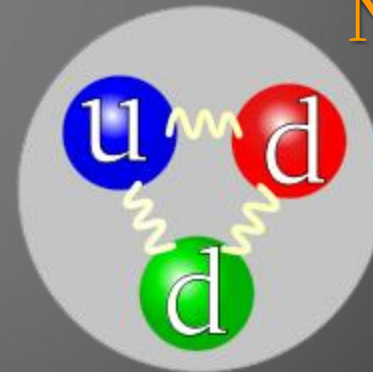
	I	II	III	
mass →	2.4 MeV	1.27 GeV	171.2 GeV	0
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
spin →	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
name →	u up	c charm	t top	γ photon
Quarks	4.8 MeV	104 MeV	4.2 GeV	0
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	d down	s strange	b bottom	g gluon
Leptons	$\ll 2.2$ eV	$\ll 0.17$ MeV	$\ll 15.5$ MeV	91.2 GeV
	0	0	0	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z^0 weak force
	0.511 MeV	105.7 MeV	1.777 GeV	80.4 GeV
	-1	-1	-1	± 1
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	e electron	μ muon	τ tau	$W^\pm$ weak force

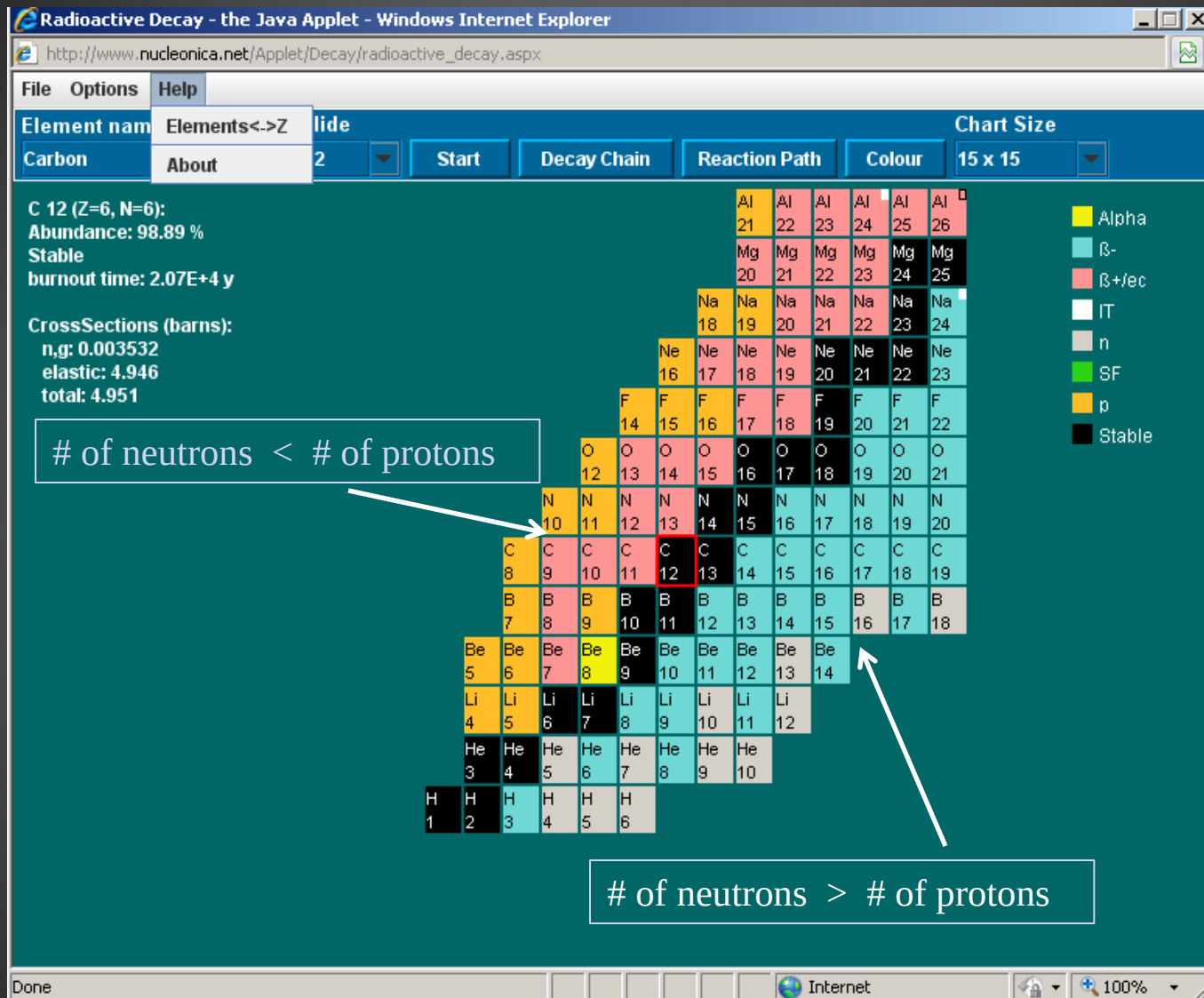
Bosons (Forces)

Proton



Neutron





Radioactive Decay - the Java Applet - Windows Internet Explorer

http://www.nucleonica.net/Applet/Decay/radioactive_decay.aspx

File Options Help

Element name Select Nuclide Chart Size

Cobalt Co 60 Start Decay Chain Reaction Path Colour 15 x 15

Co 60 (Z=27, N=33):
 Abundance: null %
 half-life: 5.27 y
 burnout time: No data!

CrossSections (barns): No data!

Daughters:
 B- (100.0% , Ni 60)

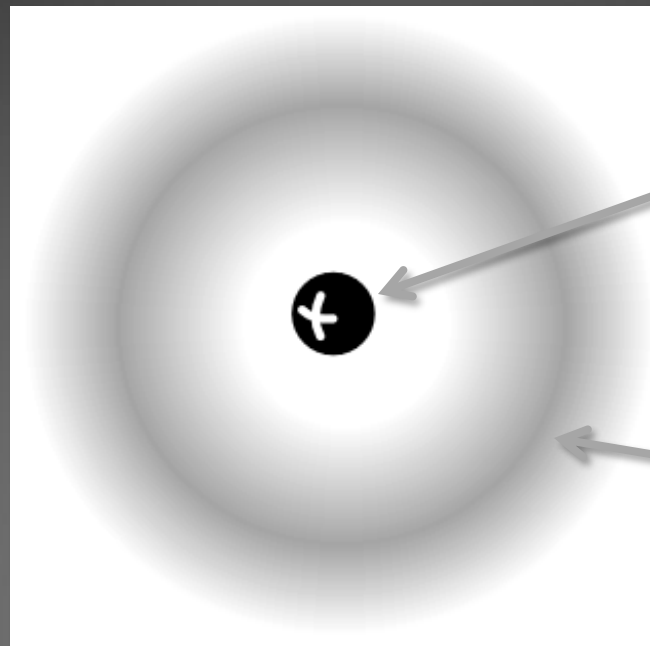
Most important gamma lines:
 Gamma1 E(keV) = 1173 EP = 0.99
 Gamma2 E(keV) = 1332 EP = 0.99

Se	Se	Se	Se	Se	Se	Se	Se	Se	Se	Se	Se	Se	Se	Se
65	66	67	68	69	70	71	72	73	74					
As	As	As	As	As	As	As	As	As	As	As	As	As	As	As
60	61	62	63	64	65	66	67	68	69	70	71	72	73	74
Ge	Ge	Ge	Ge	Ge	Ge	Ge	Ge	Ge	Ge	Ge	Ge	Ge	Ge	Ge
58	59	60	61	62	63	64	65	66	67	68	69	70	71	72
Ga	Ga	Ga	Ga	Ga	Ga	Ga	Ga	Ga	Ga	Ga	Ga	Ga	Ga	Ga
57	58	59	60	61	62	63	64	65	66	67	68	69	70	71
Zn	Zn	Zn	Zn	Zn	Zn	Zn	Zn	Zn	Zn	Zn	Zn	Zn	Zn	Zn
56	57	58	59	60	61	62	63	64	65	66	67	68	69	70
Cu	Cu	Cu	Cu	Cu	Cu	Cu	Cu	Cu	Cu	Cu	Cu	Cu	Cu	Cu
55	56	57	58	59	60	61	62	63	64	65	66	67	68	69
Ni	Ni	Ni	Ni	Ni	Ni	Ni	Ni	Ni	Ni	Ni	Ni	Ni	Ni	Ni
54	55	56	57	58	59	60	61	62	63	64	65	66	67	68
Co	Co	Co	Co	Co	Co	Co	Co	Co	Co	Co	Co	Co	Co	Co
53	54	55	56	57	58	59	60	61	62	63	64	65	66	67
Fe	Fe	Fe	Fe	Fe	Fe	Fe	Fe	Fe	Fe	Fe	Fe	Fe	Fe	Fe
52	53	54	55	56	57	58	59	60	61	62	63	64	65	66
Mn	Mn	Mn	Mn	Mn	Mn	Mn	Mn	Mn	Mn	Mn	Mn	Mn	Mn	Mn
51	52	53	54	55	56	57	58	59	60	61	62	63	64	65
Cr	Cr	Cr	Cr	Cr	Cr	Cr	Cr	Cr	Cr	Cr	Cr	Cr	Cr	Cr
50	51	52	53	54	55	56	57	58	59	60	61	62	63	64
V	V	V	V	V	V	V	V	V	V	V	V	V	V	V
49	50	51	52	53	54	55	56	57	58	59	60	61	62	63
Ti	Ti	Ti	Ti	Ti	Ti	Ti	Ti	Ti	Ti	Ti	Ti	Ti	Ti	Ti
48	49	50	51	52	53	54	55	56	57	58	59	60	61	62
Sc	Sc	Sc	Sc	Sc	Sc	Sc	Sc	Sc	Sc	Sc	Sc	Sc	Sc	Sc
47	48	49	50	51	52	53	54	55	56	57	58	59	60	61
Ca	Ca	Ca	Ca	Ca	Ca	Ca	Ca	Ca	Ca	Ca	Ca	Ca	Ca	Ca
46	47	48	49	50	51	52	53	54	55	56	57	58	59	60

- Alpha
- B-
- B+/ec
- IT
- n
- SF
- p
- Stable

Done Internet 100%

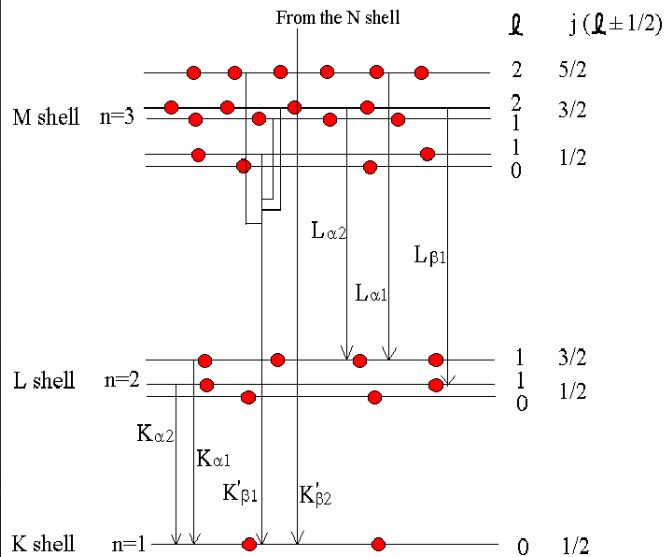
How do we
physically
describe the
electron “cloud” ?



nucleus

Electron “cloud”

Generic Energy Level Diagram

[illegible]

atomic orbitals

Intro and Definitions for Ionizing Radiation

Stochastic Quantities (Dose)

- Values occur randomly and determined by a probability distribution
- Defined for finite volumes only
- The expectation value N_e of a stochastic quantity is the mean N of its measured values as the number of observations approached infinity (Monte Carlo simulations).

Non-Stochastic Quantities (Kerma)

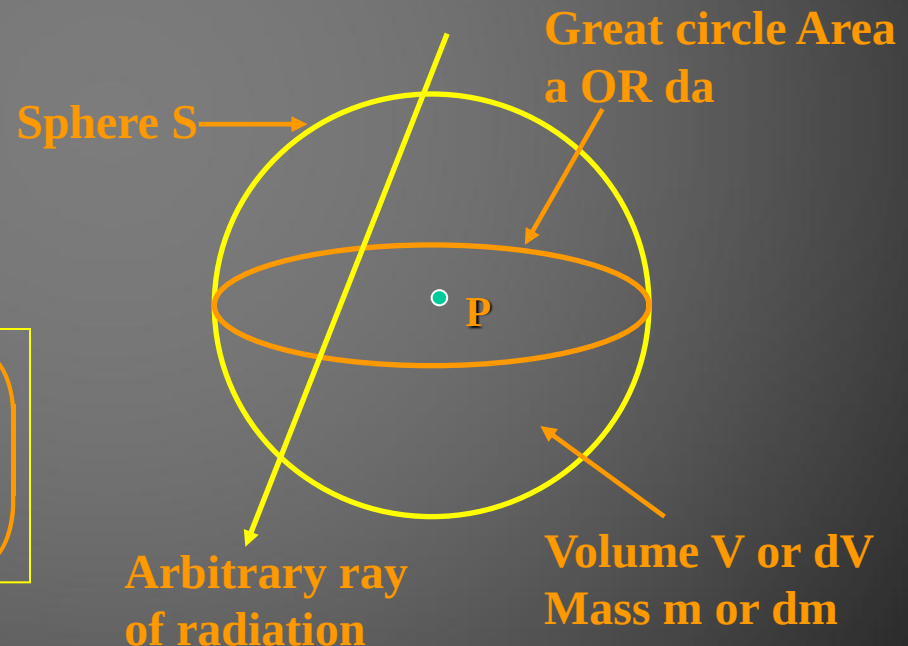
- Value can be “calculated”
- A “point function” defined for infinitesimal volumes.
- Continuous and differentiable
- With respect to ionizing radiation its value is equal to or based upon the expectation value of a related stochastic quantity.

Fluence & Fluence Rate (cm⁻²)

- N_e is the expectation value of the number of rays striking a finite sphere surrounding a point p .
- Reduce the sphere to a point with great-circle area da .

$$\Phi = \frac{dN_e}{da}$$

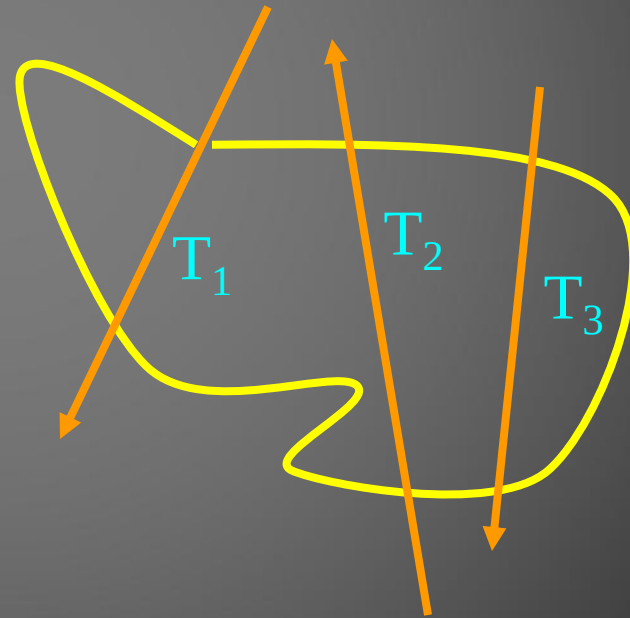
$$\varphi = \frac{d\Phi}{dt} = \frac{d}{dt} \left(\frac{dN_e}{da} \right)$$



Chilton's definition of fluence

- The fluence at a point P is numerically equal to the expectation value of the sum of the particle track lengths (assumed to be straight) that occur in an infinitesimal volume dV at P, divided by V.

$$\varphi = \frac{\sum T}{V}$$



Differential Fluence Rate ($\text{cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ keV}^{-1}$)

$$\varphi(t, \theta, \beta, E)$$

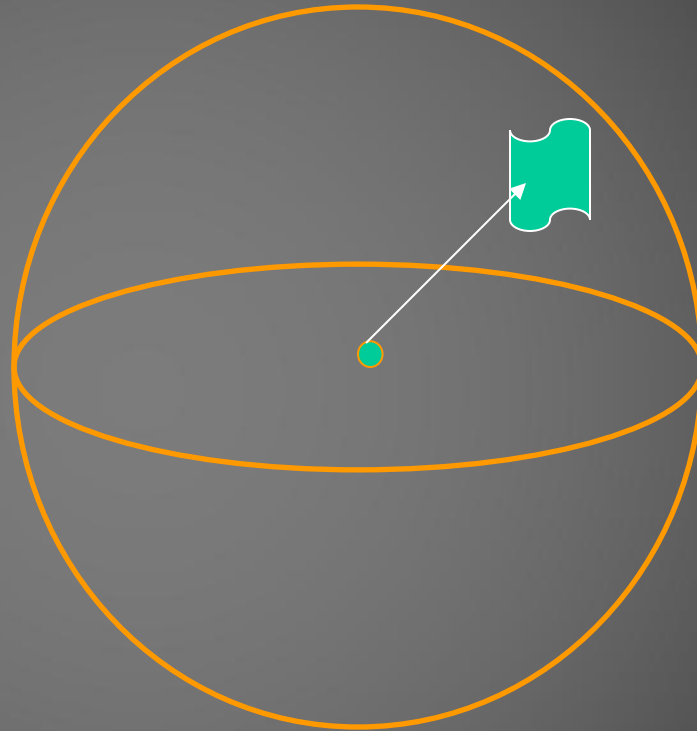
Time Dependent Fluence Rate

$$\Phi(t_o, t_1) = \int_{t_o}^{t_1} \varphi(t) dt$$

Time Independent Fluence Rate

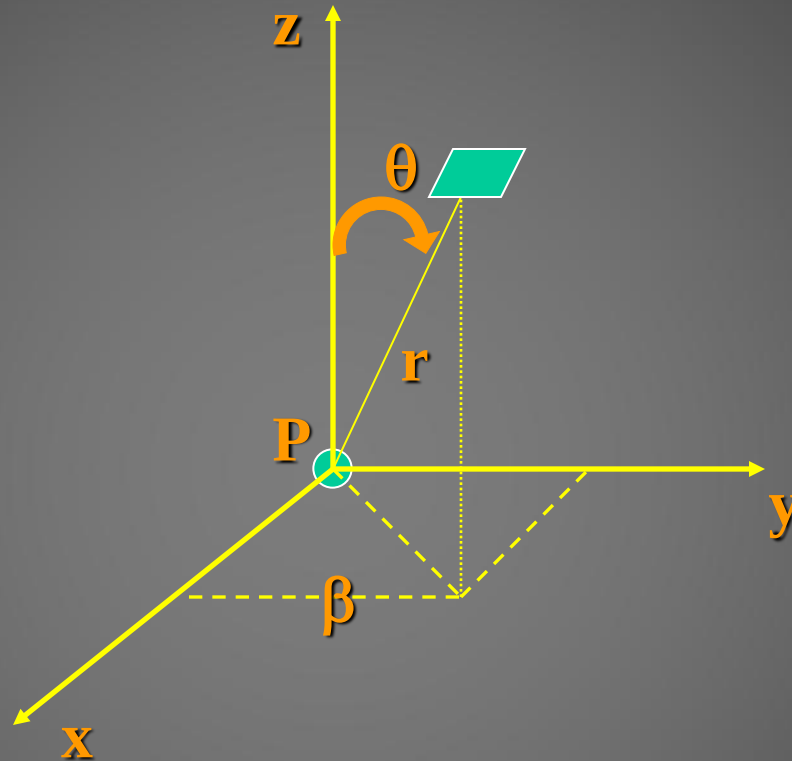
$$\Phi(t_o, t_1) = \varphi \cdot (t_1 - t_o) = \varphi \Delta t$$

Solid Angle (steradians)



$$d\Omega = \sin \theta \, d\theta \, d\beta$$

$$\Omega = \int_{\theta=0}^{\pi} \int_{\beta=0}^{2\pi} \sin \theta \, d\theta \, d\beta = 4\pi$$



$$\varphi = \int_{\theta=0}^{\pi} \int_{\beta=0}^{2\pi} \int_{E=0}^{E_{\max}} \varphi'(\theta, \beta, E) \sin \theta \, d\theta \, d\beta \, dE$$

Angular Distributions

$$\varphi = \int_{\theta=0}^{\pi} \int_{\beta=0}^{2\pi} \varphi'(\theta, \beta) \sin \theta \, d\theta \, d\beta$$

If the field is symmetric about the z-axis then $\varphi'(\theta, \beta)$ is independent of β .

$$\varphi = 2\pi \int_{\theta=0}^{\pi} \varphi'(\theta, \beta) \sin \theta \, d\theta$$

If the field is symmetric about the polar angle (θ) then $\varphi'(\theta, \beta)$ is an isotropic point source.

$$\varphi = 4\pi \varphi'(\theta, \beta)$$

Energy Spectra

$$\varphi'(E) = \int_{\theta=0}^{\pi} \int_{\beta=0}^{2\pi} \varphi'(\theta, \beta, E) \sin \theta \, d\theta \, d\beta$$

$$\varphi = \int_{E=0}^{E_{\max}} \varphi'(E) \, dE$$

$$\psi'(E) = E \varphi'(E)$$

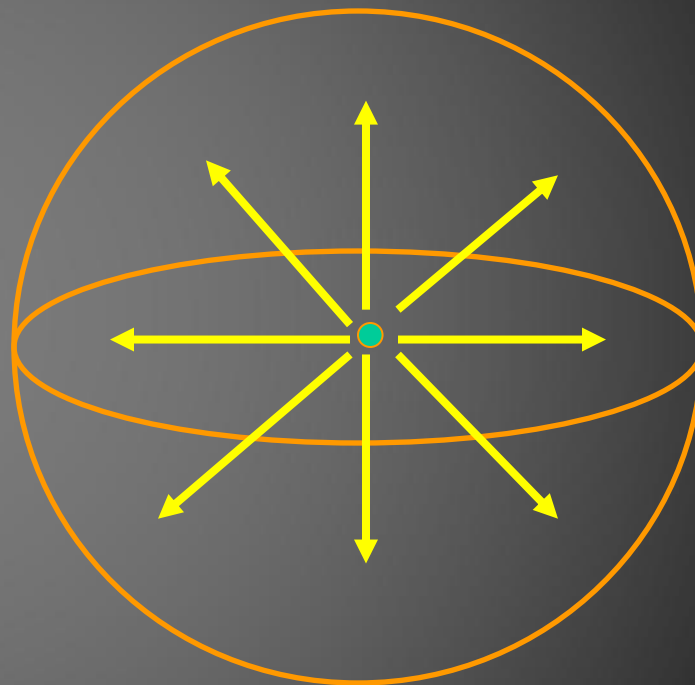
$$\psi = \int_{E=0}^{E_{\max}} E \varphi'(E) \, dE$$

Energy Fluence (MeV/cm²)

$$1 \text{ MeV} = 1.602 \times 10^{-6} \text{ erg} = 1.602 \times 10^{-13} \text{ J}$$

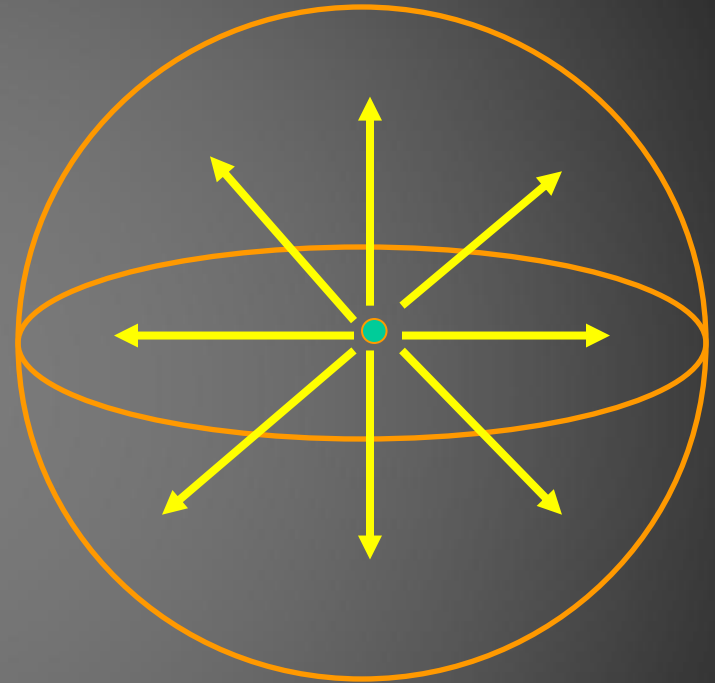
- Isotropic point source
- Emits N mono-energetic photons per unit time
- vacuum

$$\phi = \frac{N}{4\pi r^2}$$
$$\psi = \frac{EN}{4\pi r^2}$$

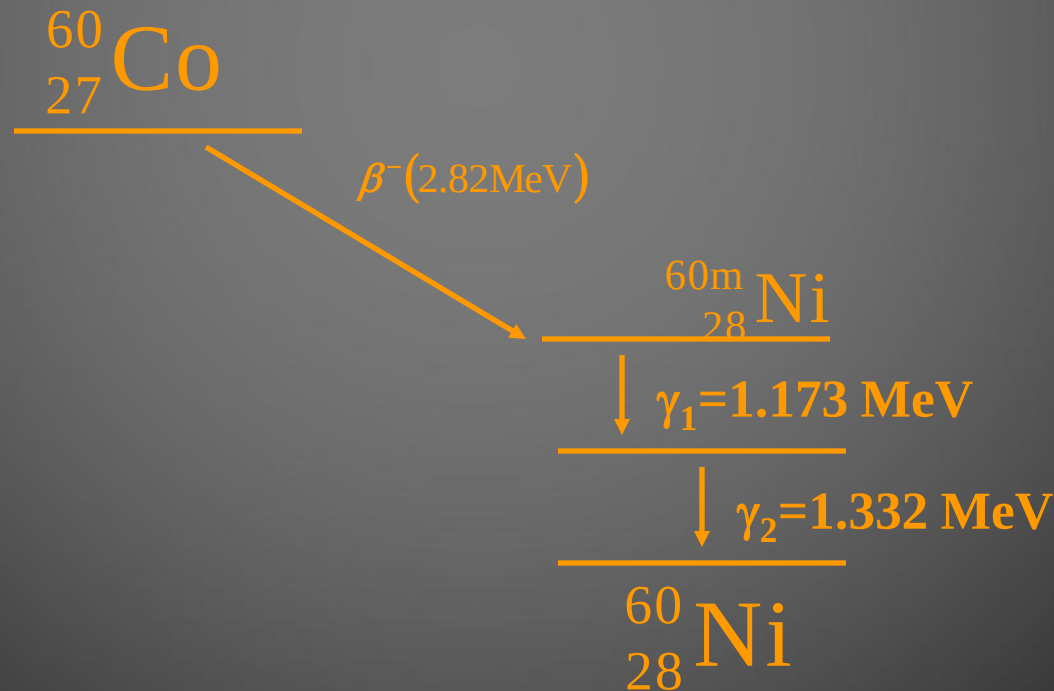


- Isotropic point source
- Emits N photons per unit time.
- Arbitrary attenuating medium.
- Arbitrary energy distribution.

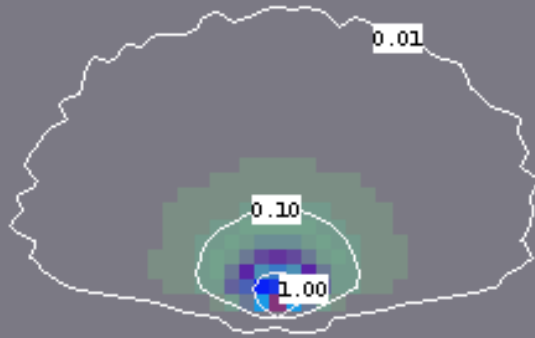
$$\phi(E) = \frac{N(E)e^{-\mu(E)x}}{4\pi r^2}$$



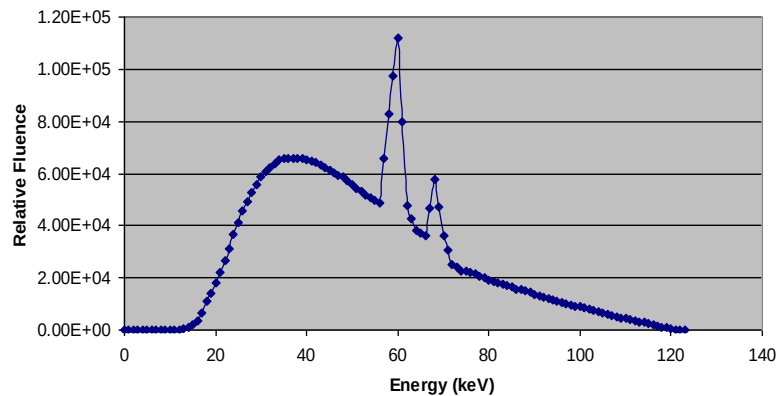
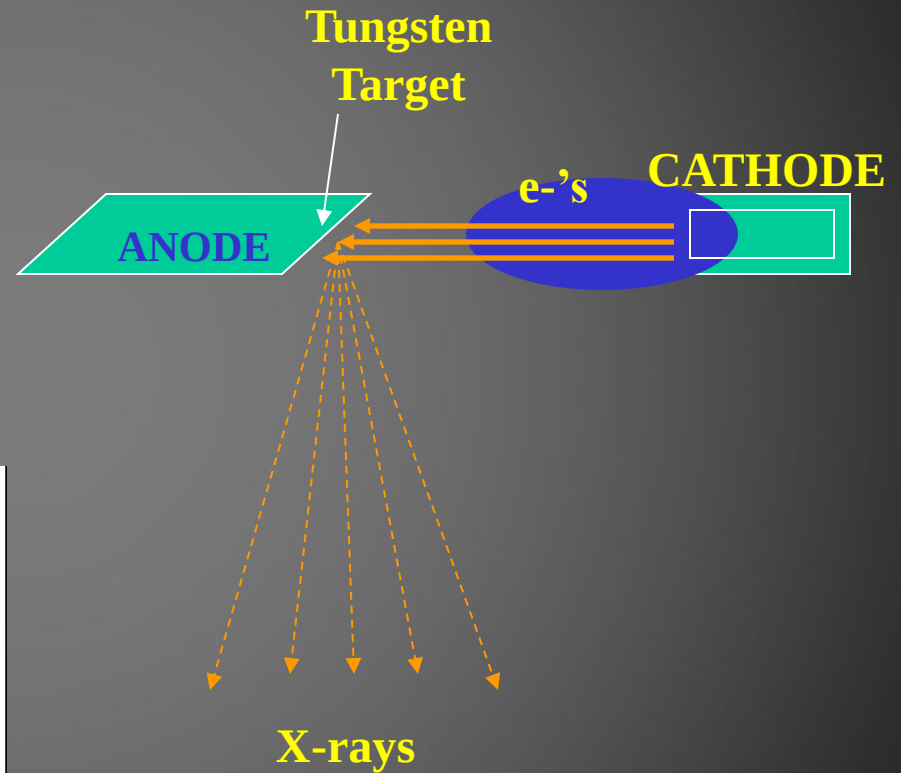
Discrete Polyenergetic Photon Sources (via decay)



$T_0 = 100 \text{ keV}$



Bremsstrahlung intensity distribution (Diagnostic)

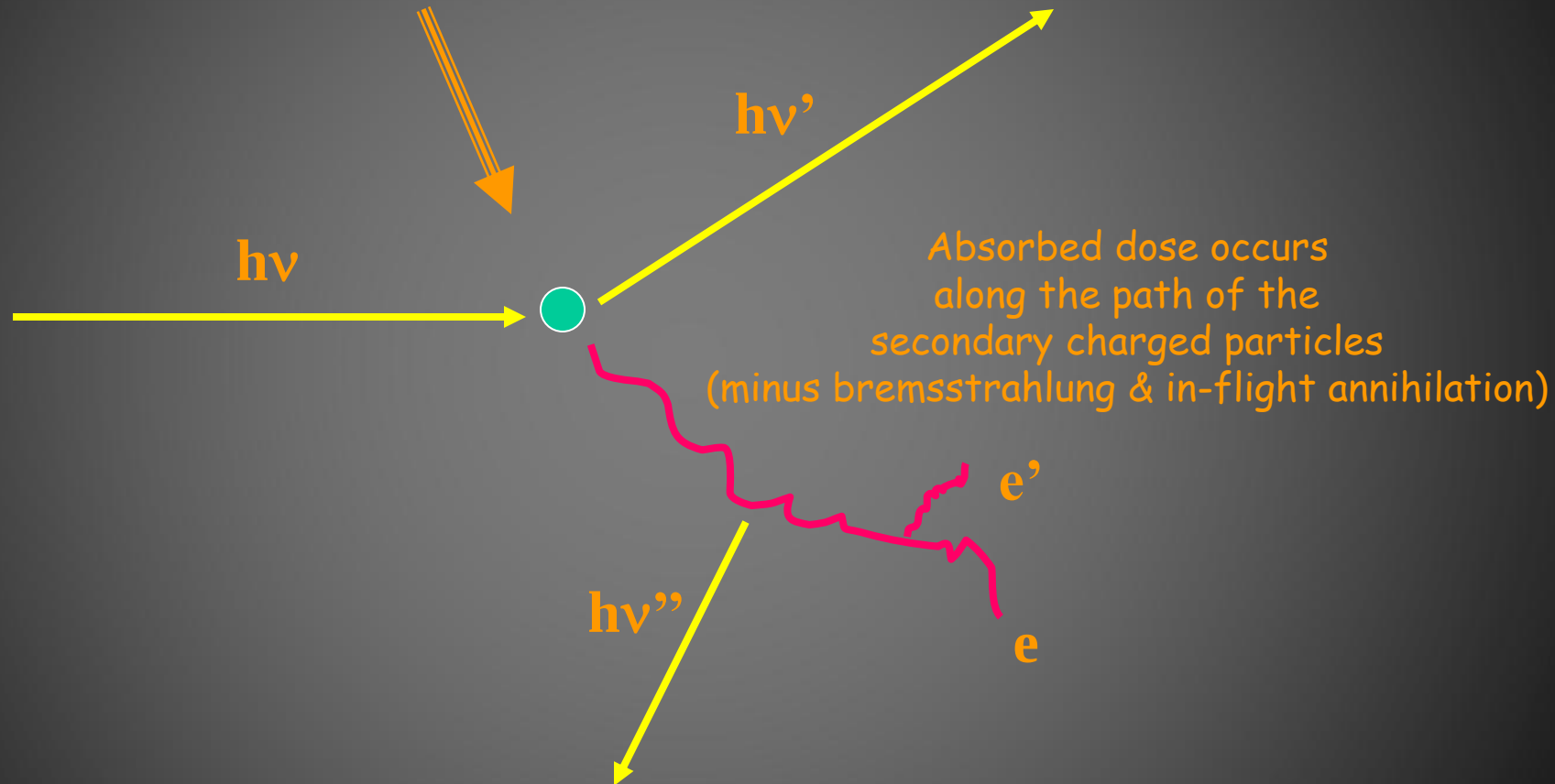


Quantities for Describing the Interaction of Ionizing Radiation with Matter

If we use an infinitesimal sphere at a point in free space as our reference location then....

- Kerma (K) - energy transferred to charged particles.
- Absorbed Dose (D) - energy imparted to matter by all kinds of ionizing radiations but delivered by the charged particles.
- Exposure (X) - described x- and γ -ray fields in terms of their ability to ionize air.

Kerma occurs at the
Initial interaction point



Kerma (Kinetic Energy Relaxed in the Medium)

- The expectation value of the energy transferred to charged particles per unit mass at a point of interest, including radiative-loss energy but excluding energy passed from one charged particle to another.
- Relevant only for fields of indirectly ionizing radiations.

$$K = \frac{d\varepsilon_{tr}}{dm}$$

- The average value of the kerma throughout a volume containing a mass m is simply the expectation value of the energy transferred divided by the mass.

$$1\text{Gy} = 1\text{ J / kg} = 100\text{ rad} = 10^4\text{ erg / g}$$

$$K = \frac{d\varepsilon_{tr}}{dm}$$

$$\varepsilon_{tr} = (R_{in})_U - (R_{out})_U^{nonR} + \sum Q$$

- $(R_{in})_U$ = the radiant energy of uncharged particles entering V.
- $(R_{out})_U^{nonR}$ = radiant energy of uncharged particles leaving V except from bremsstrahlung or in-flight annihilation.
- ΣQ = net energy derived from rest mass in V (mass to E positive, E to mass negative).
- Radiant Energy (R) is defined as the energy of particles (excluding rest energy) emitted, transferred, or received.

Energy transferred is just the kinetic energy received by charged particles in the specified finite volume V, regardless of where or how they in turn spend that energy.

- **bremsstrahlung** (German word for “braking radiation”)

An electron passing near a nucleus will undergo an inelastic radiative interaction. The electron is deflected and will give up a significant fraction of its kinetic energy (up to 100%) to produce an x-ray photon.

- **in-flight annihilation**

An antimatter interaction whereby a positron is annihilated in encountering an electron before stopping. The remaining kinetic energy of the positron is given to one or both of the annihilation photons.

Kerma for photons

$$K = \psi \left(\frac{\mu_{tr}}{\rho} \right)_{E,Z}$$

$$K = \int_{E=0}^{E_{\max}} \psi'(E) \cdot \left(\frac{\mu_{tr}}{\rho} \right)_{E,Z} dE$$

- K is the photon kerma at point P typically expressed in Gy
- $(\mu_{tr}/\rho)_{E,Z}$ = mass energy-transfer coefficient (cm²/g)
- Ψ = photon energy fluence (MeV/cm² or J/m²)
- $\Psi'(E)$ = differential distribution of photon energy fluence (J m² keV⁻¹)

Kerma for neutrons

$$K = \Phi (F_n)_{E,Z}$$

- K is the neutron kerma at point P typically expressed in rads
- Φ = neutron fluence with energy E (neutrons/cm²)
- $(F_n)_{E,Z}$ = neutron kerma factor (MeV/cm² or J/m²)
tabulated for neutrons versus the mass energy-transfer coefficient for photons

$$(F_n)_{E,Z} = \left(\frac{\mu_{tr}}{\rho} \right)_{E,Z} E$$

Components of Kerma for Photons

- kerma for photons is basically the energy transferred to electrons or positrons per unit mass of medium.
- The kinetic energy of these electrons may be spent as:
 - electrons interact via coulomb force interactions. Local energy dissipation via ionization and excitation of the atoms surrounding the electron track.
 - radiative interactions via the coulomb force field of the surrounding atoms. X-ray photons are emitted via bremsstrahlung. Also in-flight annihilation of positrons to produce photons.

$$K = K_C + K_R$$

Components of Kerma for Neutrons

- kerma for neutrons is basically the energy transferred to protons or heavier recoiling nuclei per unit mass of medium.
- Radiative interactions for heavier particles such as protons is very small

$$K = K_C$$

Collision Kerma

- The expectation value of the net energy transferred to charged particles per unit mass at a point of interest, excluding both the radiative-loss energy and the energy passed from one charged particle to another.
- R_U^R = the radiant energy emitted as radiative losses by the charged particles originating in volume V.
- $(\mu_{en}/\rho)_{E,Z}$ = mass energy-absorption coefficient (cm²/g)

$$K_C = \frac{d\varepsilon_{tr}^{net}}{dm} = \Psi \left(\frac{\mu_{en}}{\rho} \right)_{E,Z}$$

$$\varepsilon_{tr}^{net} = (R_{in})_U - (R_{out})_U^{nonR} - R_U^R + \sum Q = \varepsilon_{tr} - R_U^R$$

Total Mass Attenuation Coefficient

Present tabulations of μ/ρ rely heavily on theoretical values for the total cross section per atom, σ_{tot}

$$\frac{\mu}{\rho} = \frac{\sigma_{tot}}{uA}$$

$$\sigma_{tot} = \sigma_{pe} + \sigma_{coh} + \sigma_{incoh} + \sigma_{pair} + \sigma_{trip} + \sigma_{ph.n.}$$

$U = 1.660\,540\,2 \times 10^{-24}$ g is the atomic mass unit

A = is the relative atomic mass of the target element

Mass energy-transfer coefficient

- f_{pe} is the fraction of energy given to electrons after photoelectric effect
- f_{incoh} is the fraction given to electrons after a Compton scatter
- f_{pair} is the fraction of energy given to the electron and positron after pair production minus the annihilation energy

$$\left(\frac{\mu_{tr}}{\rho} \right) = \frac{f_{pe}\sigma_{pe} + f_{incoh}\sigma_{incoh} + f_{pair}\sigma_{pair}}{uA}$$

Mass energy-absorption coefficient

- g represents the average fraction of secondary-electron energy that is lost in radiative interactions (bremsstrahlung production or in-flight annihilation)

$$\left(\frac{\mu_{en}}{\rho} \right) = \left(\frac{\mu_{tr}}{\rho} \right) (1 - g)$$

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Elemental Data Index

Provides access to the holdings of NIST Physical Measurement Laboratory online data organized by element.

Periodic Table: Atomic Properties of the Elements

Contains NIST critically-evaluated data on atomic properties of the elements. Suitable for high-resolution color printing for desk or wall-chart display.

Physical Constants

Contains values of the fundamental physical constants and a related bibliographic database.

Atomic Spectroscopy Data

Contains databases for energy levels, wavelengths, and transition probabilities for atoms and ions and related bibliographic databases.

Molecular Spectroscopic Data

Includes databases containing spectroscopic data for small molecules, hydrocarbons, and interstellar molecules. In addition, there are two publications containing equations and the underpinning theory for molecular spectroscopy.

Atomic and Molecular Data

Contains databases on electron-impact cross sections (of atoms & molecules) and potential energy surfaces of group II dimers.

X-Ray and Gamma-Ray Data

Contains databases on the interaction of x-rays and gamma-rays with elements and compounds.

Radiation Dosimetry Data



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The use of International Units and the expression of uncertainty in measurement is critical to all data activities. For information on these topics, see [guidelines for evaluating and expressing measurement uncertainty](#), and information on the [International System of Units \(SI\)](#).

Additional data and databases are being prepared for this Web site.

Online: June 1994

Contact

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 Gaithersburg, MD 20899-8400

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X-Ray and Gamma-Ray Data

- X-Ray Attenuation and Absorption for materials of Dosimetric Interest
- XCOM: Photon Cross Sections Database
- Bibliography of Photon Attenuation Measurements
- X-Ray Form Factor, Attenuation and Scattering tables
- X-Ray Transition Energies

X-Ray Attenuation and Absorption for materials of Dosimetric Interest

J. H. Hubbell and S. M. Seltzer

Tables and graphs of computed photon mass attenuation coefficients and mass energy-absorption coefficients from 1 keV to 20 MeV are presented for all of the elements ($Z = 1$ to 92) and for 48 compounds and mixtures of radiological interest. These coefficients are basic quantities used in calculations of the penetration and the energy deposition by photons (x-ray, gamma-ray, bremsstrahlung) in biological, shielding, and other materials.

XCOM: Photon Cross Sections Database

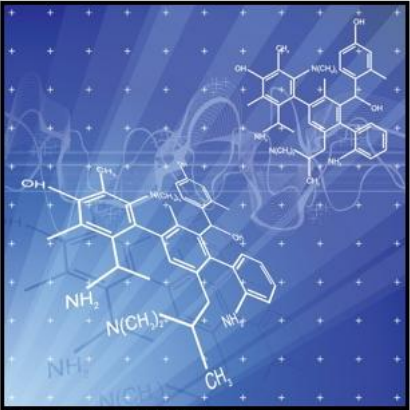
M. J. Berger and J. H. Hubbell

This database can be used to calculate photon cross sections for scattering, photoelectric absorption and pair production, as well as total attenuation coefficients, in any element, compound or mixture, at energies from 1 keV to 100 GeV. This is a web version of the PC based program XCOM (also called NIST Standard Reference Database 8 - XGAM).

Bibliography of Photon Attenuation Measurements

J. H. Hubbell

This bibliography contains papers (1907-1995) reporting absolute measurements of photon (XUV, x-ray, gamma-ray, bremsstrahlung) total interaction cross sections or attenuation coefficients for the elements and some compounds used in a variety of medical, industrial, defense, and scientific applications. The energy range covered is from 10 eV to 12.5 GeV.



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Radiation Dosimetry Data

Stopping-Power and Range Tables for Electrons, Protons, and Helium Ions

M. J. Berger

The databases ESTAR, PSTAR, and ASTAR calculate stopping-power and range tables for electrons, protons, or helium ions, according to methods described in ICRU Reports 37 and 49. Stopping-power and range tables can be calculated for electrons in any user-specified material and for protons and helium ions in 74 materials.



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Physical Reference Data

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Energy Imparted (ϵ)

- The energy imparted by ionizing radiation to the matter in a volume is regarded as the fundamental quantity of radiation dosimetry (stochastic quantity).

- Imparted Energy (δ_ϵ)

$$\delta_\epsilon = T_b - \sum_i T_{a,i} + Q$$

- T_b is the kinetic energy of the interacting ionizing particle immediately before the interaction.
- $\sum T_{a,i}$ is the sum of the kinetic energies of all ionizing particles created in the process, including the residual kinetic energy of the primary particle if this is still an ionizing particle after interaction.
- Q is the release of rest-mass energy of nuclei and elementary particles.

Absorbed dose (D)

$$D = \frac{d\bar{\varepsilon}}{dm}$$

Where $d\bar{\varepsilon}$ is the mean energy imparted by ionizing radiation to the matter in this volume element (1 J/kg = 1 Gy)

Tissue-average absorbed dose (D_T)

$$D_T = \frac{\varepsilon_T}{m_T}$$

Where ε_T is the total energy imparted in a tissue or organ and m_T is the mass of that tissue or organ.

Dose

- same general units of kerma except dose is usually converted to units of rads or Gy (100 rads = 1Gy).
- The expectation value of the energy imparted to matter per unit mass at a point.

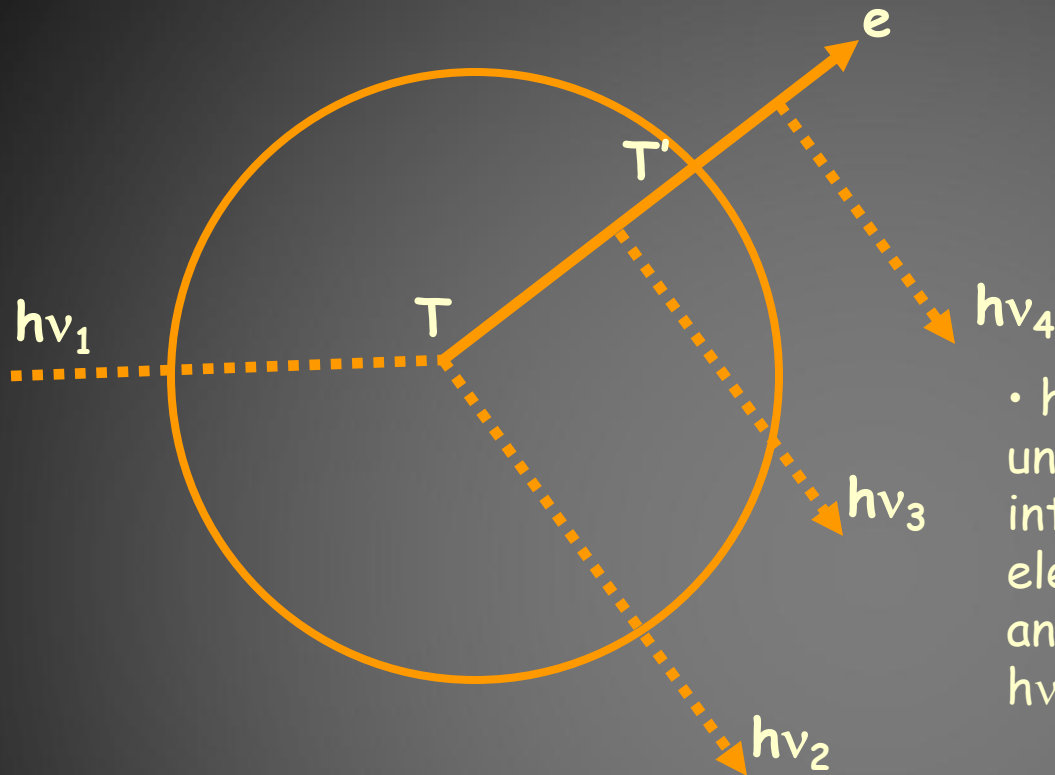
$$\epsilon = (R_{in})_U - (R_{out})_U + (R_{in})_C - (R_{out})_C + \sum Q$$

Dose Equivalent

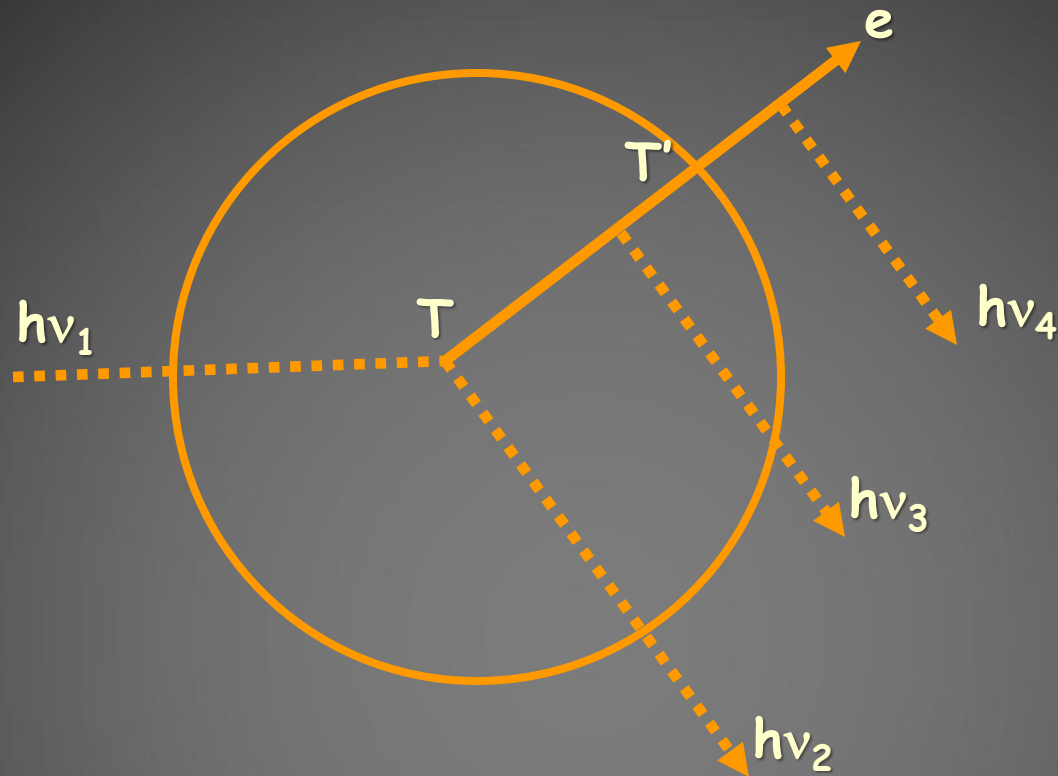
- units of rem or sievert

$$H = DQN$$

- D represents the dose in rads or cGy, Q is the quality factor relating the biological effectiveness of the radiation relative to 250 kVp x-rays, and N represents other factors such as time, oxygen tension, etc.
- Necessary when evaluating the cumulative effect of different types of radiation to the whole body.



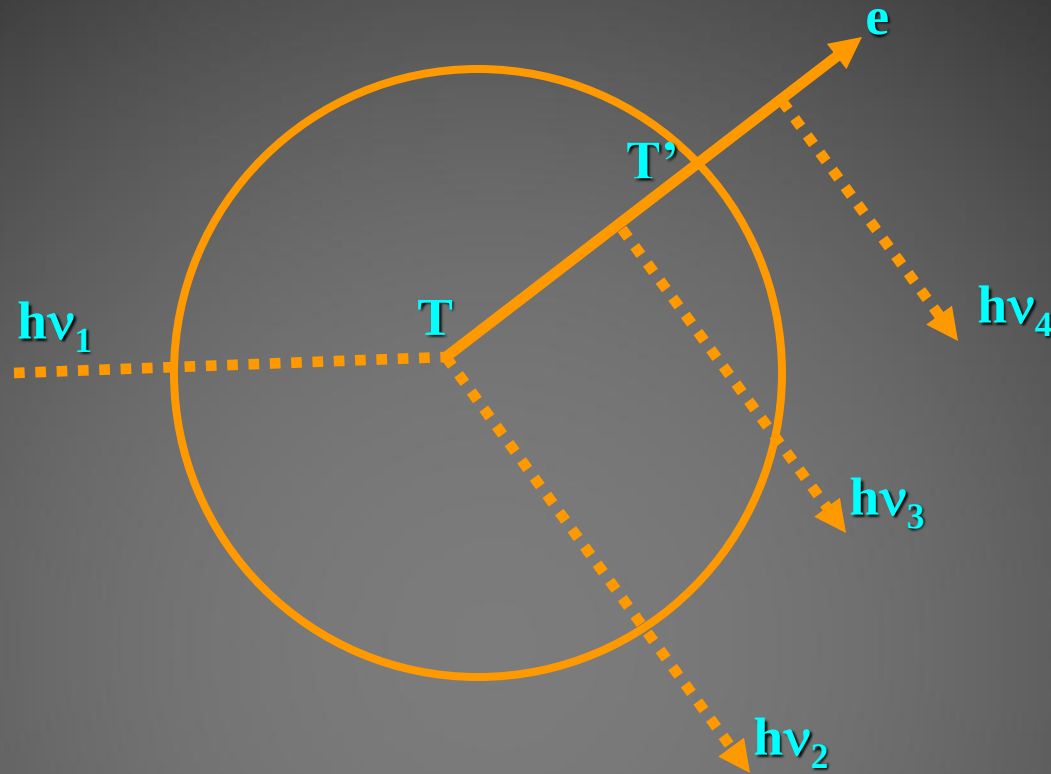
- $h\nu_1$ enters the volume and undergoes a scattering interaction to produce an electron with energy T and scattered photon with energy $h\nu_2$
- Electron produces one bremsstrahlung photon ($h\nu_3$) and leaves the volume with energy T'
- Bremsstrahlung photon $h\nu_4$ is produced outside of the volume.



$$\mathcal{E}_{tr} = (R_{in})_U - (R_{out})_U^{nonR} + \sum Q$$

$$\mathcal{E}_{tr} = \underbrace{h\nu_1 - h\nu_2}_{+0}$$

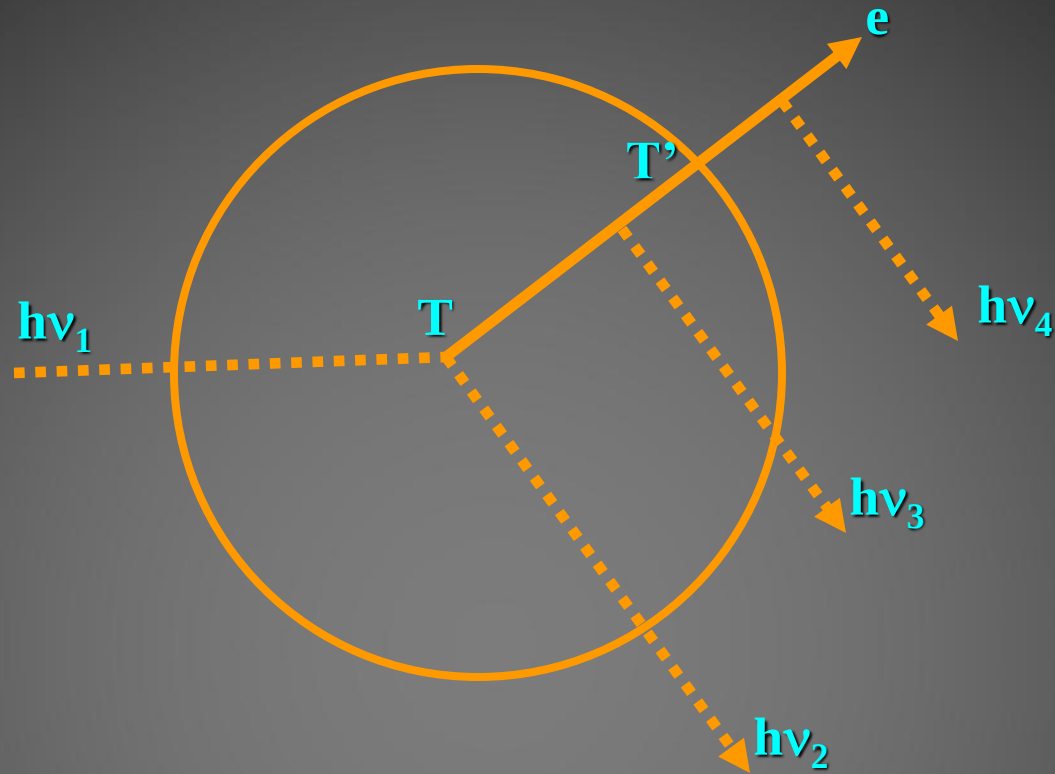
Represents the energy transferred to the electron (T) and assumes all energy is deposited at the i/a site.



$$\mathcal{E}_{tr}^{net} = (R_{in})_U - (R_{out})_U^{nonR} - R_U^R + \sum Q = \mathcal{E}_{tr} - R_U^R$$

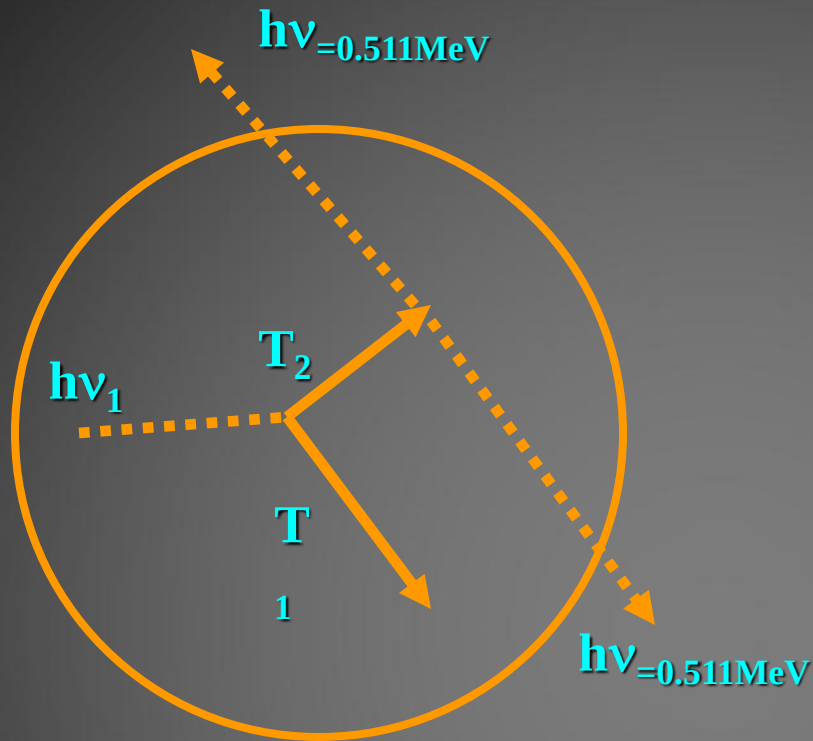
$$\mathcal{E}_{tr}^n = \mathcal{E}_{tr} - \underbrace{(h\nu_3 + h\nu_4)}$$

Represents the radiant energy taken away from the i/a site via radiative interactions.



$$\mathcal{E} = (R_{\text{in}})_U - (R_{\text{out}})_U + (R_{\text{in}})_C - (R_{\text{out}})_C + \sum Q$$

$$\mathcal{E} = \underbrace{h\nu_1}_{\text{Energy}_{\text{in}}} - \underbrace{(h\nu_2 + h\nu_3 + T')}_{\text{Energy}_{\text{out}}}$$



- $h\nu_1$ is emitted via radioactive decay and undergoes a pair production interaction producing an electron and positron with energy T_1 and T_2 respectively.
- The electron and positron deposit all of their energy in the volume.
- The positron annihilates at end of range to produce two 511 keV photons.

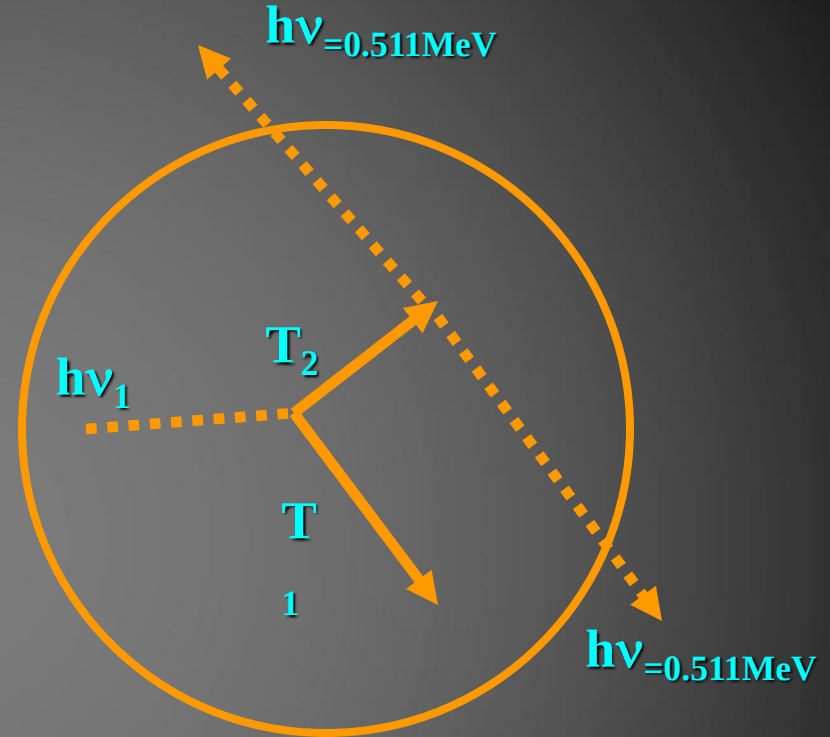
$$\mathcal{E}_{tr} = (R_{in})_U - (R_{out})_U^{nonR} + \sum Q$$

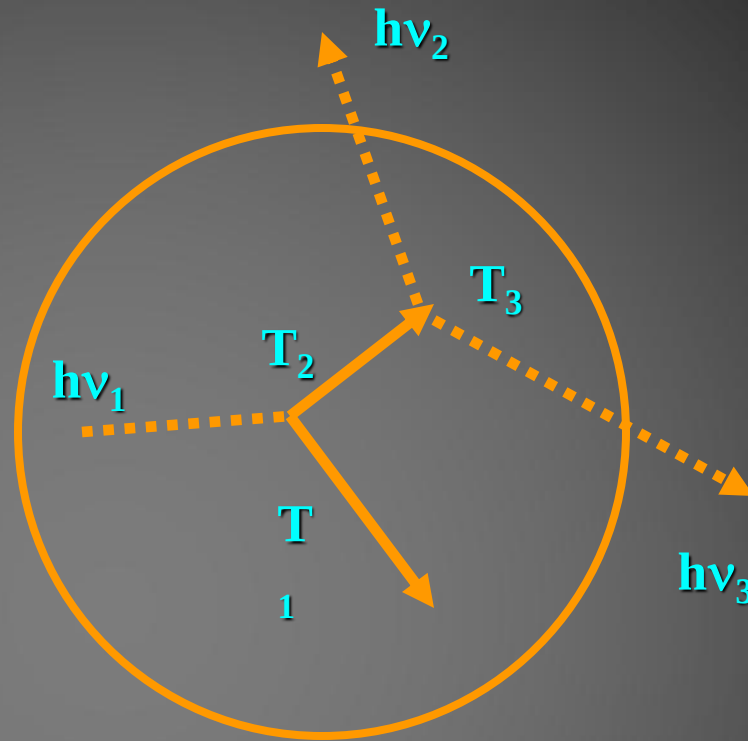
$$\mathcal{E}_{tr} = 0 - 1.022 + \sum Q$$

$$\sum Q = h\nu_1 - 2m_0c^2 + 2m_0c^2$$

$$\mathcal{E}_{tr} = h\nu_1 - 1.022 = T_1 + T_2$$

$$\mathcal{E} = \mathcal{E}_{tr} = \mathcal{E}_{tr}^n$$

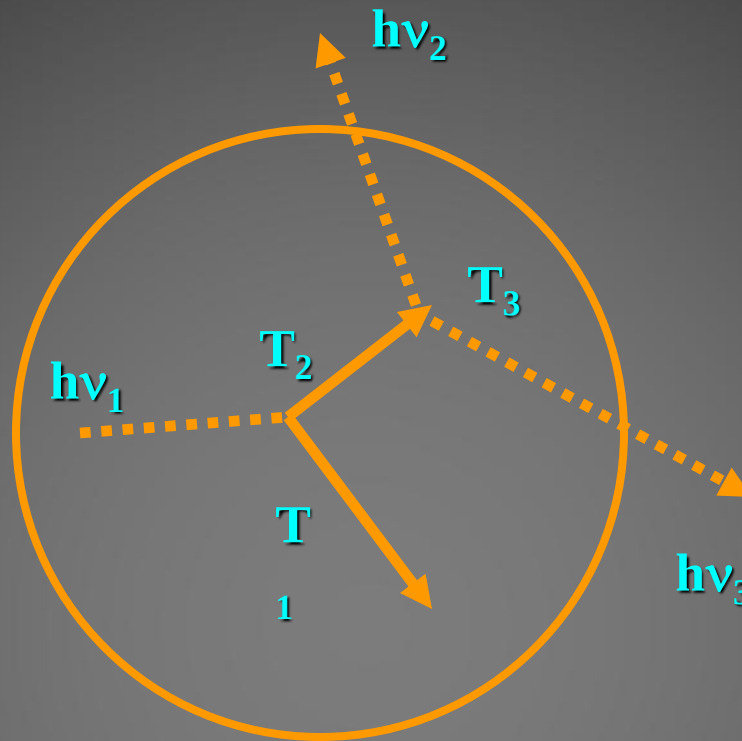




$$\mathcal{E}_{tr} = (R_{in})_U - (R_{out})_U^{nonR} + \sum Q$$

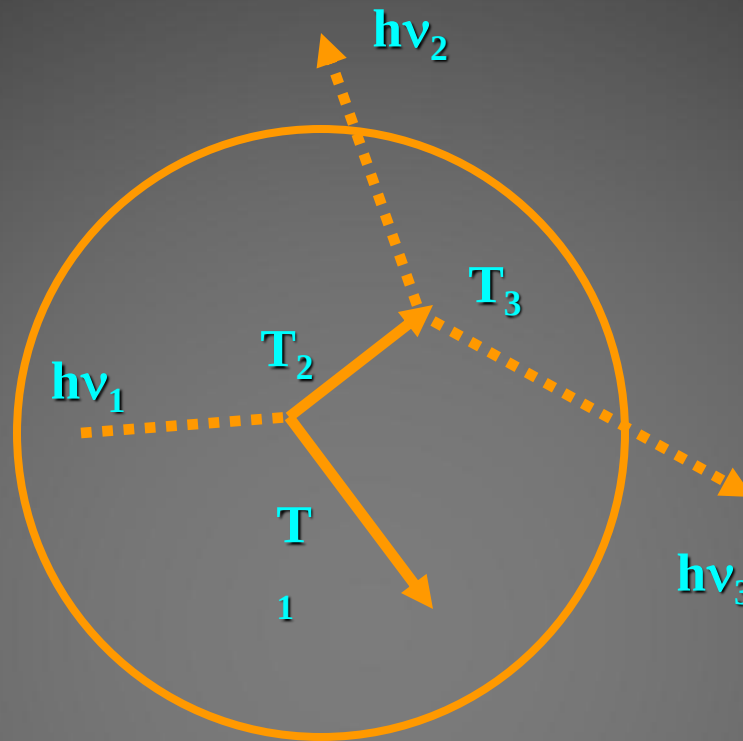
$$\mathcal{E}_{tr} = 0 - 1.022 + h\nu_1 = \underbrace{T_1 + T_2}$$

Assumes the total electron energy created at the pair production i/a is deposited on the spot.



$$\mathcal{E}_{tr}^{net} = (R_{in})_U - (R_{out})_U^{nonR} - R_U^R + \sum Q = \mathcal{E}_{tr} - R_U^R$$

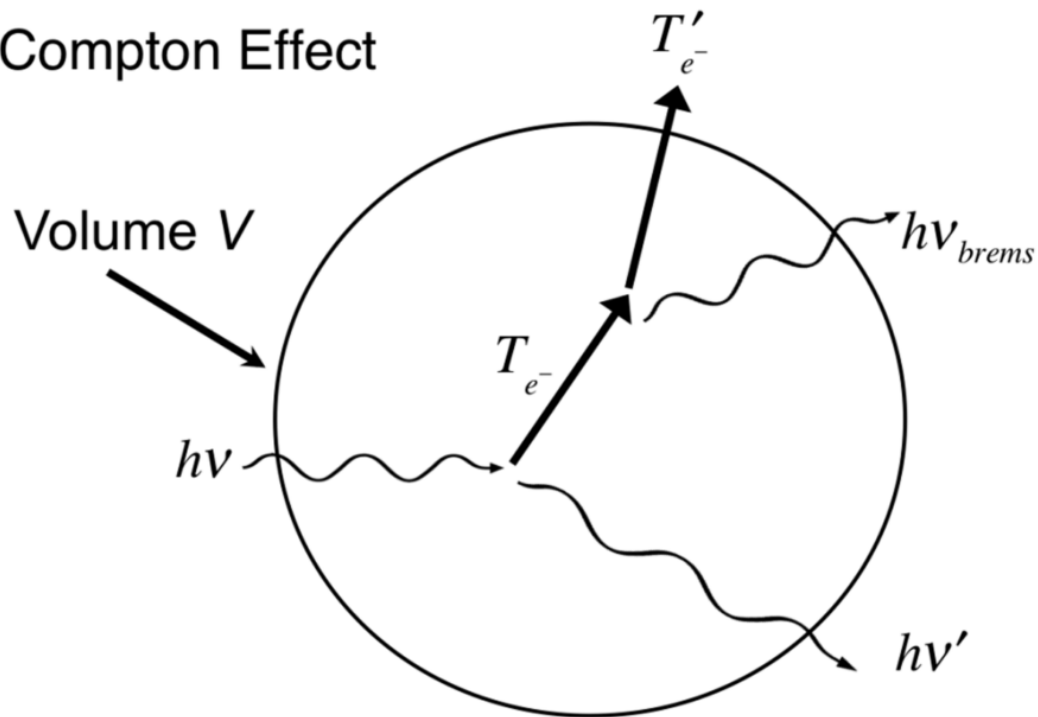
$$\mathcal{E}_{tr}^{net} = (T_1 + T_2) - \underbrace{(h\nu_3 + h\nu_2)}_{\text{where } T_3 = h\nu_3 + h\nu_2} = T_1 + T_2 - T_3$$



$$\mathcal{E} = (R_{\text{in}})_{\text{U}} - (R_{\text{out}})_{\text{U}} + (R_{\text{in}})_{\text{C}} - (R_{\text{out}})_{\text{C}} + \sum Q$$

$$\mathcal{E} = 0 - (h\nu_3 + h\nu_2) + 0 - 0 + h\nu_1 = T_1 + T_2 + T_3$$

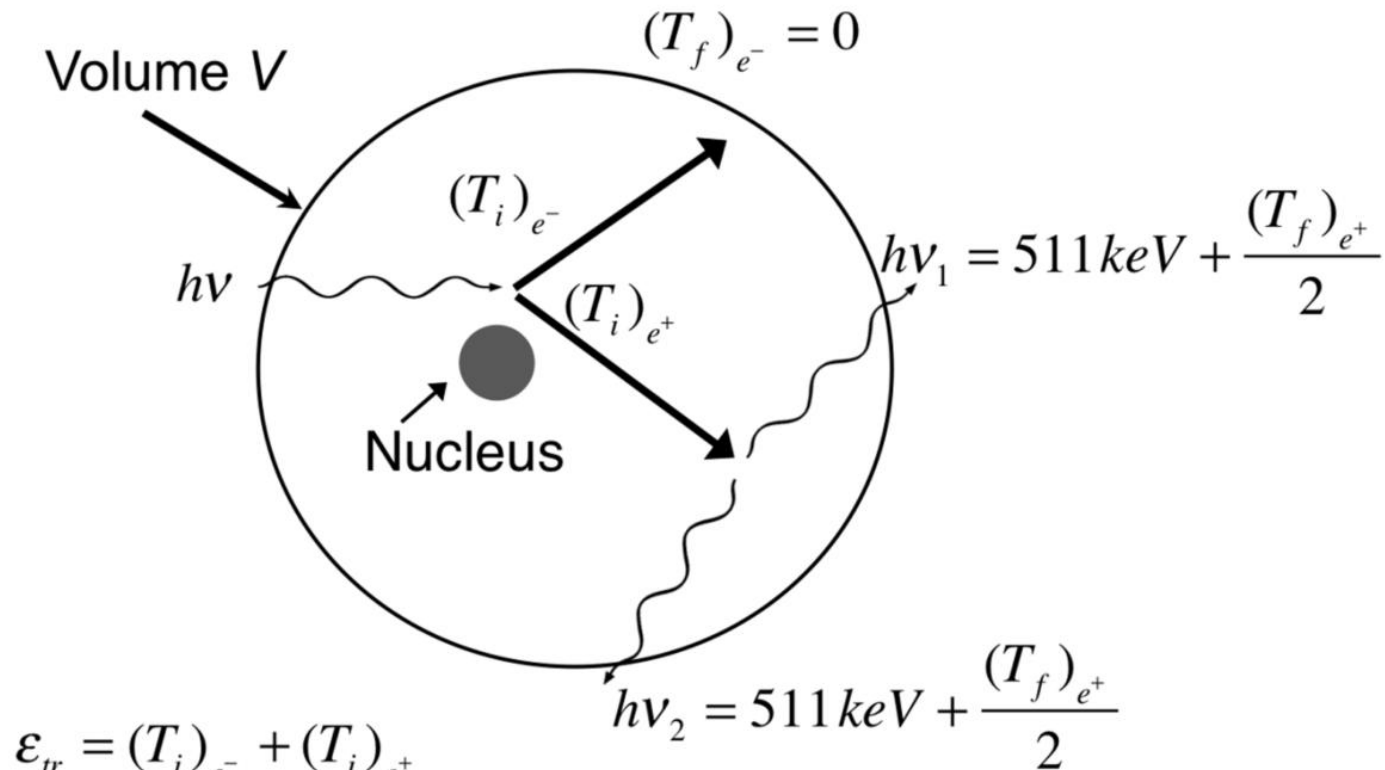
Compton Effect



$$\mathcal{E}_{tr} = T_{e^-}$$

$$\mathcal{E}_{tr}^{net} = T_{e^-} - h\nu_{brems}$$

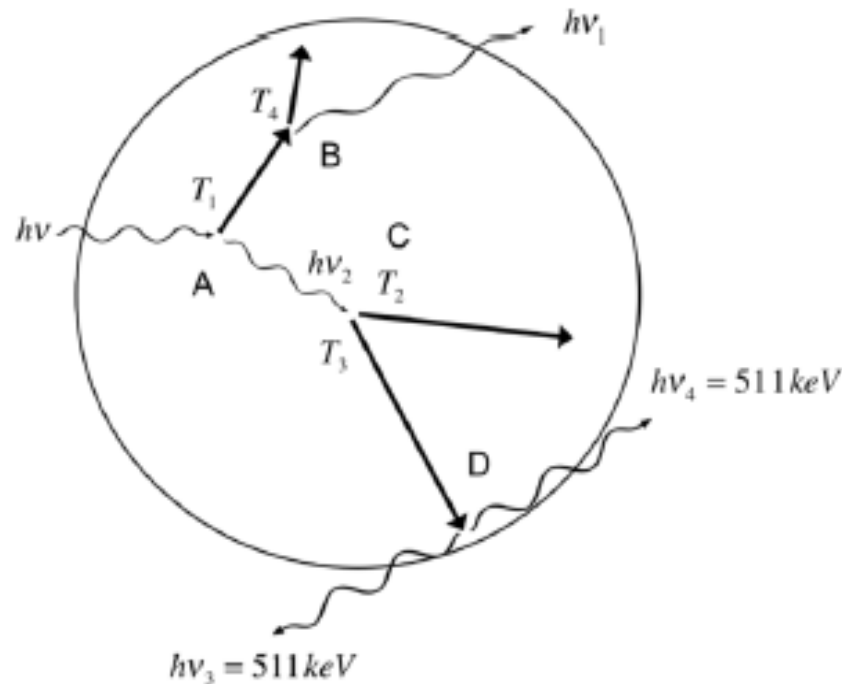
Pair production with annihilation in flight



$$\mathcal{E}_{tr} = (T_i)_{e^-} + (T_i)_{e^+}$$

$$\mathcal{E}_{tr}^{net} = (T_i)_{e^-} + (T_i)_{e^+} - \left[(T_f)_{e^-} + (T_f)_{e^+} \right]$$

3. For the geometry depicted in the figure below, calculate the energy transferred to charged particles, ϵ_{tr} , and the net energy transferred, ϵ_{tr}^{net} inside the volume encompassed by the circle. Interaction A is a Compton interaction, B is bremsstrahlung production, C is pair production, and D is positron annihilation. Assume that electrons T_2 and T_4 and positron T_3 expend all kinetic energy within the volume.



Exposure

- The absolute value of the total charge of the ions of one sign produced in air when all the e-'s (+&-) liberated by photons in air of mass dm are completely stopped in air.
- The ionization arising from the absorption of bremsstrahlung emitted by the e-'s is not to be included in dQ .
- The exposure is the ionizational equivalent of the collision kerma (K_c) in air for x- and gamma rays.

$$X = \frac{dQ}{dm}$$

Relation of exposure to collision kerma

- W/e = the mean energy expended in a gas per ion pair formed
- W/e for air = 33.97 eV/i.p.

$$\frac{\overline{W}_{air}}{e} = \left(\frac{33.97 \text{ eV/i.p.}}{1.602 \times 10^{-9} \text{ C/e}} \right) (1.692 \times 10^{-19} \text{ J/eV})_{air} = 33.97 \text{ J/C}$$

$$X = \psi \left(\frac{\mu_{en}}{\rho} \right)_{E,air} \left(\frac{e}{\overline{W}} \right)_{air} = \frac{K_C^{air}}{33.97}$$

$$1R = \left(\frac{1esu}{0.001293g} \right) \left(\frac{1c}{2.998 \times 10^9 esu} \right) \left(\frac{1000g}{1kg} \right) = 2.580 \times 10^{-4} c/kg$$

$$K_C^{air} = 0.876 \cdot X = D_{air} \text{ (in the presence of CPE)}$$

This relationship is significant because it allows one to calculate the absorbed dose based upon the exposure reading from a calibrated ion chamber

charged-particle equilibrium

Equivalent dose ($H_{T,R}$)

$$H_{T,R} = w_R D_{T,R}$$

Where $D_{T,R}$ is the average dose from radiation R in the tissue or organ T and w_R is the radiation weighting factor (1 J/kg = 1 Sv)

Effective dose (E)

$$E = \sum_T w_T H_T$$

Where H_T is the equivalent dose in tissue or organ T and w_T is the weighting factor for tissue T.

Radiation Weighting Factors

Type and energy range	Radiation weighting factor (w_R)
Photons, all energies	1
Electrons & muons, all energies	1
Neutrons, energy < 10keV	5
10 keV to 100 keV	10
100 keV to 2 MeV	20
2 MeV to 20 MeV	10
> 20 MeV	5
Protons, other than recoil protons, $E > 2\text{MeV}$	5
Alpha particles, fission fragments, heavy nuclei	20

Tissue Weighting Factors

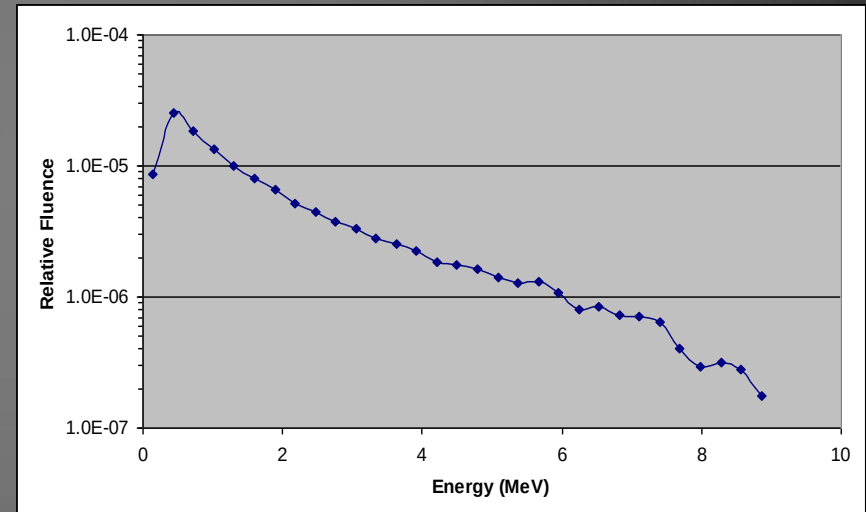
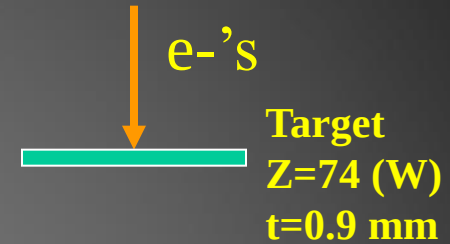
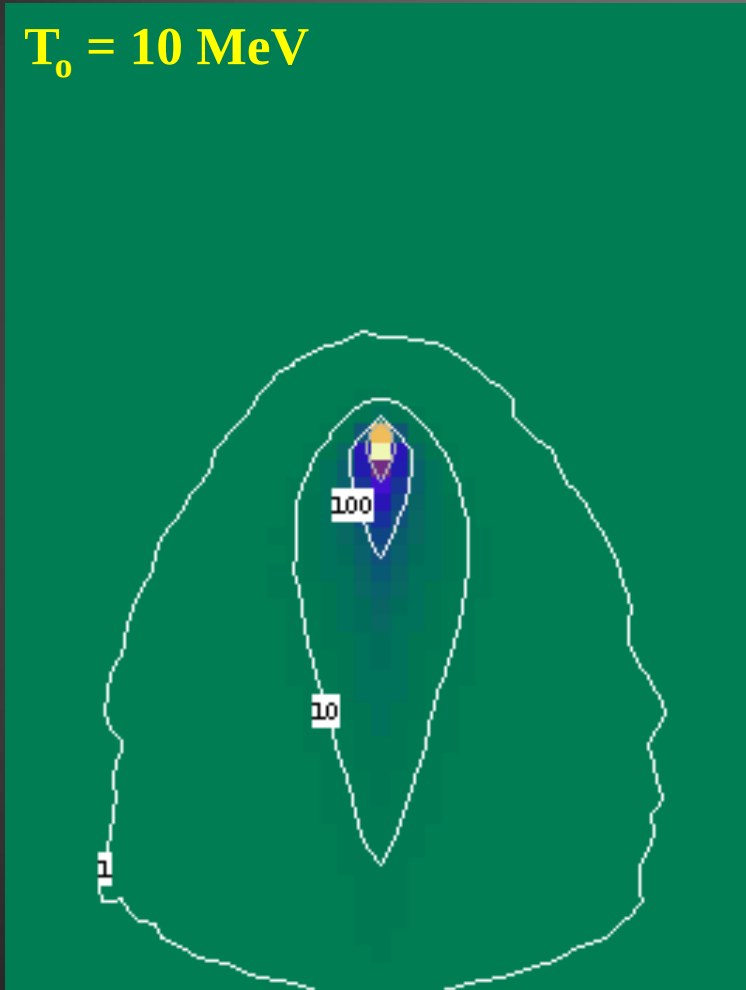
Tissue or organ	Tissue weighting factor (w_T)
Gonads	0.20
Bone Marrow (red)	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Esophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surface	0.01
Remainder	0.05

Radiation Exposure Limits (10 CFR 20)

	Annual Limit	
Whole Body:	50	mSv/yr
Eyes:	150	mSv/yr
Extremities & Skin:	500	mSv/yr
Member of Public:	1	mSv/yr
Embryo-Fetus:	5	mSv/9 mo.
Minors:	10%	of above

Bremsstrahlung intensity distribution (Therapy)

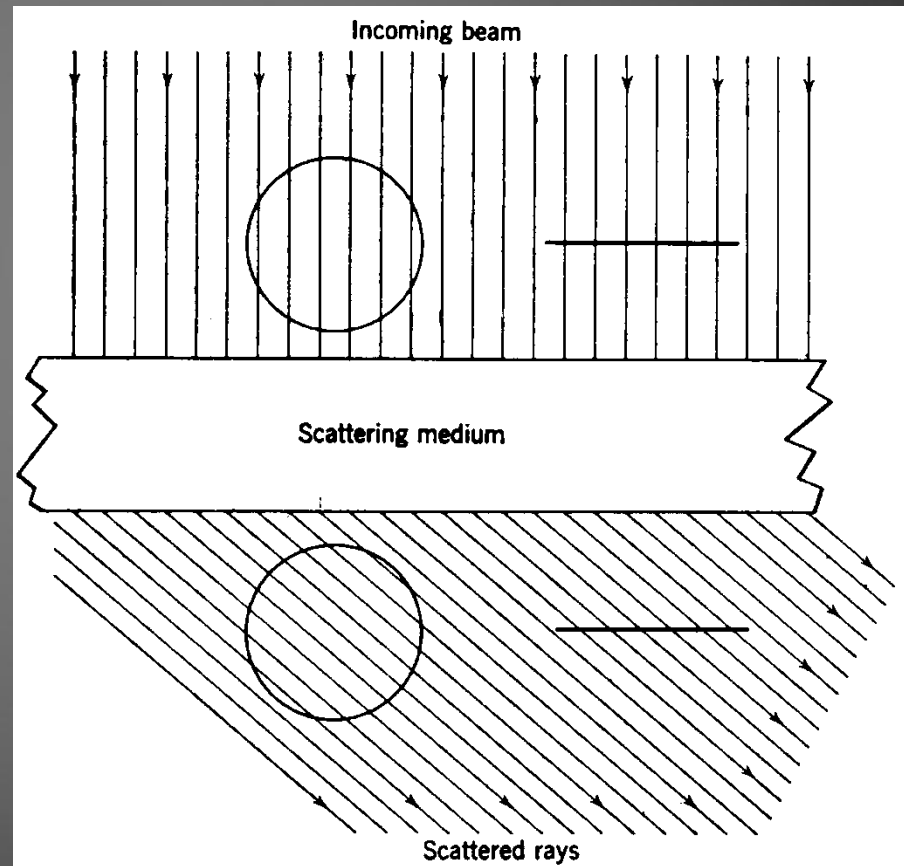
$T_0 = 10 \text{ MeV}$



Planar fluence

- The number of particles crossing a fixed plane in either direction (i.e., summed by scalar addition) per unit area of the plane.

The number of incident particles striking each detector above the scattering foil is the same and the planar fluence is equal to the fluence. This is only true for a plane-parallel beam orthogonal to the flat detector.

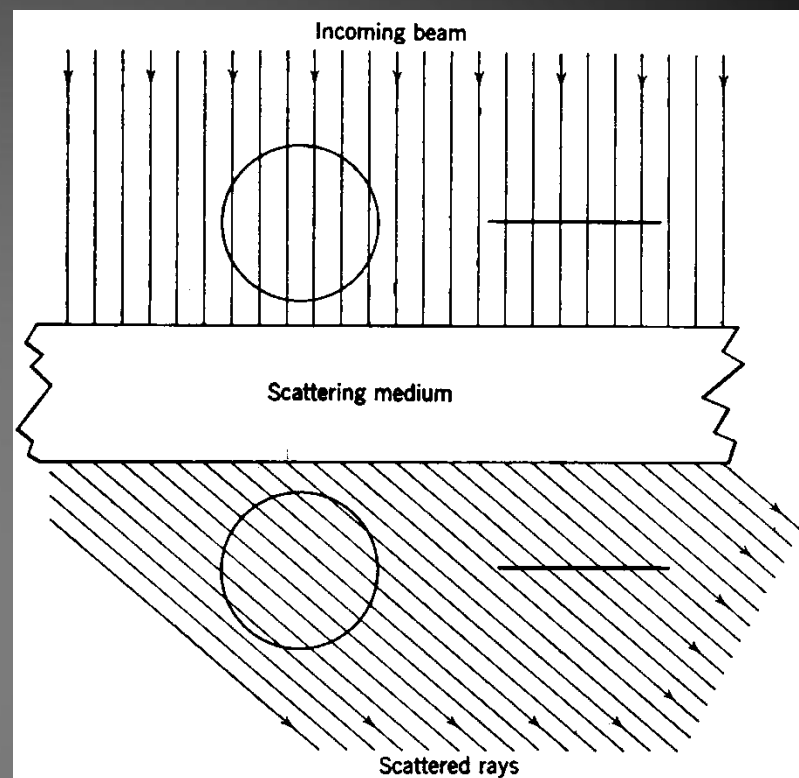


For the sphere

- The number of scattered particles striking the spherical detector below the foil is $1/\cos\theta$ times the number striking above.
- The average track length through the sphere is the same, above and below

For the foil

- The number of scattered particles striking the foil detector is the same above and below.
- The average track length through the foil is $1/\cos\theta$ times the number striking above.



In broad beam geometry, the fluence behind an attenuating layer can be greater than that incident.

$$Fluence = \frac{Planar\ Fluence}{\cos \theta}$$