A Practical Introduction to Particle Physics

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Students Orientation Session

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With figures from William R. Leo, *Techniques for Nuclear and Particle Physics Experiments*

We need to know the interactions because it is critical to our understanding of our detectors

- How is the signal I am looking for going to look like?
- Considering the material I am using, what kind of background am I expecting?
- How can I shield the detector?

What are the “particles” and the “matter

Dreamstime.com

“Matter” can be anything

- Molecules
- Crystals
- Atoms
- A large sphere of liquified noble 2km underground…

A non-exhaustive list of particles

- Photons
- Electrons/positrons
- Nuclei (Proton, α, recoil nuclei…)
- Ions
- Muons
- Neutrinos
- WIMPs
- …

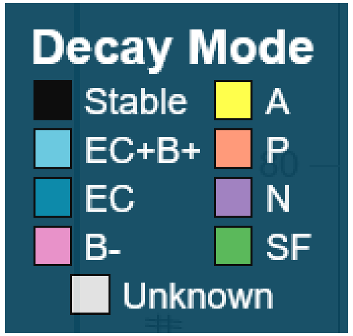
Natural radioactivity: broad source of particles

- Electromagnetic: X-rays and γ-rays
- Corpuscular: Electrons/Positrons, α-particles, neutrons, protons, fission fragments, muons, neutrinos…

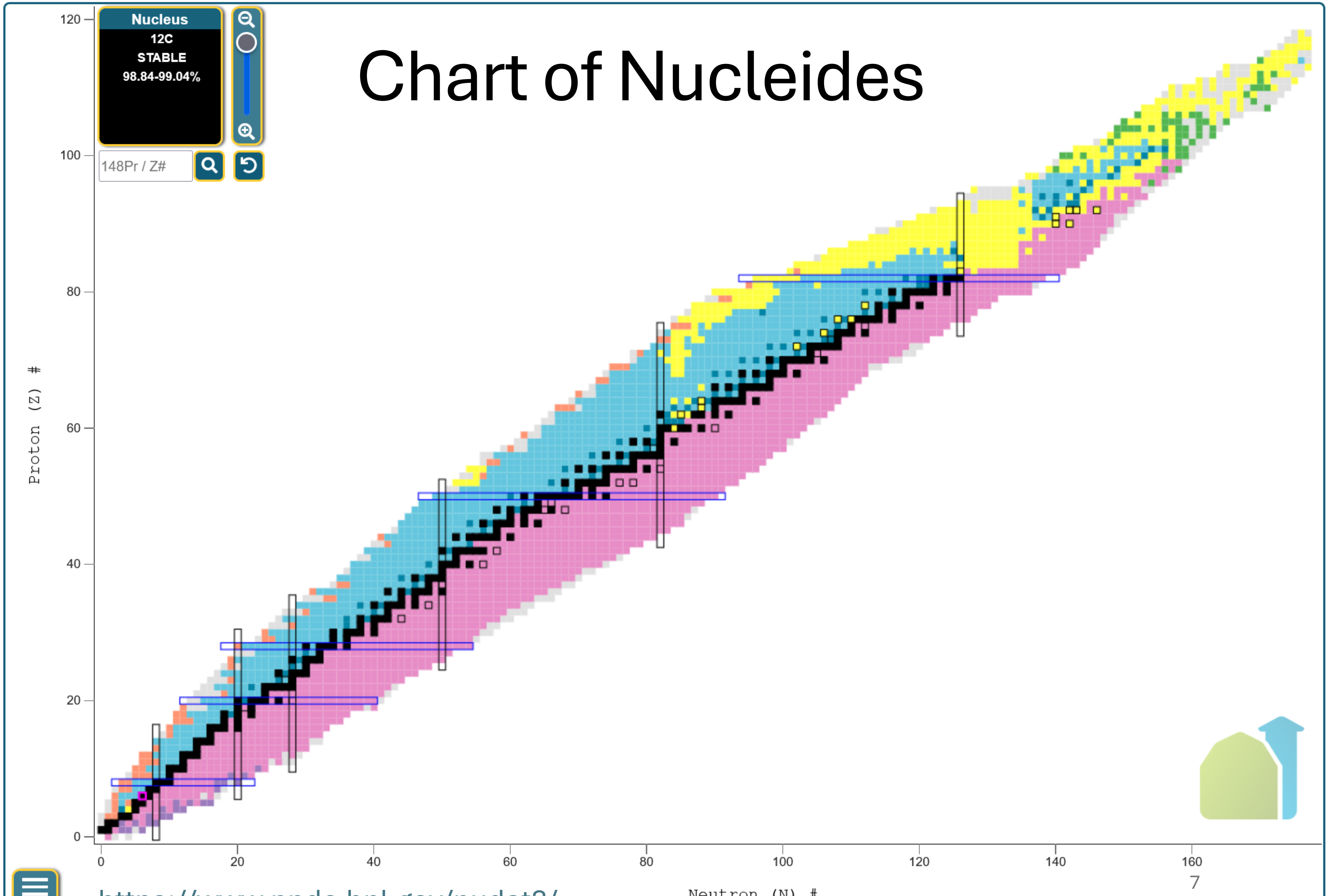
Table 1.1. Characteristics of nuclear radiations

Type	Origin	Process	Charge	Mass [MeV]	Spectrum (energy)
α-particles	Nucleus	Nuclear decay or reaction	+2	3727.33	Discrete [MeV]
β^--rays	Nucleus	Nuclear decay	−1	0.511	Continuous [keV – MeV)
β^+-rays (positrons)	Nuclear	Nuclear decay	+1	0.511	Continuous [keV – MeV]
γ-rays	Nucleus	Nuclear deexcitation	0	0	Discrete [keV – MeV]
x-rays	Electron cloud	Atomic deexcitation	0	0	Discrete [eV – keV]
Internal conversion electrons	Electron cloud	Nuclear deexcitation	−1	0.511	Discrete [high keV]
Auger electrons	Electron cloud	Atomic deexcitation	−1	0.511	Discrete [eV – keV]
Neutrons	Nucleus	Nuclear reaction	0	939.57	Continuous or discrete [keV – MeV]
Fission fragments	Nucleus	Fission	≃20	80 – 160	Continuous 30 – 150 MeV

Chart of Nucleides

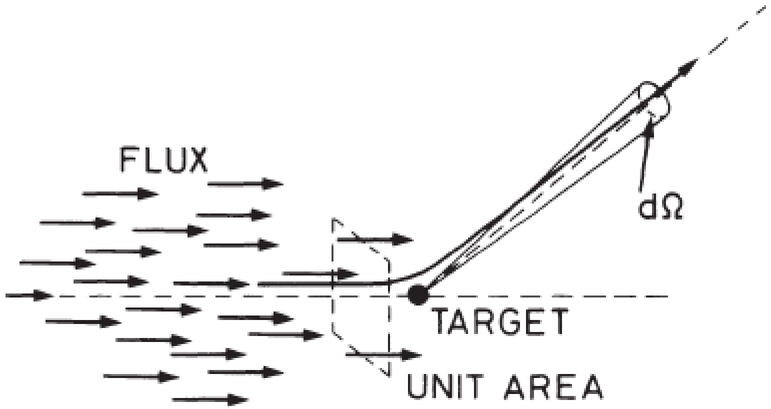


EC: electron capture
A: α-emission
B: β-emission
N: Neutron
P: Proton
SF: Spontaneous Fission



https://www.nndc.bnl.gov/nudat3/

Cross section



Large beam, homogeneous on target, with flux F : number of incident particle per unit of area, per unit of time

Probability for scattering in a solid angle dΩ:

$$\frac{d\sigma}{d\Omega}(E, \Omega) = \frac{1}{F}\frac{dN_s}{d\Omega}$$

$\Rightarrow$ $d\sigma$ has dimension of area, referred as Cross section

Total cross section:

$$\sigma(E) = \int d\Omega \frac{d\sigma}{d\Omega}$$

For a real material (many scattering centers):

$$N_s(\Omega) = F A\, N\, \delta x \frac{d\sigma}{d\Omega}$$

Target area

Thickness

Density centers

For all angles: $N_{tot} = F A\, N\, \delta x\, \sigma$

If single particle on large target of thickness δx: $P_{int} = N\sigma\delta x$

Probability not having an interaction after a distance *x*: $P(x)$

wdx: probability of having an interaction between *x* and *x*+*dx*
So Probability of not having an interaction between *x* and *x*+*dx* is:

$$P(x + dx) = P(x)(1 - wdx)$$

$$P(x) + \frac{dP}{dx}dx = P - Pwdx$$

$$dP = -wPdx$$

Probability of not having had any interaction after distance x :
$P(x) = e^{-wx}$ (with P(0)=1)

Mean distance λ traveled by the particle without suffering a collision is the *Mean Free Path*

Proba interaction in distance x: $P_{int}(x) = 1 - e^{-wx}$

$$\lambda = \frac{\int xP(x)dx}{P(x)dx} = \frac{1}{w}$$

If we consider a thin target δx, $P_{int} \approx \frac{\delta x}{\lambda}$ ➔ $\lambda = \frac{1}{N\sigma}$

Charged particles through material (not e-)

Loss of energy

Change of trajectory

Mainly due to :

- Inelastic collisions with atomic e^-
- Elastic scattering from nuclei

Also :

- Cherenkov radiation
- Nuclear reactions
- Bremsstrahlung

Inelastic collisions responsible for most of the energy losses

Energy transferred from particles to atom ➔ excitation or ionization

Small transfer for each collision, but number of collisions large

Elastic collisions are less frequent

Large mass of the nucleus usually means that little energy is transferred

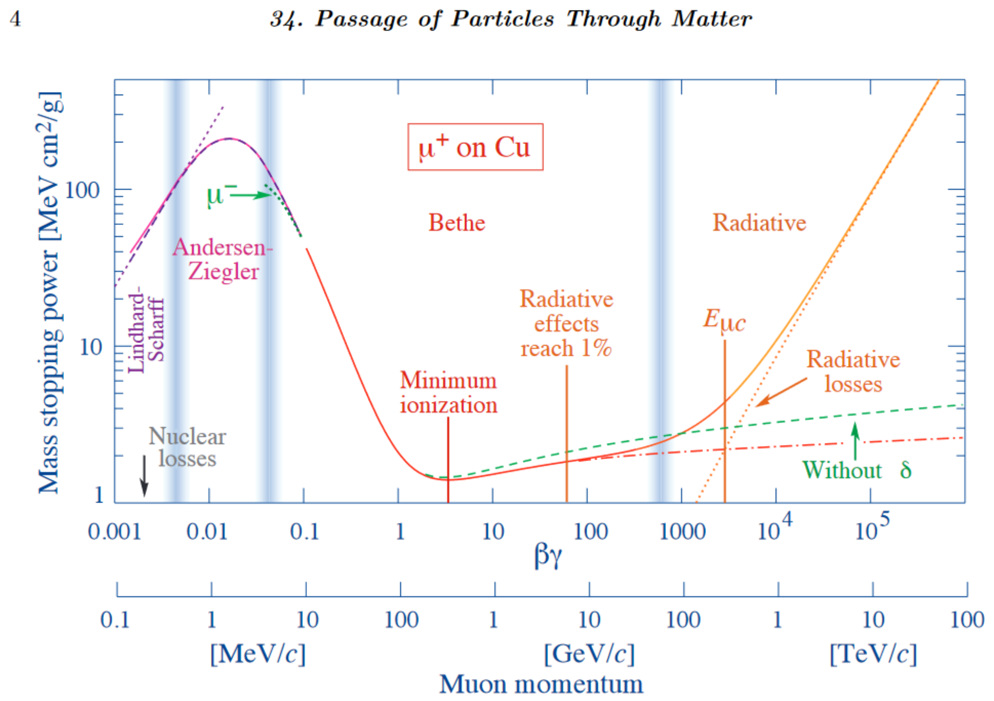
Stopping power or ${dE}/{dx}$

Large number of collision

➔fluctuation in the energy losses are small

➔Easier to work with the average energy loss per unit path length

Bethe-Bloch Formula:

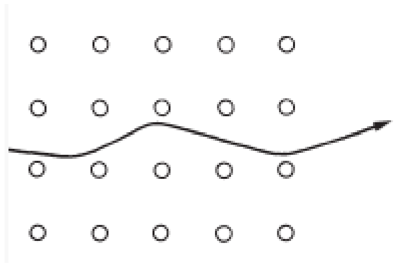


Remarks on the Bethe-Bloch formula

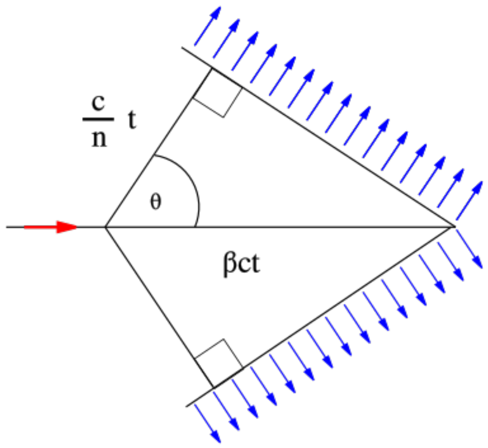
- If $\frac{dE}{dx}$ is expressed in units of mass thickness, it vary little over a wide range of materials.

- For slow moving particles, $\frac{v}{c} < 0.05$ many of the assumptions in the formulas are not valid anymore.

- In crystals, “channeling” may occur and the energy loss will be lower



Cherenkov Radiation

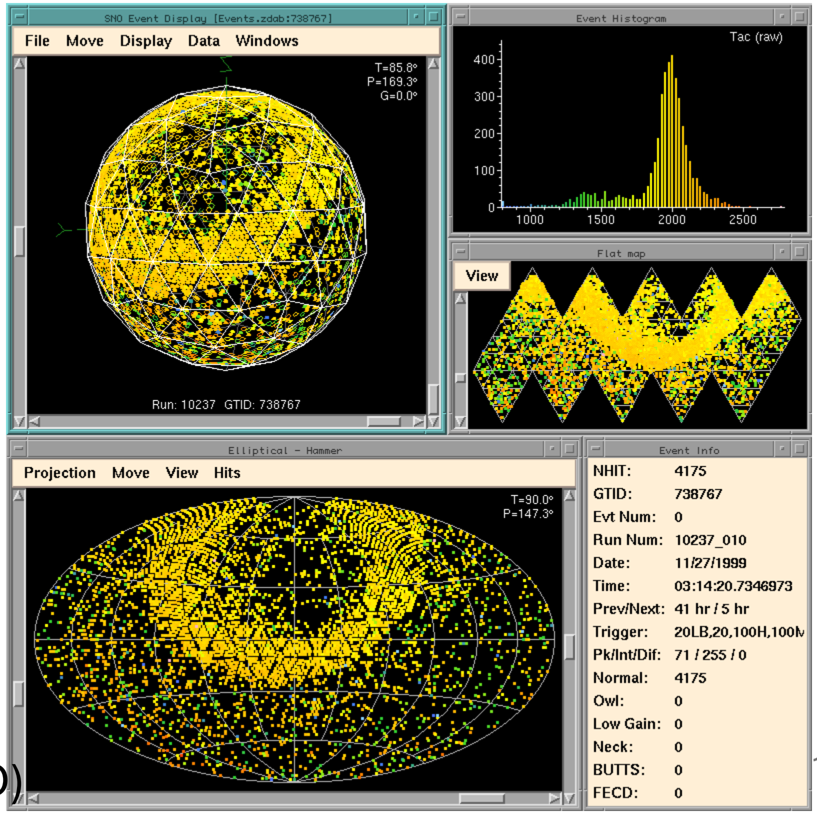


$$\frac{c}{n} \leq v_p < c$$

$$\beta = \frac{v_p}{c}$$

$$\rightarrow \cos\theta = \frac{1}{n\beta}$$

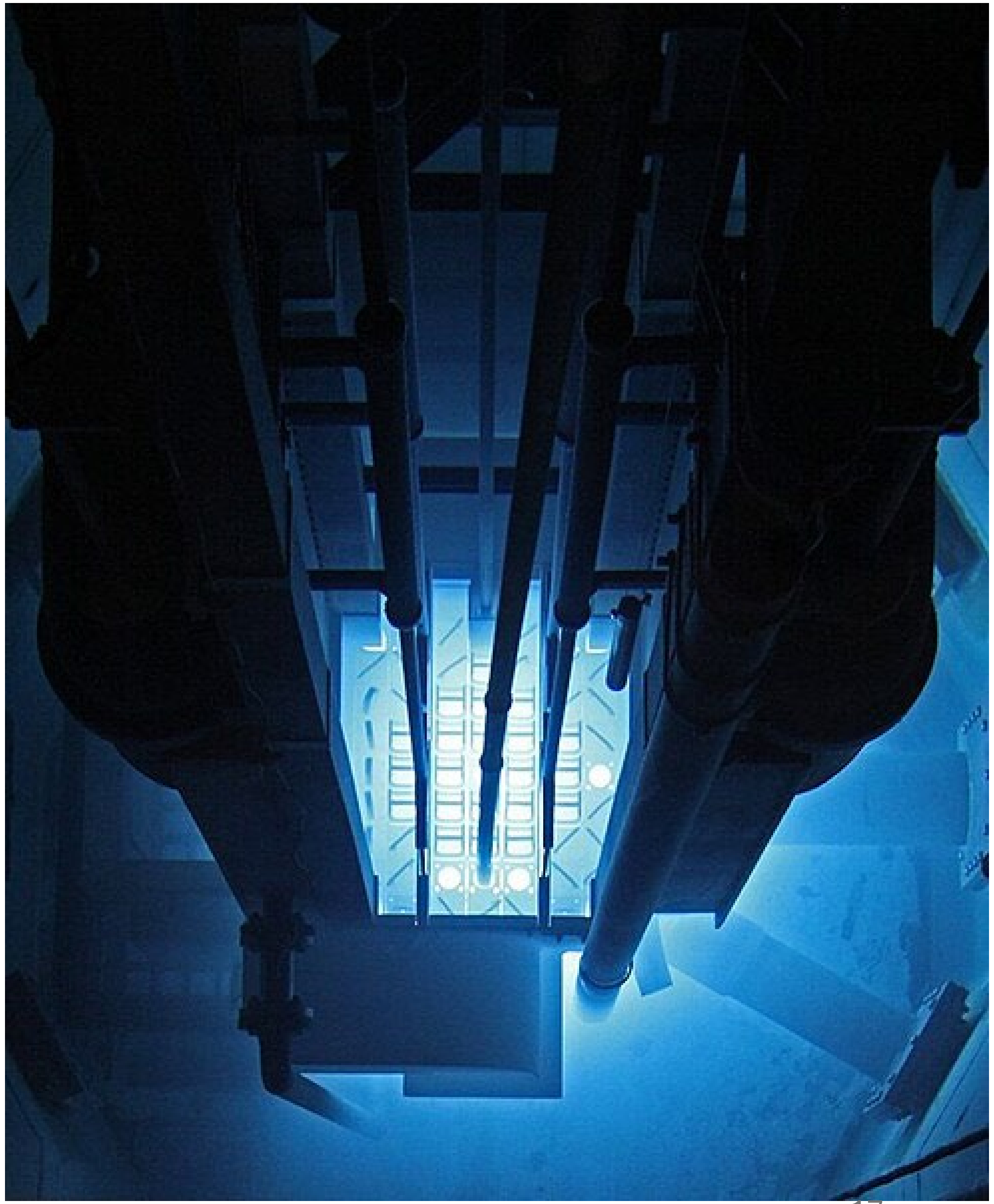
- "Sonic Boom" of light
- Particle must be traveling faster than the speed of light in the medium
- Light is emitted only at angle θ



An upward going contained event (SNO)

Cherenkov Radiation

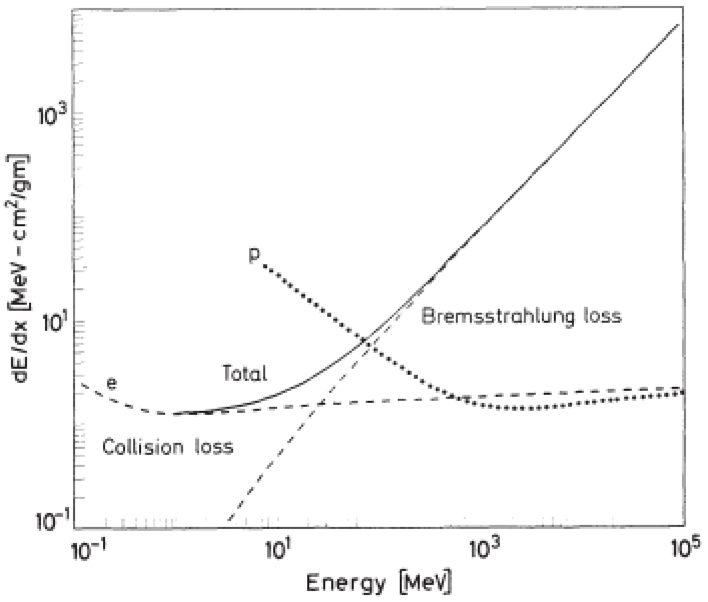
- “Sonic Boom” of light
- Particle must be traveling faster than the speed of light in the medium
- Light is emitted only at angle θ_c
- Extremely weak source of light



Electrons and Positrons

Collisional Energy losses through matter

Due to small mass, Bremsstrahlung is not negligeable and can become dominant at high energies



$$\left(\frac{dE}{dx}\right)_{tot} = \left(\frac{dE}{dx}\right)_{brem} + \left(\frac{dE}{dx}\right)_{coll}$$

Modified Bethe-Block formula

Radiation length: distance at which e- energy is divided by 2

Table 2.3. Radiation lengths for various absorbers

Material	[gm/cm^2]	[cm]
Air	36.20	30050
H_2O	36.08	36.1
NaI	9.49	2.59
Polystyrene	43.80	42.9
Pb	6.37	0.56
Cu	12.86	1.43
Al	24.01	8.9
Fe	13.84	1.76
BGO	7.98	1.12
BaF_2	9.91	2.05
Scint.	43.8	42.4

Photons (X-rays and Y-rays)

Main interactions:

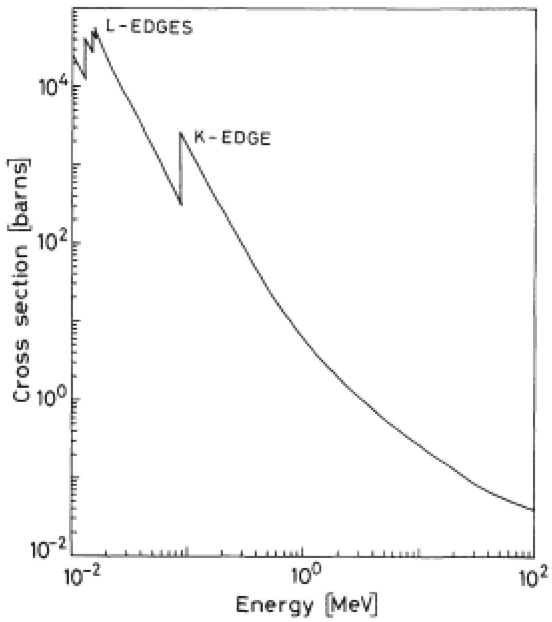
- Photoelectric effect
- Compton scattering
- Pair production

A beam of photon is not degraded by passing through matter, but attenuated in intensity $I(x) = I_0 \exp(-\mu x)$ with μ the absorption coefficient

Photoelectric Effect

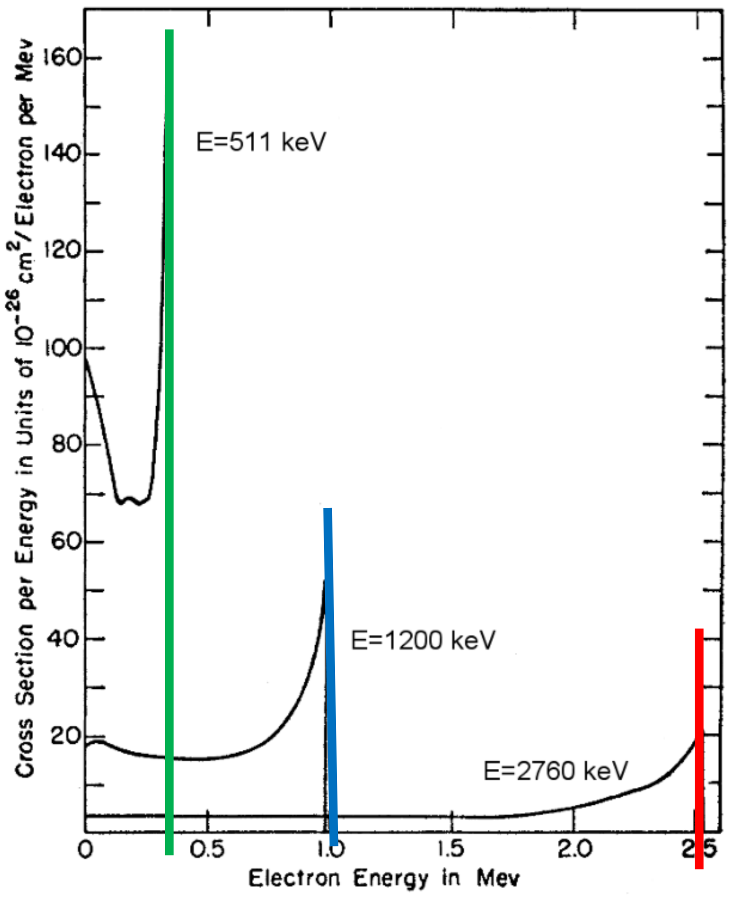
- Photon is absorbed by atom, electron is released

- Electron has energy equal to photon energy – atomic binding energy



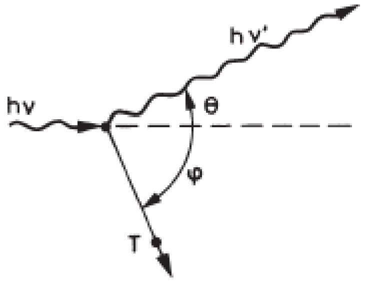
Calculated photoelectric cross section for lead

Compton Scattering



Electron Energy

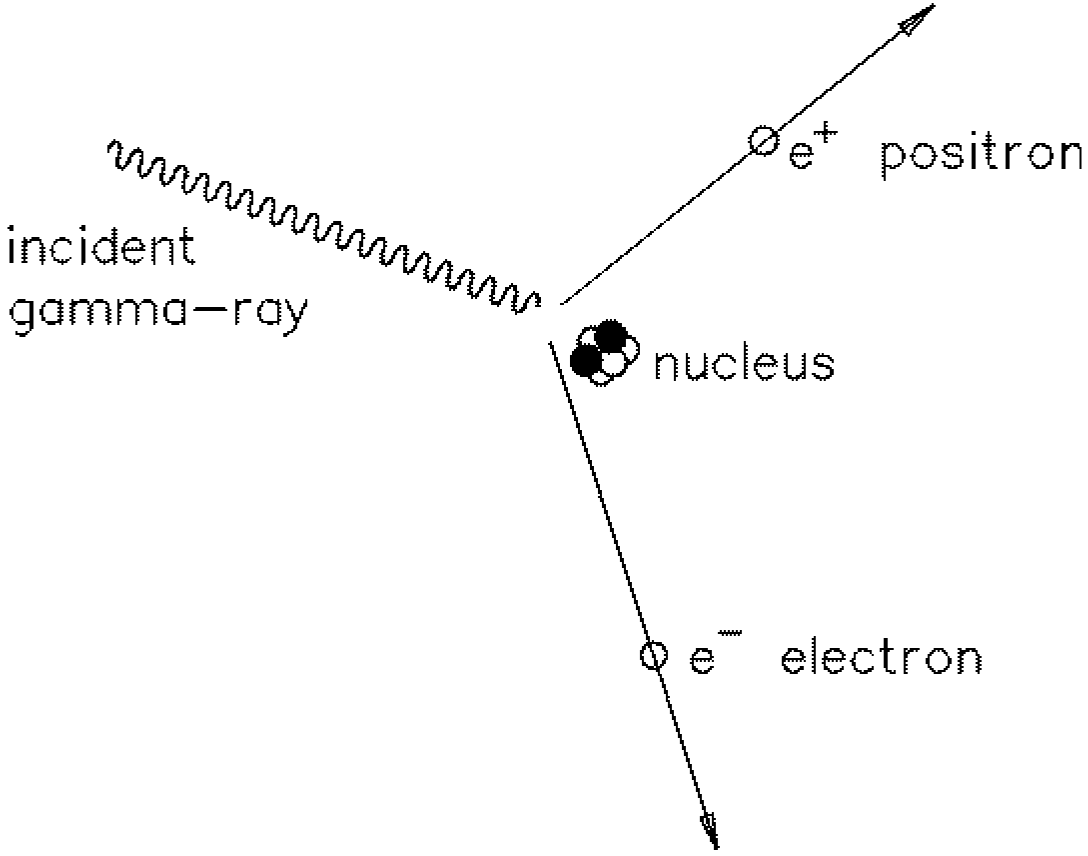
Photon bounces off an electron like billiard balls



Exit direction of photon determines energy of photon and electron.

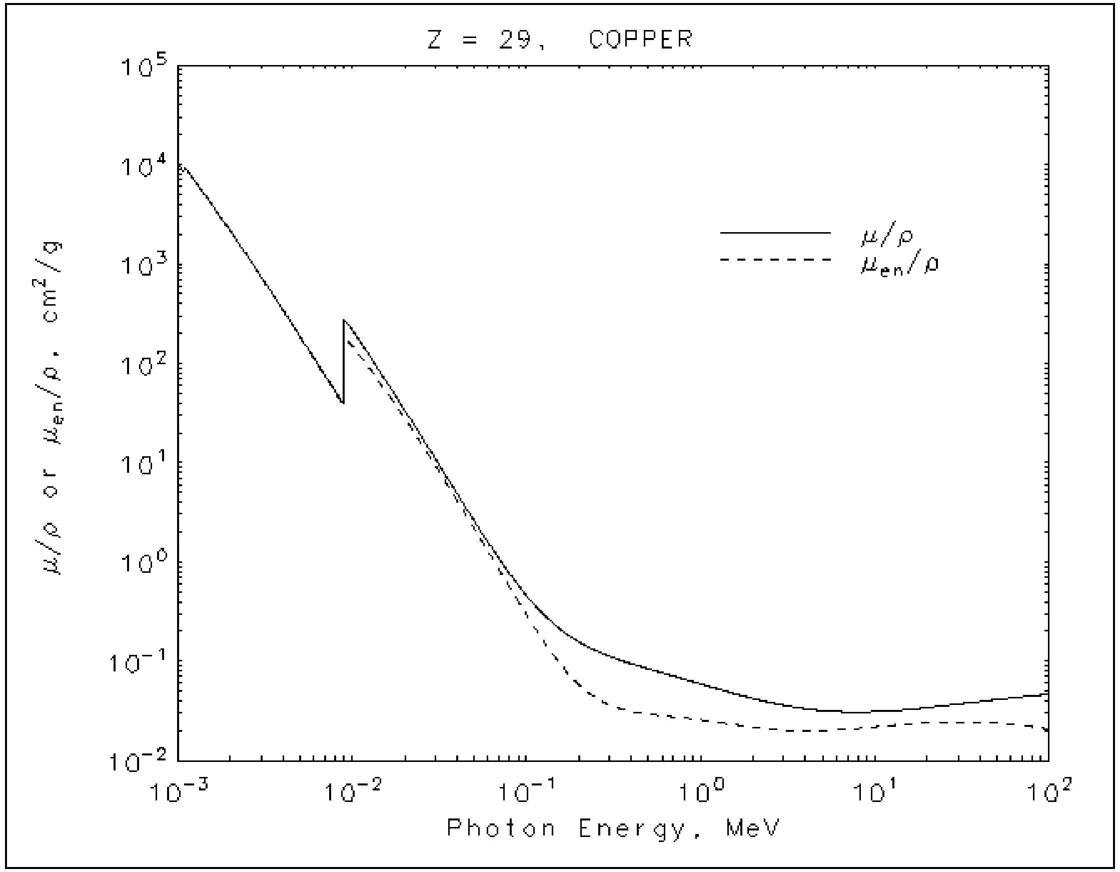
Pair Production

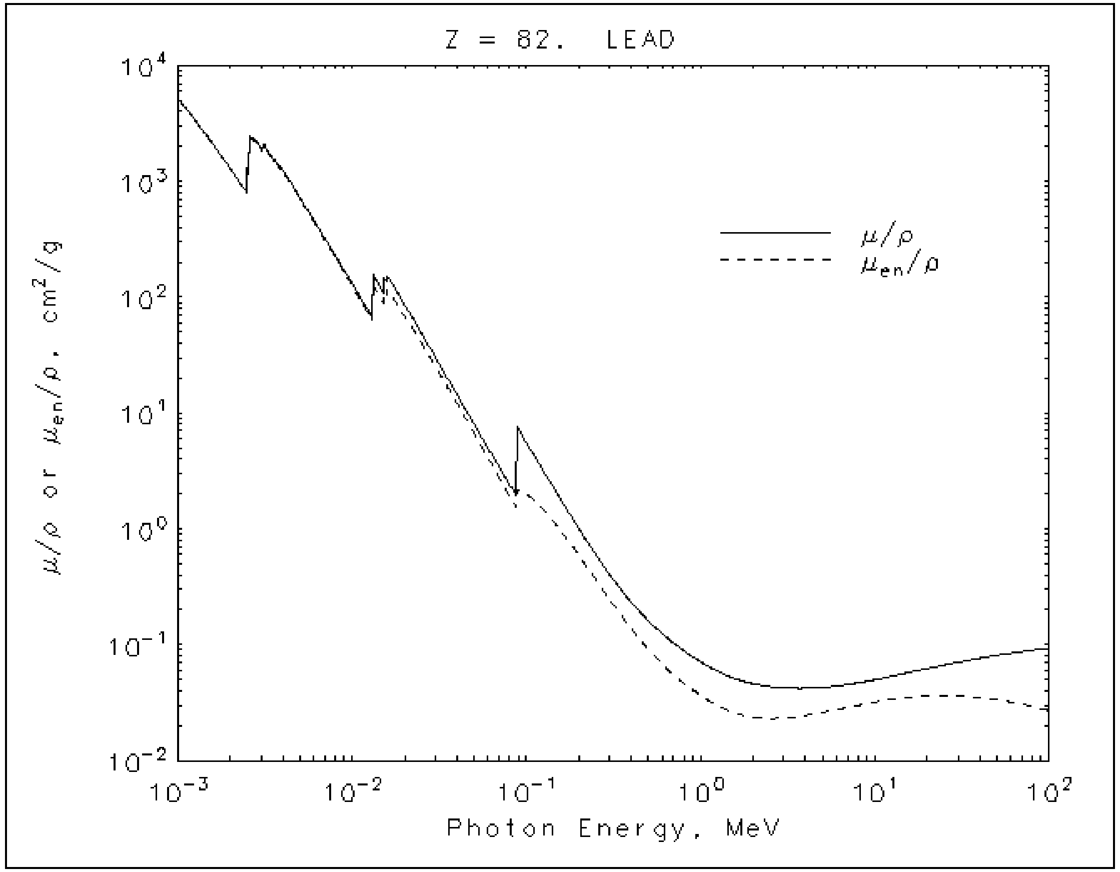
- Incident photon converts into an electron-positron pair
- Only possible in the presence of matter to conserve momentum
- Only possible if gamma ray energy is > 1 MeV



- Positron will quickly annihilate with an electron, producing 2 gamma rays with 511 keV each

Photon Attenuation

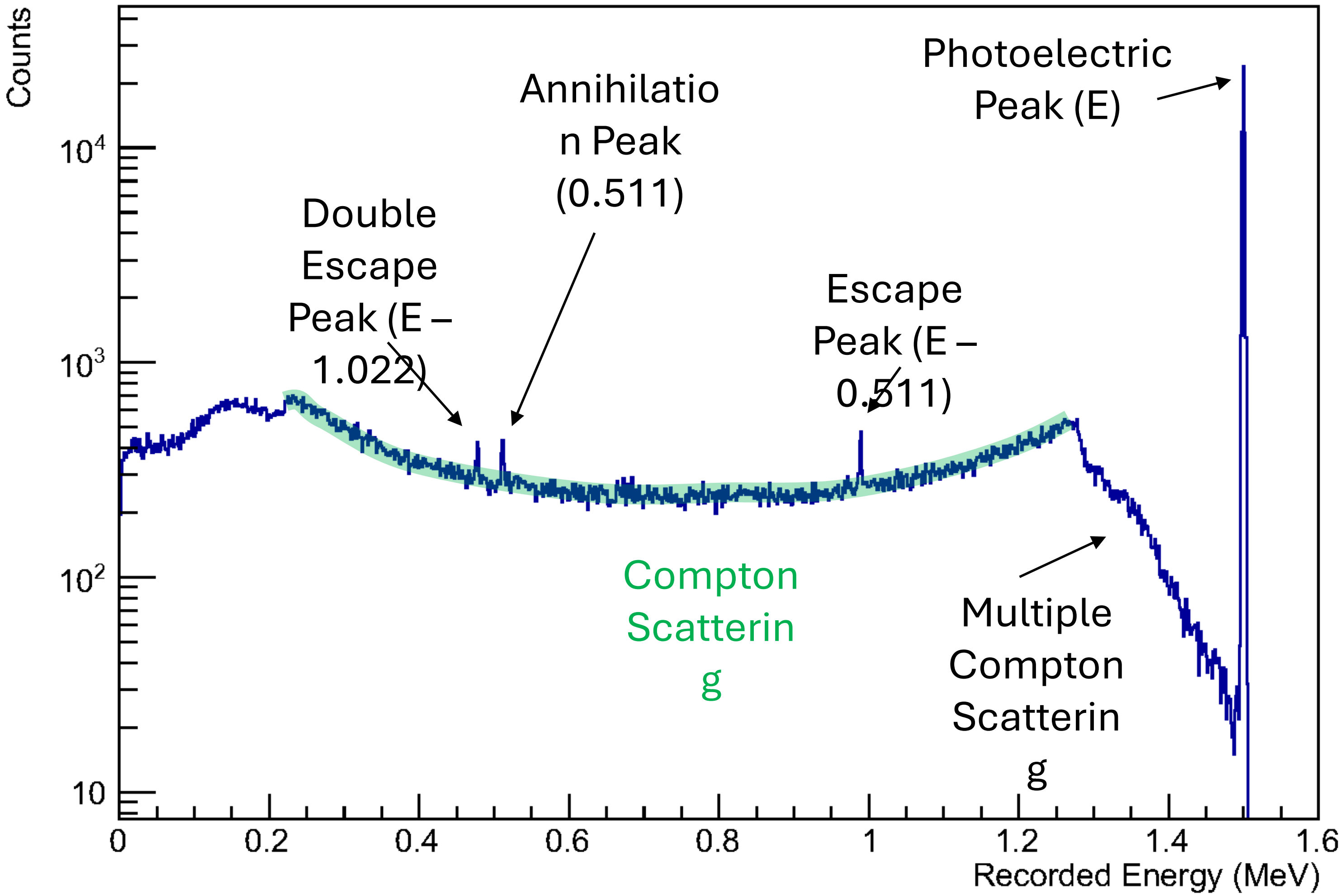




At 1 MeV, gamma rays are attenuated by 1/e at 1.9 cm in copper.

At 1 MeV, gamma rays are attenuated by 1/e at 1.2 cm in lead.

Simulation of 1.5 MeV Gamma Rays



Line widths are usually set by the resolution of the detector.
Germanium detectors have resolutions of 1 to 3 keV.

Muons (and anti-muon)

- Same charge as electron, 206 times more massive
- Unstable: half-life ~1.5μs
- Deeply penetrating (hence the depth of SNOLAB)
- Created in accelerator or when high energy particles interact with atmosphere (“shower”)

- Nuclear reactions will create radioactive elements and neutrons

Neutrons

No charge!

Energy transfer through atomic collisions

➔Max energy transfer to with light nuclei

➔Best shielding with H-rich material

Decays or get absorbs, producing Y-rays

Common Interactions at SNOLAB

- Comic Ray muons
    - Produced in the atmosphere by cosmic rays (extremely energetic protons)
    - Travel through the detectors
    - Deposit tons of energy
    - Can break up nuclei (spallation) which releases neutrons, and can activate other materials
- Alpha Decays
    - Nuclear decay that releases a helium-4 nucleus
    - Very energetic
    - Very short-ranged (mm in material)
- Beta Decays
    - Nuclear decay that releases an electron or positron (and neutrino)
    - Range of around 10 mm
- Gamma Decays
    - De-excitation of a nucleus after another decay
    - Highly penetrating
- Neutrons
    - Very rarely released
        - fission decays
        - spallation
        - alpha particle interactions
    - Highly penetrating
    - Detected as either nuclear recoil or capture on another nucleus

Periodic table of elements

Some elements near the dashed staircase are sometimes called *metalloids*

Transition metals (sometimes excluding group 12)

Group ▶ / Period ▼	1	2		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
																			Noble gases
Nonmetals 1	1 H																		2 He
Metals 2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca		21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr		39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	La to Yb	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	Ac to No	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
	s-block (plus He)		f-block	d-block										p-block (excluding He)					

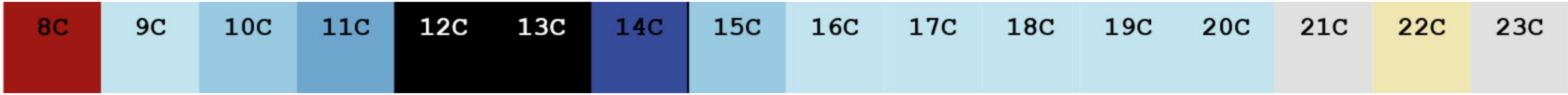
Lanthanides	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb
Actinides	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No

https://en.wikipedia.org/wiki/Periodic_table

Example of isotopes: Carbon

- Natural isotopes: ^{12}C (98.9%), ^{13}C (1.06%), and ^{14}C (Traces)

- Many isotopes can be made artificially: from ^{8}C to ^{23}C with very different half lifes (from National Nuclear Data Center):



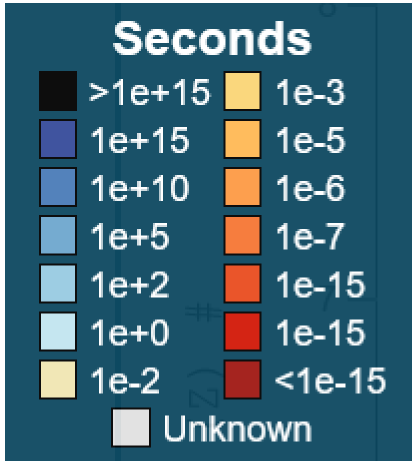
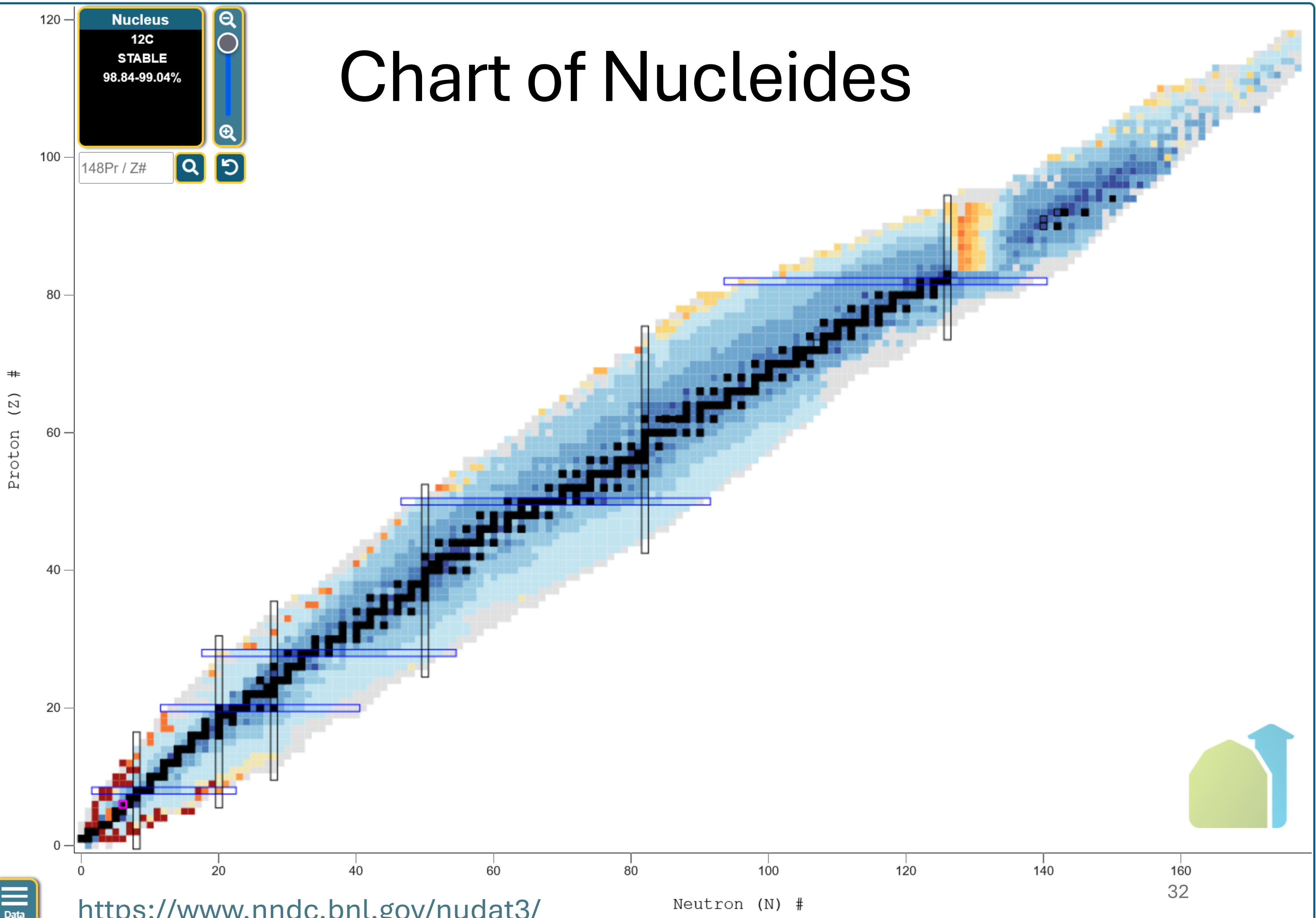


Chart of Nucleides

Half-life:

Seconds			
■	>1e+15	■	1e-3
■	1e+15	■	1e-5
■	1e+10	■	1e-6
■	1e+5	■	1e-7
■	1e+2	■	1e-15
■	1e+0	■	1e-15
■	1e-2	■	<1e-15
■	Unknown		



https://www.nndc.bnl.gov/nudat3/