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Fundamental interactions
Medical applications
New Nuclear systems

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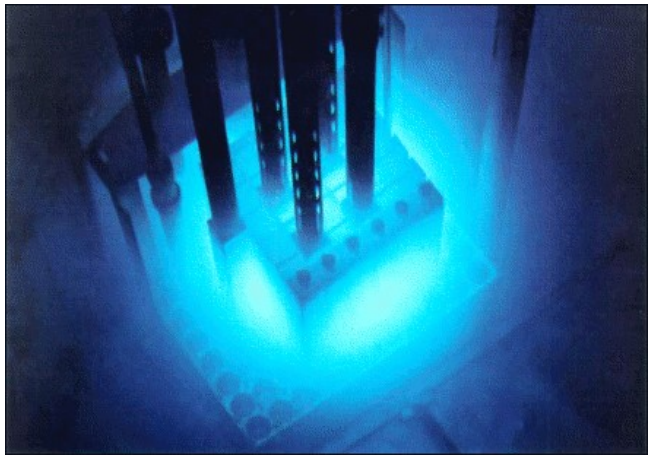
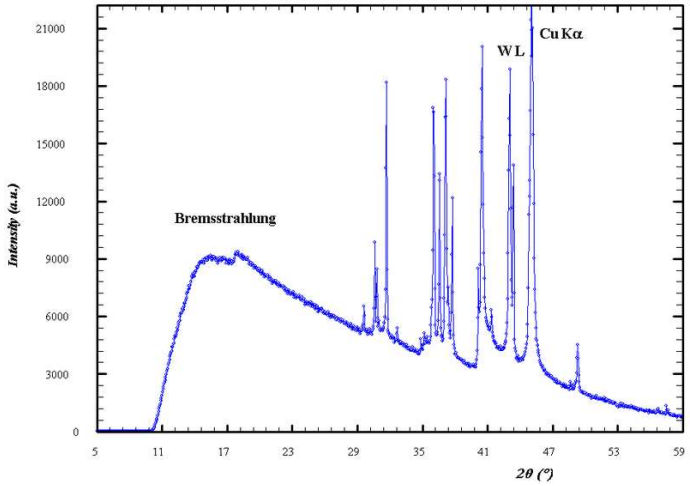
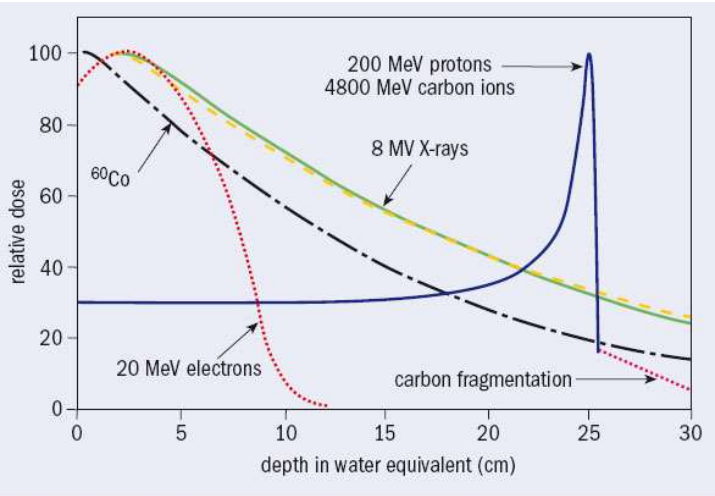
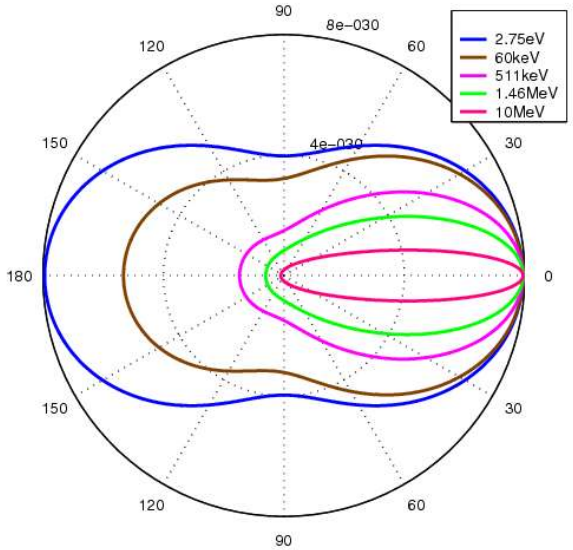




Particle Matter Interactions

For medical applications





Outline

Introduction

Aim, Units, particule, energy, cross section

Charged Particles

Protons, Heavy ions
Bethe formula, corrections
Range, Bragg peak
Straggling

Bremmstrhalung, Cerenkov

Electrons/Positrons

Neutral Particles

- Beer Lambert Law

Photons

- Photo Electric
- Compton
- Pair production
- dominant effect vs energy and Z

Neutrons

- Diffusion
- Absorption
- Nuclear reaction

The goal of these lectures is to give an overall knowledge of particle matter interaction
In the medical energies ranges

Medical energies ranges ?

Ranges define by application

Medical
Nuclear energy
Nuclear physics

Particles

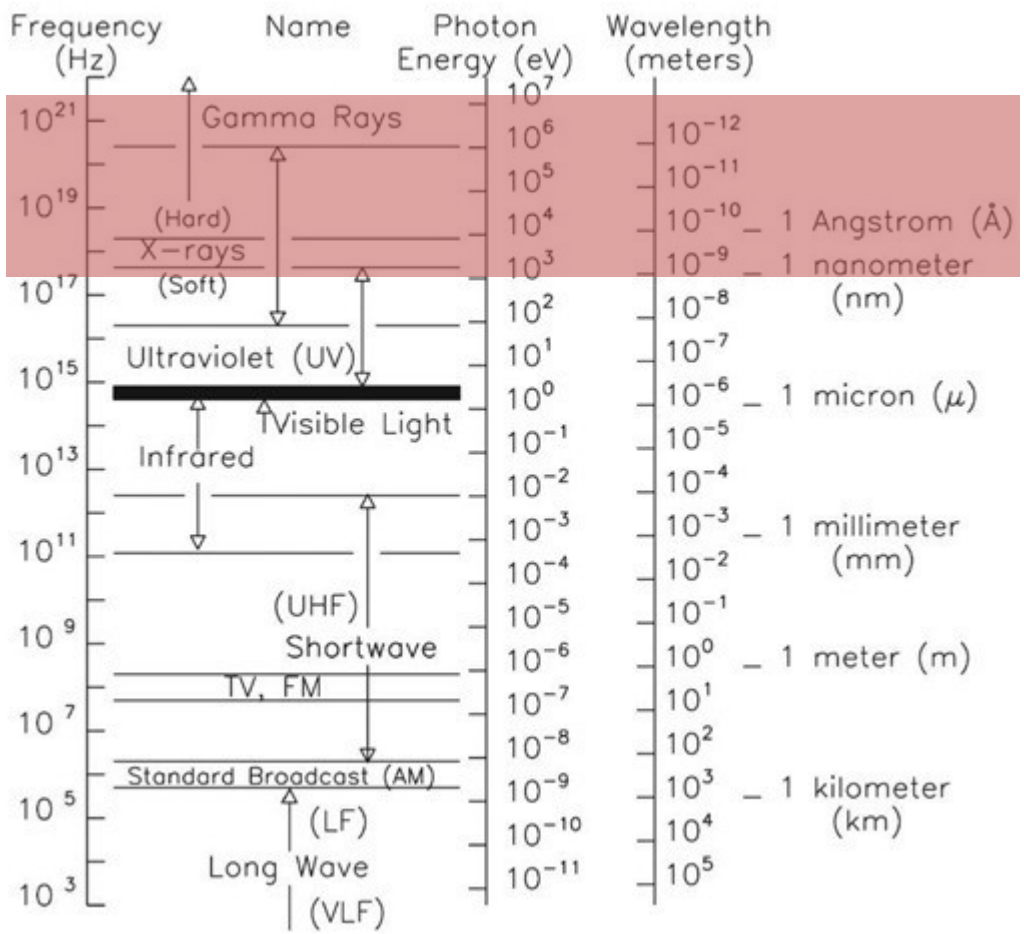
Photons, neutrons, ions
Electrons, positrons

No HEP particles

Forces

EM, **Strong**

Weak, Gravitation



Some formulaes and units

- Velocity m/s, cm/ns, light?
- Length m, µm, fm
- Energy J, eV

  Rx 100 keV-Few MeV, PET 511 keV,
  Proton Therapy 200 MeV, Carbon therapy 400 MeV/A
  Fission 200 MeV, thermal neutron 0,025 eV…

- Mass Kg, g, amu
- Energy per nucleon E/A

  Same energy per nucleon→ same velocity

- Photon Energy/momentum

  $E(keV) = 12{,}394/\lambda(Å)$

Solid angle $d\Omega$, sr

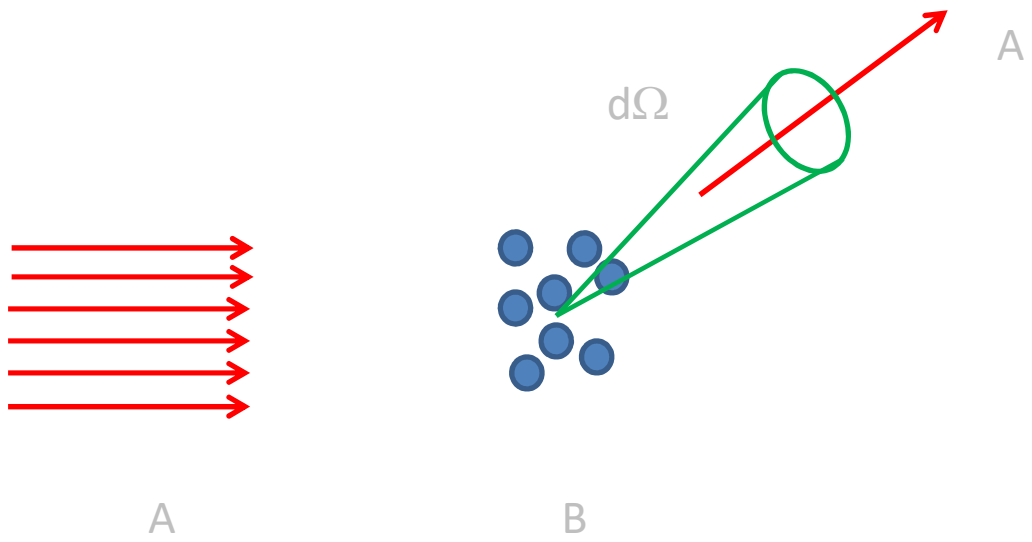
$$d\Omega = \sin\varphi \, d\varphi \, d\theta \rightarrow S/R^2$$

Whole space 4π sr

Solid angle is fundamental for detection as well as radiation safety

Cross section

Considered a flux of particle type A hitting a medium made of particle B
How many particle A are scattered in a solid angle $d\Omega$?



The number of scattered A particles in a thckness dx is

$$N_s = F\ S\ N\ \delta x\ d\sigma/d\Omega$$

Where F is the flux (particle per unit area)
S is the surface covered by the beam
N the density of B particle
δx the thickness

By dimensionnal analysis $d\sigma/d\Omega$ is a surface
It is called the differential cross section the unit is cm^2 or barn $=10^{-24} cm^2$
It can be interpreted as a probability of interaction

$d\sigma/d\Omega$ can be dependant of angle, energy, spin….

The total cross section is given by

$\int d\sigma/d\Omega$ over all parameters

The total number of interaction is

$$N_s = FS\ N\sigma\ dx$$

Cross Section

Cross section σ is the interaction probability
If the incident particle and the target particle are in the same projected area(along the incident particle velocity) they will interact

The physical size of the particles does not relate to the cross section

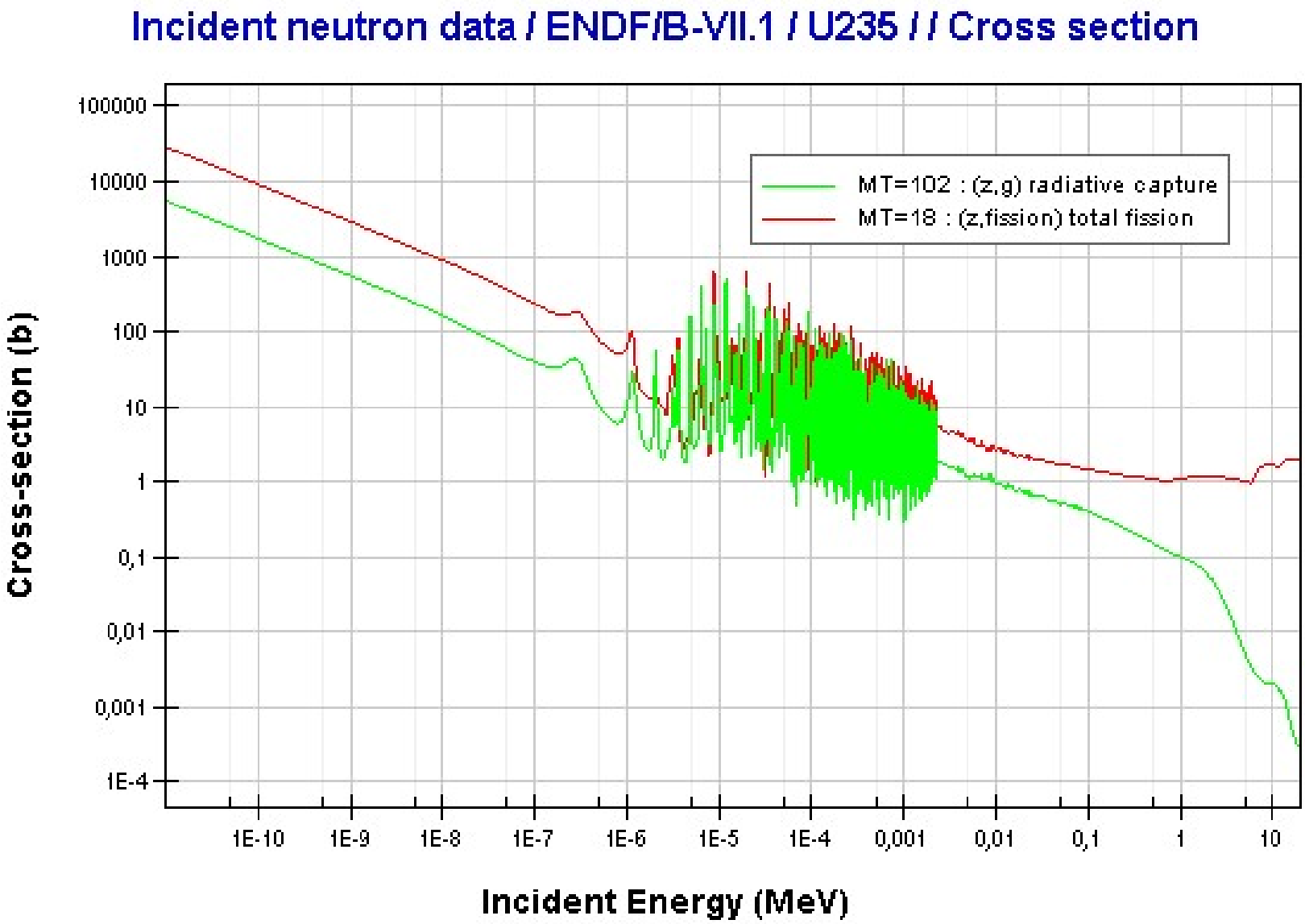
the cross section depends on what force it acting on the particle

It has the dimension of a surface m^2, cm^2 …or usually barn
1barn = 10^{-24} cm2

Reaction rate is directly related to cross section

Nreactions=Nprojectiles*Ntarget*cross section

example

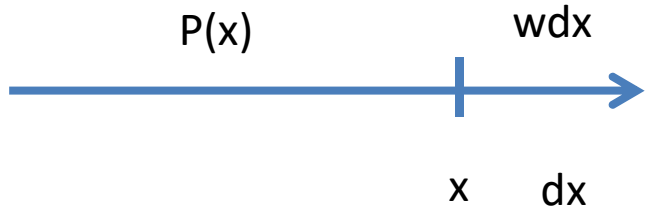

Incident neutron data / ENDF/B-VII.1 / U235 / / Cross section
MT=102 : (z,g) radiative capture
MT=18 : (z,fission) total fission
Cross-section (b)
100000
10000
1000
100
10
1
0,1
0,01
0,001
1E-4
1E-10
1E-9
1E-8
1E-7
1E-6
1E-5
1E-4
0,001
0,01
0,1
1
10
Incident Energy (MeV)

Mean free path

The cross section is the interaction probability we can define a quantity λ where a particle A Does not intearct with the B particles

What is the probability for a particle to survive up to x

P(x) probability of non interaction up to x
ωdx probability to interact in dx



$P(x+dx) = P(x)\,(1-\omega dx)$

$P(x)+dP/dx\ dx = P(x)-P(x)\ \omega dx$

$dP=-P\omega dx$

$P=C\exp(-\omega x)$ C=1 as P(0)=1
The mean distance without an interaction is

$\lambda= \int xP(x)dx/ \int p(x)dx =1/\omega$

N si the target density
σ the cross section

ω? we saw that $N\sigma$ is the probability to interact within dx $\rightarrow \lambda =1/N\sigma$

Surface density, thickness

Thickness t homogeneous with a length

For a given material of mass density ρ we can define ρt which is in g/cm^2 and called Surface density
This unit is related to the density of interacting centers

we will see that equivalent surface density make the same effects on an incoming beam

IONIZING RADIATION

Two types of particles

Neutral particles (photons) and charged particles (electron positron, ions)

The common fact between these two types of particles is that when they interact with matter

Electric charge is produced by ionization

Either directly (charged particle) or indirectly (neutral particle)

The two types of particle will exhibit different behavior

CP always interact with all electrons (coulomb interaction) therefore the cross section is very high and actually non measurable the particle will always interact and produce charges

→ **Radiation effect =100% Detection Efficiency =100%**

Range

CP lose energy along their path

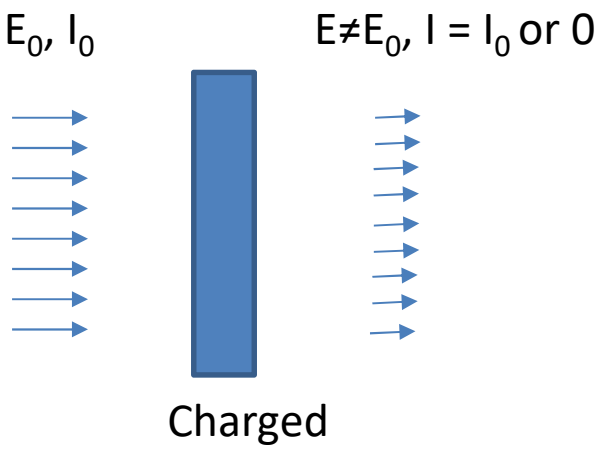
Neutral very rare interaction → crosssection (interaction probability)

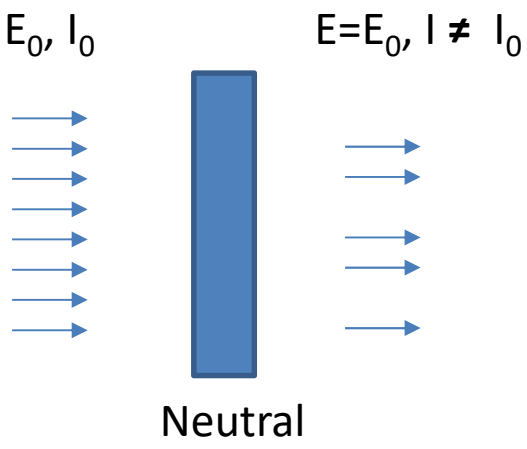
Sometimes no interaction or very little

→**Radiation effect ≠100% Detection Efficiency ≠ 100%**

Mean free path

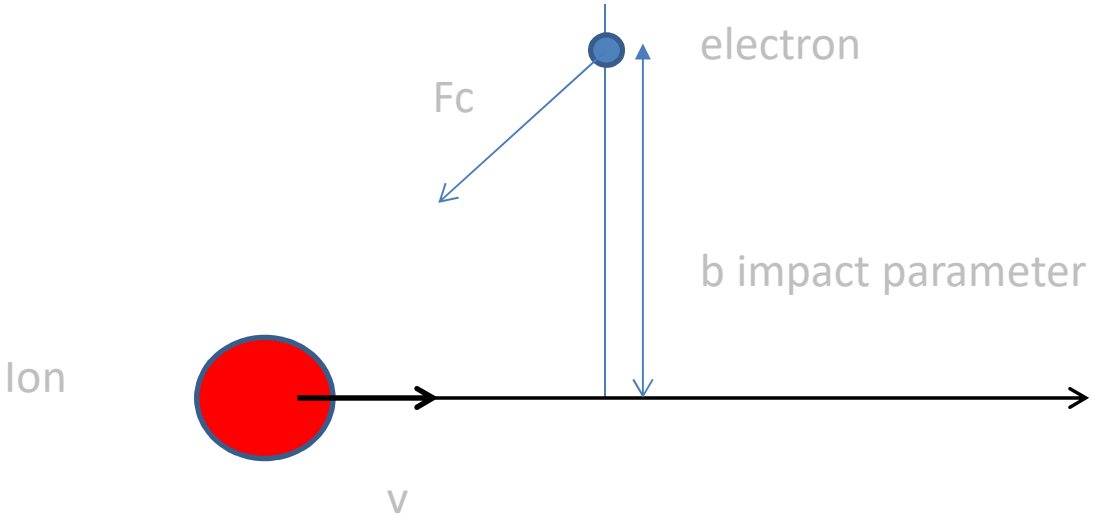
NP number will be attenuated along their path





CHARGED PARTICLES

Energy loss. Bethe formula



Ion travelling along x with a velocity v
Fc Coulomb force between the electron and the ion

Only the perpendicular component of the force Fc will modify P by ΔP

$$F_{c\perp} = F_c \frac{b}{\sqrt{x^2 + b^2}}$$

Then the change in momentum is given by

$$\Delta p = \int_{-\infty}^{\infty} F_{c\perp} \frac{dx}{v} = \frac{ze^2 b}{v} \int_{-\infty}^{\infty} \frac{dx}{(x^2 + b^2)^{\frac{3}{2}}} = \frac{2ze^2}{vb}$$

The electron gains an energy of

$$\Delta E = \frac{(\Delta p)^2}{2m_e} = \frac{2z^2 e^4}{m_e v^2 b^2}$$

Which is also the energy loss of the particle

This is the energy loss due to a single electron
We have to sum up all the contributions for all impact parameters b

The number of electrons between b and b+db is given by

$$ZN2\pi\ b\ db\ dx$$

Where Z is the atomic number of the medium and N number of atoms per cm^3
The energy loss induced by these electrons is then

$$dE = 2\pi\ b\ db\ dx\ ZN\ \frac{2z^2e^4}{m_e v^2 b^2}$$

We have now to integrate over all the impact parameters the following expression, finally the energy loss for a thickness dx is

$$-\frac{dE}{dx} = \frac{4\pi z^2 e^4}{m_e v^2}\ NZ \ln \frac{b_{max}}{b_{min}}$$

We have to define the to integration limits bmin and bmax

The natural choice will be 0 and infinity
But the physics meaning of zero and infinity is ??
The other point is that the integral will not be finite…

We have to find physics arguments to choose bmin and bmax

bmin is the closest the ion and electron will be, this is also the impact parameter where the electron will gain the maximum energy

The electron change in momentum can be at most

$$2m_e v$$

Which correspond to back scattering then b is derived as

$$2ze^2/vb_{min}=2m_e v$$

For b max even though the coulomb interaction is infinite screening will affect its range

bmax is related to the minimum energy change the ion can induce on the electron
We will choose this minimum as the electron ionization potential I
It means that the minimum energy transfer has to be I, the ionization potential

$$b_{max} = \frac{z\,e^2}{v}\left(\frac{2}{m_e\,I}\right)^{1/2}$$

A common formula for I is
I= 11,5 x Z (eV)

Finally the enrgy loss through a thickness dx is

$$-\frac{dE}{dx} = \frac{4\pi z^2\,c^4}{m_e v^2}\,NZ\,\ln\left[\frac{2m_e v^2}{I}\right]^{1/2}$$

The previous calculation is an a classical approximation and a full quantum mechanics calculation gives

$$\boxed{-\frac{dE}{dx} = \frac{4\pi\,z^2 e^4}{m_e v^2}\,NZ\left[\ln\frac{2m_e v^2}{I} - \ln\left(1-\beta^2\right) - \beta^2 - \frac{C_k}{Z}\right]}$$

Bethe Bloch
in CGS
erg cm^{-1}

It differs from the classical approximation by the square root and there are some corrections
Relativistic and electron shells (K)

Energy loss rate for ions- Bethe Bloch formula

In CGS unit

$$-\frac{dE}{dx} = \frac{4\pi z^2 e^4}{m_e v^2} NZ \left[\ln \frac{2 m_e v^2}{I} - \ln\left(1-\beta^2\right) - \beta^2 - \frac{C_k}{Z} \right]$$

Linear stopping power

Z target atomic number

N target density cm^{-3}

z projectile atomic number z=1 for proton

e unit charge (1,6 10-19C)

m_e electron mass 9.1 10-31 kg

v ion velocity

I ionization potential of the target material

Relativistic corrections

Atomic Shell correction

Units

The formula is in CGS units to have it in J cm^{-1}
we have to multiply it by $1/(4\pi\varepsilon_0)^2$
Then from J to MeV divide by 1,6 10^{-13}

The energy loss should be in MeV/cm but it sometimes appear in MeV cm^2/g

$$\frac{dE}{dx}\,(\mathrm{MeV/mg/cm^2}) = \frac{1}{\rho}\frac{dE}{dx}\,(\mathrm{MeV/cm})$$

Application
Do we have to calculate the Bethe formula for a given ion and material??

Tables, data bases
https://www.nist.gov/pml/stopping-power-range-tables-electrons-protons-and-helium-ions
Software , SRIM
http://www.srim.org/

Is the energy loss by a single electron very small so we can consider the ion trajectory as straight ?

The maximun transfer is (Backscattering) given by the previous arguments

Maximum change of momentum is at most $2m_e v$ a thousand times less than the ion momentum

We can consider the ion trajectory as straight

At the end of its path the ion will have very little enrgy and this statement will not be true anymore

For electron multiple scattering will occur and the trajectory will be « cahotic »

Due to their mass and that the electron diffuse on electron the bethe formula is different For electrons

$$-\frac{dE}{dx} = \frac{2\pi e^4 NZ}{m_e \gamma^2}\left[\ln\frac{m_e \upsilon^2 E}{2 I^2 (1-\beta^2)} - \ln 2\left(2\sqrt{1-\beta^2} - 1 + \beta^2\right) + (1-\beta^2) + \frac{1}{8}\left(1-\sqrt{1-\beta^2}\right)^2\right]$$

$$g = \frac{}{\sqrt{1-b^2}}\pi r^2$$

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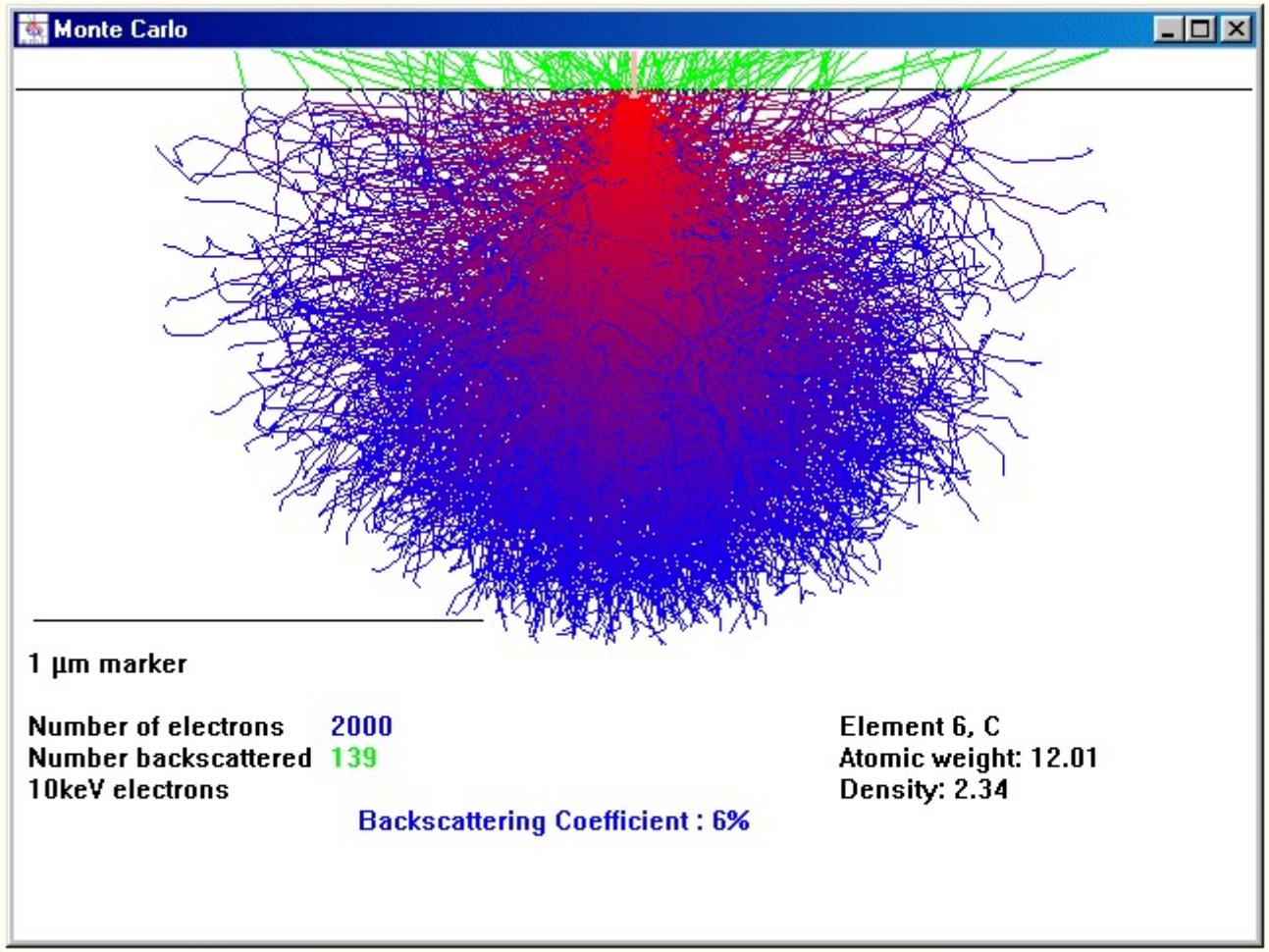
$$\gamma = \frac{1}{\sqrt{1-\beta^2}} \qquad \beta = \frac{v}{c}$$

v the electron velocity, c speed of light


Monte Carlo
1 µm marker
Number of electrons 2000
Number backscattered 139
10keV electrons
Backscattering Coefficient : 6%
Element 6, C
Atomic weight: 12.01
Density: 2.34

ELECTRONS

Bethe Bloch Formula

$$-\frac{dE}{dx} = \frac{4\pi z^2 e^4}{m_e v^2} NZ \left[\ln \frac{2m_e v^2}{I} - \ln\left(1-\beta^2\right) - \beta^2 - \frac{C_k}{Z} \right]$$

The stopping power is dependant on

the incident particle charge z^2

The target atomic number Z

Energy dependance three zones

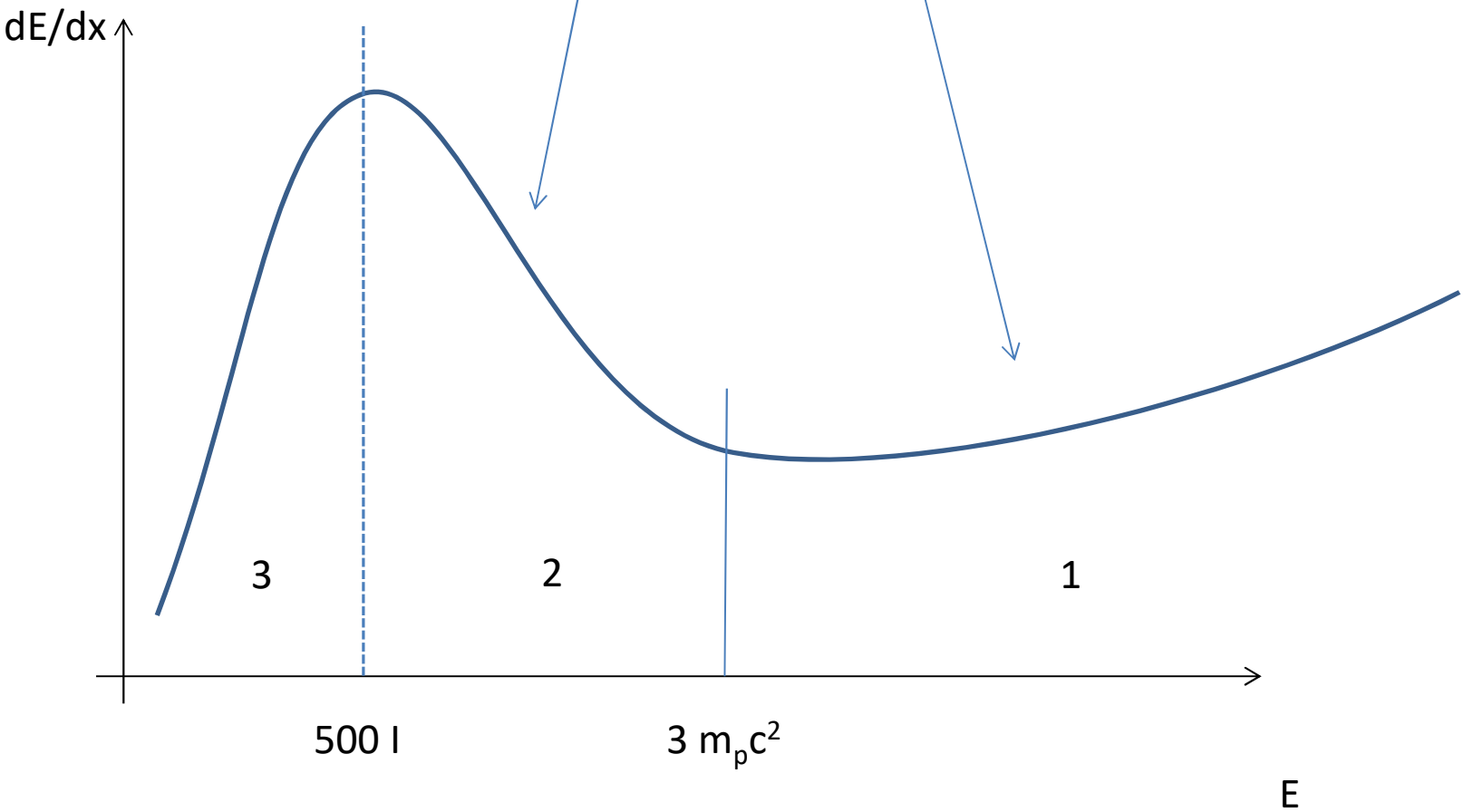
For high energy the relativistic term ln $(1-\beta^2)$ dominates and as vincrease dE/dx increase

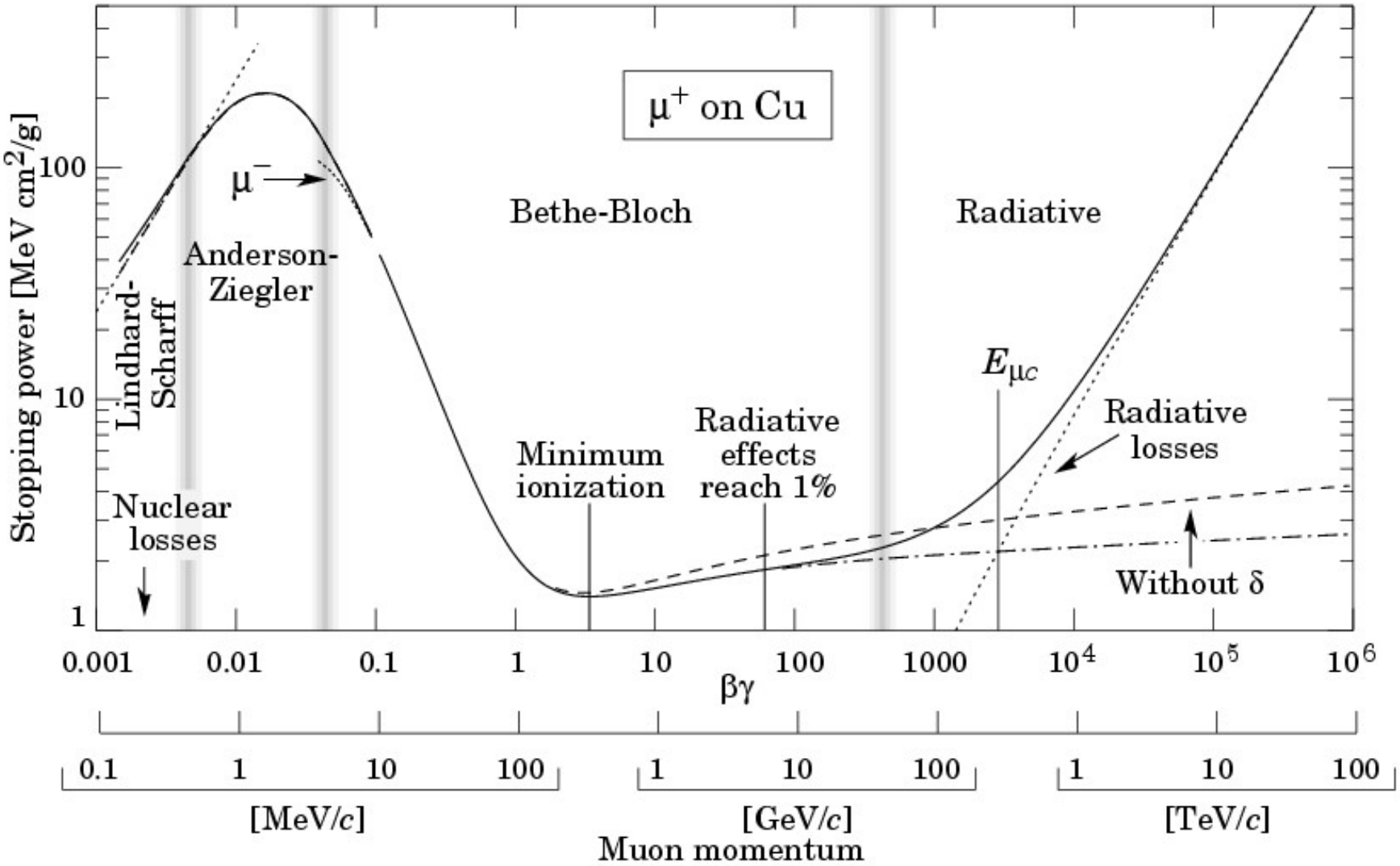
For lower energy the first term ln $(2m_e v^2/I)$ dominates

We know that for E=0 dE/dx=0 note that the ion will neutrlized at the end of its path

Bethe Bloch Formula

$$-\frac{dE}{dx} = \frac{4\pi z^2 e^4}{m_e v^2} NZ \left[\ln \frac{2 m_e v^2}{I} - \ln\left(1-\beta^2\right) - \beta^2 - \frac{C_k}{Z} \right]$$




μ+ on Cu
Stopping power [MeV cm2/g]
100
10
1
μ−
Anderson-
Ziegler
Lindhard-
Scharff
Nuclear
losses
Bethe-Bloch
Minimum
ionization
Radiative
effects
reach 1%
Radiative
Eμc
Radiative
losses
Without δ
0.001
0.01
0.1
1
10
100
1000
10^4
10^5
10^6
βγ
0.1
1
10
100
[MeV/c]
1
10
100
[GeV/c]
1
10
100
[TeV/c]
Muon momentum

The domains' limit are

3 x incident particle mass, 3 $m_p c^2$ for ptoton 3 GeV

500 x the ionization potential I, if I~10 eV and Z= 25 → 125 keV

It means that considering the energy range we are interestred in only the zone 2 and 3 will be of interest for our applications

Proton therapy 150 Mev

Hadron Therapy Carbon ion 400 MeV/A (limit)

Fission product 100 MeV → ~1MeV/A very slow

For the medium energy

$dE/dx=k (\ln k'v^2)/v^2$

→ **Stopping power decreases as the energy increases**

Incident particle dependance
dE/dx varies with z square

Same z different mass

Same energy
dE/dx is proportional to $z^2 m_p \lambda(E)$ for a same charge (isotope) the heavier one is stopped faster

Deuteron and proton of same energy …

Same velocity
dV/dx is proportional to $z^2/m_p \lambda(v)$ for a same charge (isotope) the lightest one is stopped Faster

Deuteron and proton of same velocity…

Target dependance

dE/dx is proportional to NZ and I
Heavy material will have a larger stoping power

In units of energy per path unit it will have a broad range of variation

If dE/dx is express in mev/g/cm^2 it is more or less constant

$dE/dx \alpha NZ$

$1/\rho\ dE/dx \alpha NZ/NAm_n \alpha Z/A$
which is more or less contant over the entire table of elements

For the same mass the dE/dX is independant of the element

$^{1}_{1}H$ IONS

ENERGY PER MASS UNIT	ELECTRONIC STOPPING POWER IN UNITS OF MEV/(MG/SQ CM)												ENERGY FOR A=1
MEV/AMU	BE	C	AL	TI	NI	GE	ZR	AG	EU	TA	AU	U	MEV
0.0125	0.348	0.288	0.211	0.140	0.114	0.103	0.096	0.089	0.056	0.048	0.044	0.038	0.0126
0.0160	0.394	0.326	0.239	0.159	0.129	0.117	0.108	0.100	0.064	0.055	0.050	0.043	0.0161
0.0200	0.441	0.364	0.267	0.178	0.144	0.131	0.121	0.112	0.071	0.061	0.056	0.048	0.0202
0.0250	0.497	0.411	0.301	0.200	0.163	0.148	0.137	0.126	0.080	0.069	0.063	0.054	0.0252
0.0320	0.559	0.463	0.339	0.225	0.183	0.167	0.154	0.142	0.091	0.078	0.072	0.061	0.0322
0.0400	0.611	0.509	0.371	0.248	0.202	0.184	0.170	0.157	0.100	0.086	0.079	0.068	0.0403
0.0500	0.655	0.549	0.400	0.268	0.220	0.200	0.184	0.171	0.108	0.094	0.087	0.075	0.0504
0.0600	0.683	0.578	0.419	0.282	0.232	0.211	0.195	0.180	0.116	0.101	0.093	0.080	0.0605
0.0700	0.699	0.598	0.430	0.292	0.241	0.219	0.202	0.188	0.121	0.105	0.098	0.084	0.0705
0.0800	0.707	0.613	0.437	0.298	0.247	0.224	0.207	0.192	0.125	0.109	0.101	0.087	0.0806
0.0900	0.709	0.622	0.440	0.303	0.251	0.228	0.210	0.195	0.128	0.112	0.104	0.090	0.0907
0.1000	0.706	0.628	0.440	0.305	0.253	0.230	0.211	0.198	0.130	0.114	0.106	0.091	0.1008
0.1250	0.688	0.635	0.433	0.305	0.255	0.231	0.212	0.199	0.133	0.116	0.109	0.094	0.1260
0.1600	0.651	0.632	0.415	0.297	0.250	0.226	0.208	0.195	0.133	0.117	0.109	0.095	0.1612
0.2000	0.605	0.614	0.391	0.284	0.240	0.218	0.200	0.187	0.130	0.114	0.107	0.094	0.2016
0.2500	0.551	0.580	0.362	0.268	0.227	0.206	0.189	0.177	0.125	0.110	0.104	0.090	0.2519
0.3200	0.488	0.530	0.327	0.246	0.210	0.192	0.175	0.164	0.117	0.104	0.098	0.086	0.3225
0.4000	0.431	0.478	0.295	0.225	0.193	0.177	0.161	0.151	0.110	0.098	0.092	0.080	0.4031
0.5000	0.376	0.423	0.263	0.203	0.176	0.162	0.147	0.137	0.102	0.090	0.085	0.075	0.5039
0.6000	0.331	0.373	0.236	0.185	0.161	0.148	0.135	0.125	0.094	0.084	0.079	0.070	0.6047
0.7000	0.298	0.334	0.216	0.170	0.149	0.137	0.124	0.116	0.088	0.078	0.074	0.066	0.7055
0.8000	0.271	0.302	0.199	0.159	0.139	0.129	0.117	0.109	0.082	0.074	0.070	0.062	0.8062
0.9000	0.249	0.275	0.186	0.149	0.131	0.122	0.110	0.102	0.078	0.071	0.067	0.059	0.9070
1.0000	0.231	0.253	0.174	0.141	0.124	0.115	0.104	0.097	0.075	0.067	0.064	0.057	1.0078
1.2500	0.196	0.210	0.151	0.124	0.111	0.103	0.093	0.086	0.068	0.061	0.058	0.052	1.2597
1.6000	0.163	0.171	0.129	0.108	0.096	0.090	0.081	0.075	0.060	0.054	0.051	0.046	1.6125
2.0000	0.138	0.144	0.111	0.094	0.084	0.079	0.071	0.066	0.053	0.049	0.046	0.041	2.0156
2.5000	0.115	0.121	0.095	0.082	0.074	0.069	0.062	0.058	0.047	0.043	0.041	0.037	2.5195
3.2000	0.095	0.100	0.079	0.069	0.063	0.059	0.053	0.049	0.041	0.038	0.036	0.032	3.2250
4.0000	0.079	0.084	0.067	0.059	0.054	0.051	0.046	0.043	0.036	0.033	0.031	0.029	4.0312
5.0000	0.066	0.071	0.057	0.051	0.047	0.044	0.040	0.037	0.031	0.029	0.028	0.025	5.0390
6.0000	0.057	0.061	0.050	0.045	0.041	0.039	0.035	0.032	0.028	0.026	0.025	0.023	6.0468
7.0000	0.050	0.054	0.044	0.040	0.037	0.035	0.032	0.029	0.025	0.023	0.022	0.021	7.0546
8.0000	0.045	0.049	0.040	0.036	0.034	0.032	0.029	0.027	0.023	0.021	0.021	0.019	8.0624
9.0000	0.041	0.045	0.037	0.033	0.031	0.029	0.027	0.025	0.022	0.020	0.019	0.018	9.0702
10.0000	0.038	0.041	0.034	0.031	0.029	0.027	0.025	0.023	0.020	0.019	0.018	0.017	10.078
11.0000	0.035	0.038	0.032	0.029	0.027	0.025	0.023	0.022	0.019	0.018	0.017	0.016	11.086
12.0000	0.033	0.036	0.030	0.027	0.025	0.024	0.022	0.020	0.018	0.017	0.016	0.015	12.094

$^{238}_{92}U$ IONS

ENERGY PER MASS UNIT	ELECTRONIC STOPPING POWER IN UNITS OF MEV/(MG/SQ CM)												ENERGY FOR A=238
MEV/AMU	BE	C	AL	TI	NI	GE	ZR	AG	EU	TA	AU	U	MEV
0.0125	9.903	8.192	6.002	3.991	3.241	2.941	2.725	2.521	1.602	1.371	1.260	1.080	2.9756
0.0160	11.493	9.508	6.966	4.632	3.761	3.413	3.162	2.926	1.860	1.592	1.463	1.254	3.8088
0.0200	13.150	10.878	7.970	5.300	4.304	3.905	3.618	3.347	2.128	1.821	1.674	1.435	4.7610
0.0250	15.045	12.446	9.118	6.064	4.924	4.468	4.140	3.830	2.435	2.083	1.919	1.641	5.9512
0.0320	17.440	14.456	10.583	7.037	5.725	5.207	4.804	4.445	2.826	2.423	2.233	1.915	7.6176
0.0400	19.905	16.576	12.108	8.076	6.587	6.005	5.533	5.122	3.257	2.803	2.579	2.216	9.5220
0.0500	22.691	19.020	13.853	9.281	7.605	6.926	6.386	5.915	3.754	3.242	3.006	2.584	11.902
0.0600	25.237	21.355	15.464	10.422	8.567	7.778	7.191	6.665	4.268	3.711	3.425	2.946	14.283
0.0700	27.578	23.590	16.971	11.506	9.504	8.621	7.976	7.399	4.752	4.158	3.852	3.309	16.663
0.0800	29.763	25.789	18.395	12.564	10.393	9.418	8.701	8.094	5.243	4.599	4.249	3.661	19.044
0.0900	31.817	27.926	19.750	13.588	11.257	10.230	9.421	8.769	5.747	5.026	4.661	4.019	21.424
0.1000	33.779	30.032	21.046	14.585	12.122	10.986	10.102	9.450	6.230	5.451	5.051	4.356	23.805
0.1250	38.286	35.324	24.079	16.952	14.158	12.834	11.799	11.052	7.404	6.477	6.056	5.237	29.756
0.1600	43.848	42.618	27.946	20.010	16.824	15.259	14.001	13.135	8.943	7.853	7.364	6.428	38.088
0.2000	49.496	50.231	31.974	23.245	19.664	17.810	16.339	15.316	10.615	9.368	8.793	7.674	47.610
0.2500	55.715	58.605	36.582	27.034	22.974	20.852	19.096	17.889	12.621	11.158	10.463	9.146	59.512
0.3200	63.347	68.824	42.458	31.971	27.300	24.923	22.715	21.229	15.200	13.502	12.674	11.145	76.176
0.4000	71.019	78.840	48.577	37.015	31.866	29.146	26.571	24.823	18.071	16.079	15.107	13.261	95.220
0.5000	79.476	89.313	55.578	42.962	37.237	34.180	31.124	29.012	21.453	19.119	17.979	15.840	119.02
0.6000	86.371	97.276	61.606	48.237	42.015	38.688	35.215	32.713	24.458	21.870	20.607	18.297	142.83
0.7000	92.264	103.571	66.906	52.856	46.232	42.619	38.805	35.995	27.164	24.287	22.949	20.339	166.63
0.8000	97.220	108.388	71.590	57.057	50.042	46.319	41.880	39.017	29.638	26.632	25.128	22.336	190.44
0.9000	101.650	112.330	75.745	60.748	53.552	49.689	44.841	41.736	32.040	28.783	27.193	24.239	214.24
1.0000	105.418	115.427	79.441	64.267	56.721	52.669	47.585	44.248	34.159	30.744	29.075	25.977	238.05
1.2500	112.863	120.868	87.018	71.355	63.523	59.172	53.342	49.513	38.897	35.068	33.154	29.673	297.56
1.6000	119.757	125.527	94.595	78.987	70.568	65.933	59.406	54.865	43.987	39.824	37.649	33.770	380.88
2.0000	124.220	129.633	100.256	84.918	76.296	71.584	64.165	59.453	48.124	43.913	41.507	37.396	476.10
2.5000	125.663	132.720	104.421	89.698	81.135	76.228	68.187	63.279	52.002	47.303	44.901	40.724	595.12
3.2000	127.234	134.404	107.010	93.098	84.752	79.722	71.482	66.132	55.217	50.509	47.940	43.553	761.76
4.0000	125.740	133.908	107.470	94.466	86.514	81.462	73.402	67.706	57.282	52.445	49.974	45.460	952.20
5.0000	122.633	131.453	106.267	94.153	86.714	81.826	73.750	68.224	58.447	53.346	51.115	46.651	1190.2
6.0000	119.220	128.182	104.213	92.958	85.767	81.286	73.366	67.843	58.151	53.670	51.377	47.209	1428.3
7.0000	115.499	124.768	101.851	91.259	84.333	80.157	72.518	67.120	58.055	53.370	51.231	47.157	1666.3
8.0000	112.053	121.300	99.426	89.483	82.822	78.745	71.587	66.118	57.468	52.994	50.906	46.929	1904.4
9.0000	108.985	117.914	97.048	87.635	81.229	77.348	70.360	65.119	56.773	52.406	50.368	46.583	2142.4
10.0000	105.951	114.670	94.768	85.955	79.605	75.909	69.086	64.158	55.913	51.838	49.943	46.152	2380.5
11.0000	103.162	111.774	92.605	84.270	78.159	74.547	67.879	63.249	55.193	51.303	49.544	45.654	2618.5
12.0000	100.616	108.948	90.563	82.594	76.707	73.266	66.745	62.307	54.428	50.715	48.904	45.100	2856.6

Orders of magnitude

Heavy charged particle loss their energy very rapidly, and they are highly ionizing

10 MeV protons in Al (ρ=2,7 g/cm3)

0,034 MeV/mg/cm2

Range ?

10 MeV p dE/dx ~ 90 MeV/cm → in about 1 mm the protons have lost all their energy
5 MeV Alphas' range is about 5 cm in air
250 Mev protons in Tissue → ~35 cm

Definition of range

$$R = \int_0^v \left(\frac{dv}{dx}\right)^{-1} dx$$

$$R = \int_0^E \left(\frac{dE}{dx}\right)^{-1} dx \quad \ldots.$$

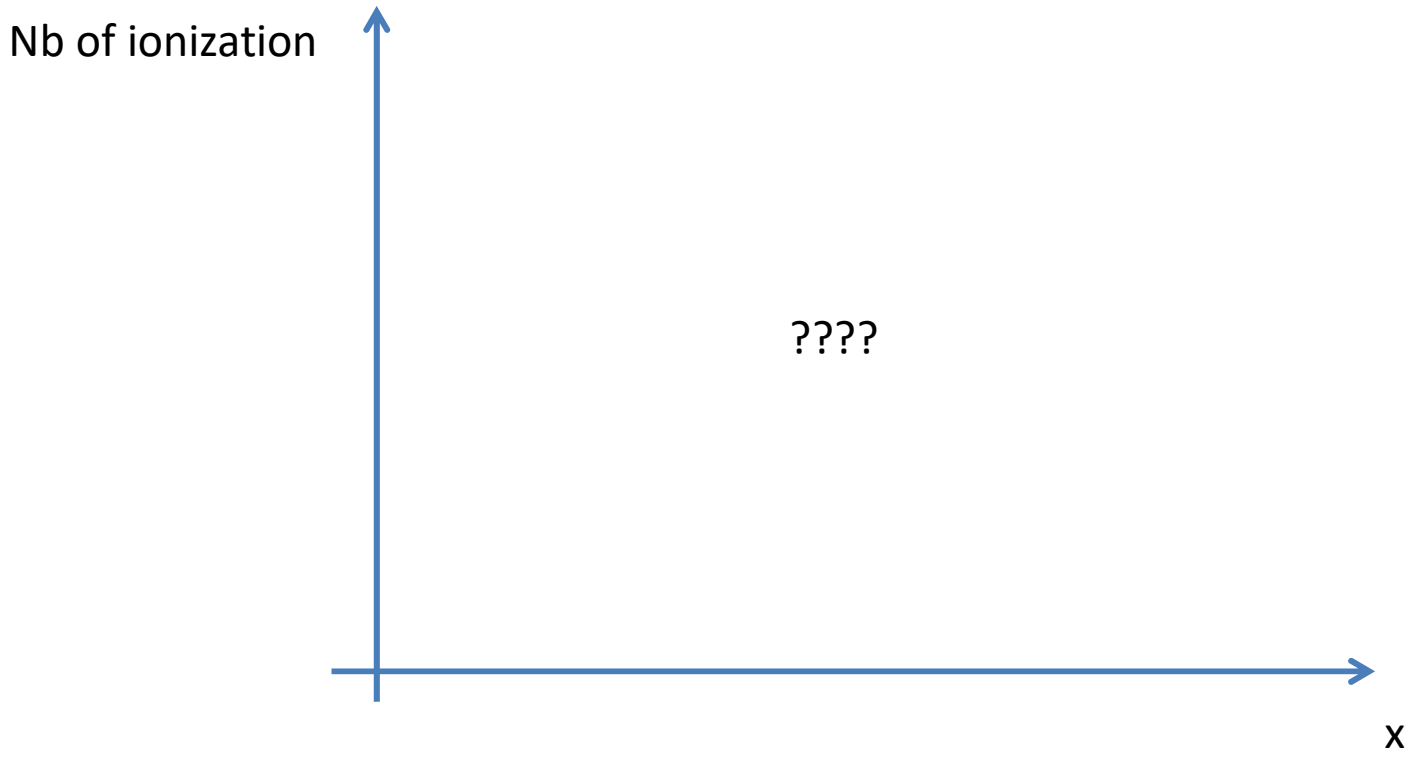
Tables, software
http://www.srim.org/

$^{1}_{1}H$ IONS

ENERGY PER MASS UNIT	RANGE IN UNITS OF MG/SQ CM												ENERGY FOR A=1
MEV/AMU	BE	C	AL	TI	NI	GE	ZR	AG	EU	TA	AU	U	MEV
0.0125	0.059	0.070	0.102	0.158	0.193	0.216	0.231	0.246	0.373	0.421	0.449	0.491	0.0126
0.0160	0.068	0.082	0.118	0.181	0.222	0.247	0.265	0.283	0.430	0.488	0.521	0.575	0.0161
0.0200	0.078	0.093	0.134	0.205	0.251	0.279	0.300	0.320	0.489	0.556	0.595	0.661	0.0202
0.0250	0.089	0.106	0.151	0.231	0.283	0.315	0.338	0.362	0.554	0.632	0.678	0.757	0.0252
0.0320	0.102	0.122	0.173	0.264	0.323	0.360	0.386	0.414	0.635	0.727	0.781	0.877	0.0322
0.0400	0.116	0.139	0.196	0.298	0.365	0.406	0.436	0.468	0.719	0.824	0.886	0.999	0.0403
0.0500	0.132	0.158	0.222	0.337	0.413	0.458	0.493	0.529	0.815	0.935	1.006	1.139	0.0504
0.0600	0.147	0.175	0.246	0.374	0.458	0.507	0.546	0.586	0.905	1.038	1.117	1.268	0.0605
0.0700	0.161	0.193	0.270	0.409	0.500	0.554	0.597	0.641	0.990	1.136	1.223	1.391	0.0705
0.0800	0.175	0.209	0.293	0.443	0.541	0.600	0.646	0.694	1.072	1.230	1.324	1.509	0.0806
0.0900	0.190	0.226	0.316	0.476	0.582	0.644	0.694	0.746	1.152	1.321	1.423	1.623	0.0907
0.1000	0.204	0.242	0.339	0.510	0.622	0.688	0.742	0.797	1.230	1.410	1.519	1.734	0.1008
0.1250	0.240	0.281	0.397	0.592	0.721	0.798	0.861	0.924	1.421	1.629	1.754	2.006	0.1260
0.1600	0.293	0.337	0.480	0.709	0.861	0.952	1.029	1.103	1.686	1.931	2.077	2.378	0.1612
0.2000	0.357	0.402	0.580	0.848	1.025	1.133	1.227	1.314	1.993	2.280	2.448	2.804	0.2016
0.2500	0.444	0.486	0.714	1.031	1.241	1.371	1.486	1.591	2.389	2.728	2.926	3.351	0.2519
0.3200	0.580	0.614	0.919	1.306	1.564	1.726	1.874	2.006	2.973	3.387	3.628	4.151	0.3225
0.4000	0.756	0.774	1.179	1.649	1.964	2.164	2.355	2.520	3.685	4.188	4.481	5.122	0.4031
0.5000	1.007	0.998	1.542	2.122	2.511	2.761	3.010	3.222	4.642	5.262	5.624	6.422	0.5039
0.6000	1.293	1.253	1.947	2.642	3.110	3.412	3.727	3.992	5.676	6.421	6.855	7.814	0.6047
0.7000	1.615	1.539	2.394	3.210	3.761	4.119	4.506	4.828	6.789	7.666	8.174	9.301	0.7055
0.8000	1.971	1.857	2.881	3.824	4.461	4.877	5.344	5.726	7.976	8.990	9.577	10.881	0.8062
0.9000	2.359	2.207	3.405	4.480	5.207	5.682	6.235	6.684	9.230	10.385	11.054	12.541	0.9070
1.0000	2.780	2.589	3.967	5.177	5.997	6.533	7.178	7.697	10.546	11.848	12.602	14.275	1.0078
1.2500	3.967	3.685	5.524	7.088	8.153	8.851	9.746	10.461	14.095	15.789	16.769	18.935	1.2597
1.6000	5.944	5.552	8.056	10.148	11.584	12.529	13.827	14.869	19.647	21.933	23.269	26.189	1.6125
2.0000	8.643	8.132	11.435	14.165	16.068	17.317	19.155	20.629	26.796	29.798	31.589	35.443	2.0156
2.5000	12.661	11.975	16.361	19.938	22.471	24.137	26.772	28.843	36.865	40.850	43.256	48.349	2.5195
3.2000	19.456	18.433	24.518	29.373	32.867	35.196	39.120	42.169	52.948	58.480	61.830	68.810	3.2250
4.0000	28.827	27.268	35.569	42.008	46.704	49.898	55.475	59.875	74.010	81.494	86.028	95.428	4.0312
5.0000	42.846	40.307	51.055	60.461	66.794	71.210	79.124	85.476	104.075	114.385	120.447	133.199	5.0390
6.0000	59.307	55.720	70.767	81.732	89.870	95.609	106.176	114.724	138.207	151.568	159.272	175.591	6.0468
7.0000	78.125	73.180	92.199	105.704	115.830	122.961	136.444	147.441	176.200	192.816	202.300	222.377	7.0546
8.0000	99.234	92.701	116.062	132.276	144.562	153.185	169.769	183.485	217.769	237.963	249.315	273.414	8.0624
9.0000	122.542	114.237	142.262	161.361	175.962	186.185	206.058	222.734	262.856	286.831	300.174	328.493	9.0702
10.0000	147.989	137.754	170.795	192.866	209.966	221.870	245.277	265.037	311.387	339.290	354.688	387.461	10.078
11.0000	175.544	163.200	201.546	226.713	246.486	260.164	287.342	310.256	363.240	395.146	412.594	450.213	11.086
12.0000	205.152	190.534	234.483	262.868	285.442	300.978	332.155	358.304	418.272	454.277	473.872	516.684	12.094

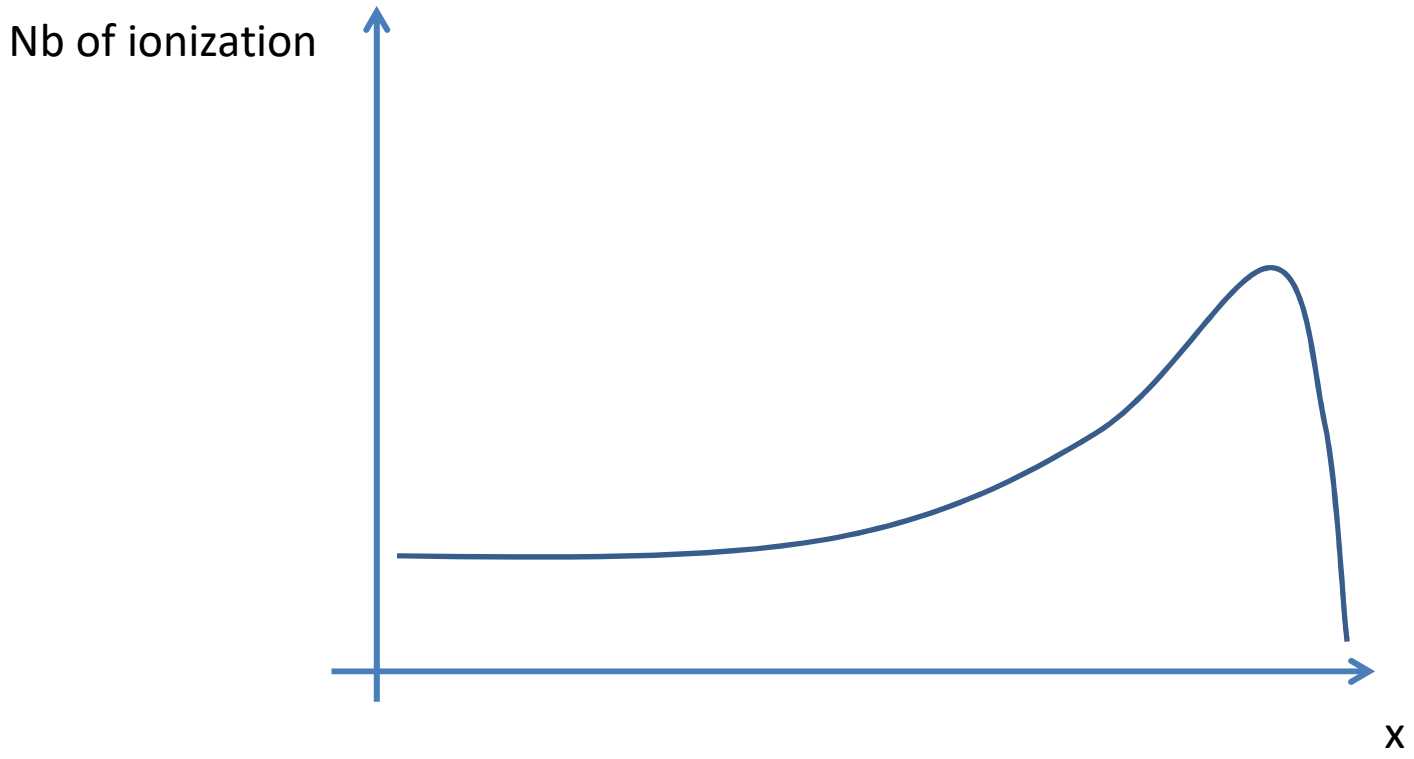
Bragg curve

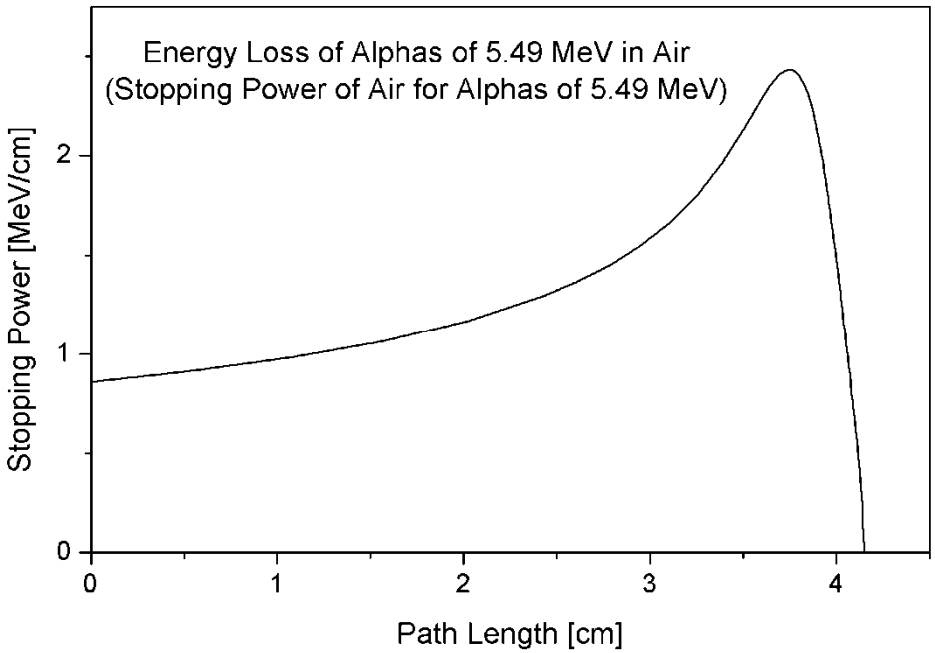
Ionization as a function of range, penetration in matter

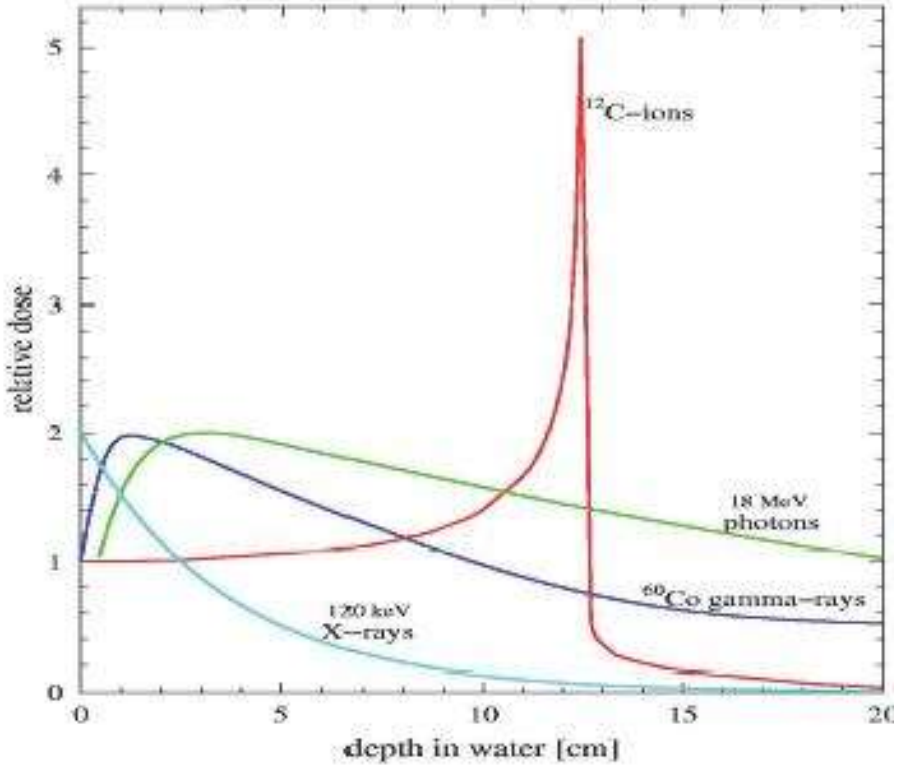


Bragg curve

Ionization as a function of range




Energy Loss of Alphas of 5.49 MeV in Air
(Stopping Power of Air for Alphas of 5.49 MeV)
Stopping Power [MeV/cm]
Path Length [cm]
0
1
2
3
4


^{12}C–ions
18 MeV
photons
^{60}Co gamma–rays
120 keV
X–rays
relative dose
depth in water [cm]
0
5
10
15
20

Other energy loss processes

Nuclear/Atomic

At the end of the path the ion is neutralized or almost neutralized
It can hit a nucleus and sometimes displace it

$dE/dx = (dE/dx)_{elec} + (dE/dx)_{nuc}$

This process is very small but can have consequences on detector (local deffect)

Nuclear reactions can be responsible of particle loss as well

Bremmsthralung/ braking radiation

Any accelerated charge particle emits photons
Acceleration = change in velocity (vector)

This penomenom will be large for light particle (electrons)

m x accleration =Σforces → very easy to accelerate electrons

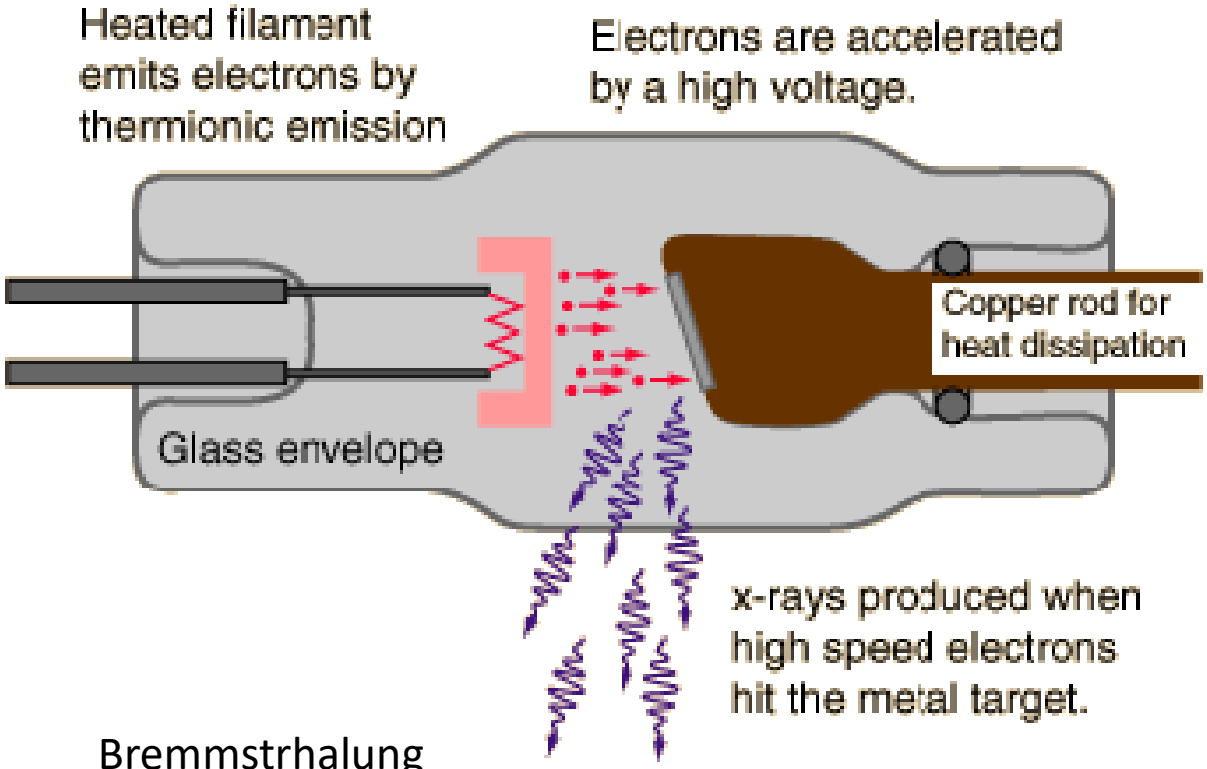
For the coulomb force it scales as z^2/m

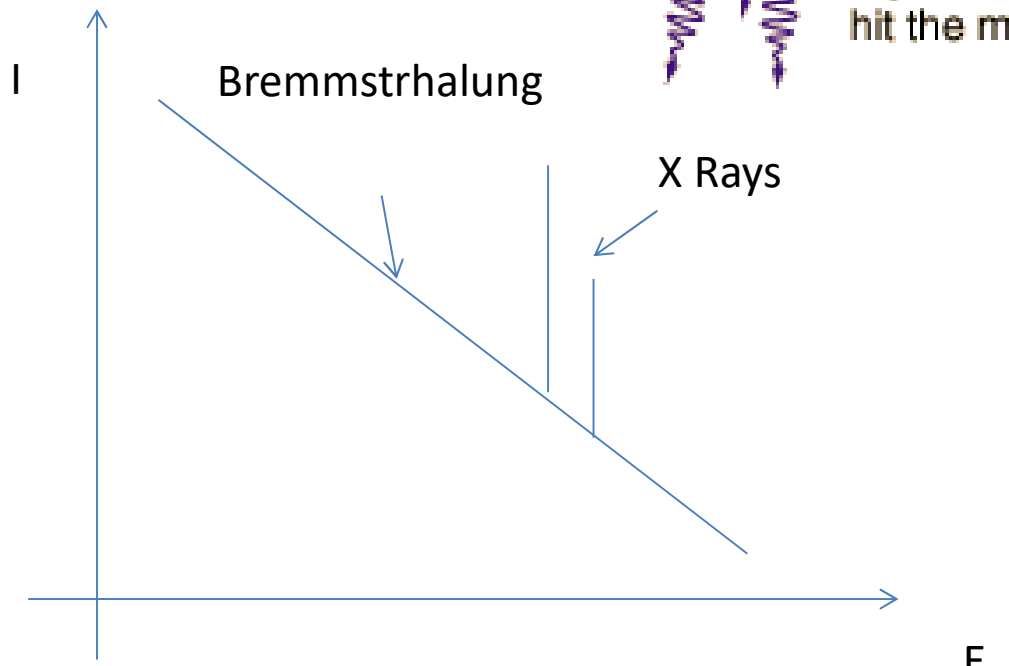
For electron the ratio between ionization loss and radiation loss is given by

$$(dE/dx)_{bremstr} / (dE/dx)_{bethe} \cong \frac{E\,(MeV)\,Z}{700}$$

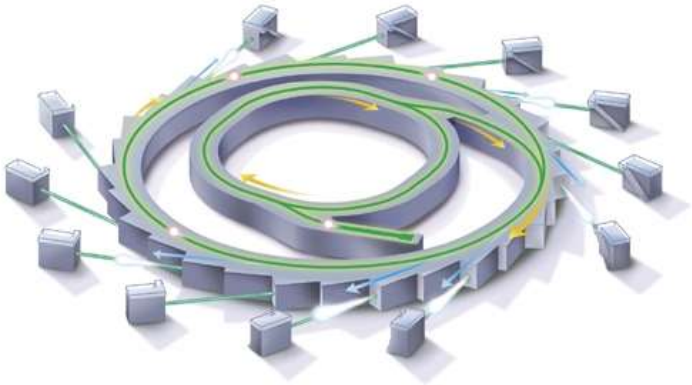
For lead Z=82 9 MeV electrons loss equally by ionization and by radiations

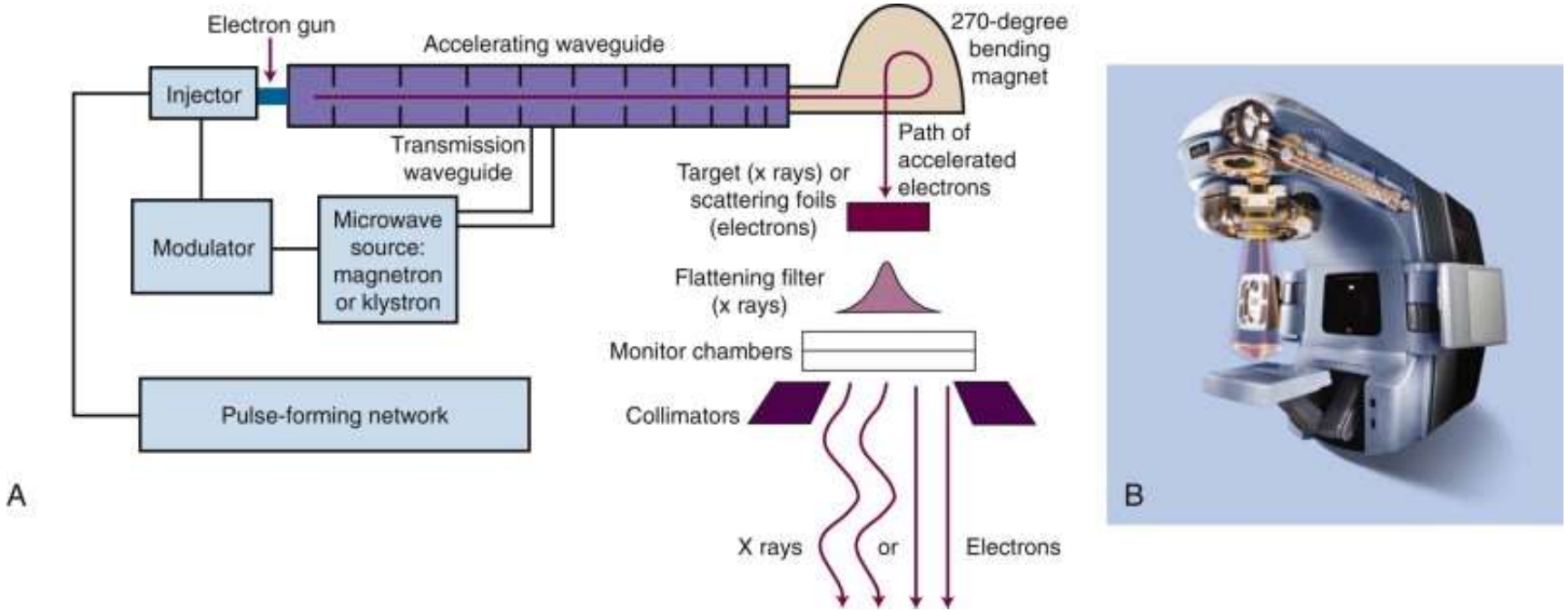
Aplication X ray Tubes, synchrotron light sources


Heated filament emits electrons by thermionic emission
Electrons are accelerated by a high voltage.
Copper rod for heat dissipation
Glass envelope
x-rays produced when high speed electrons hit the metal target.


I
Bremmstrhalung
X Rays
E

$I \alpha 1/E^2$

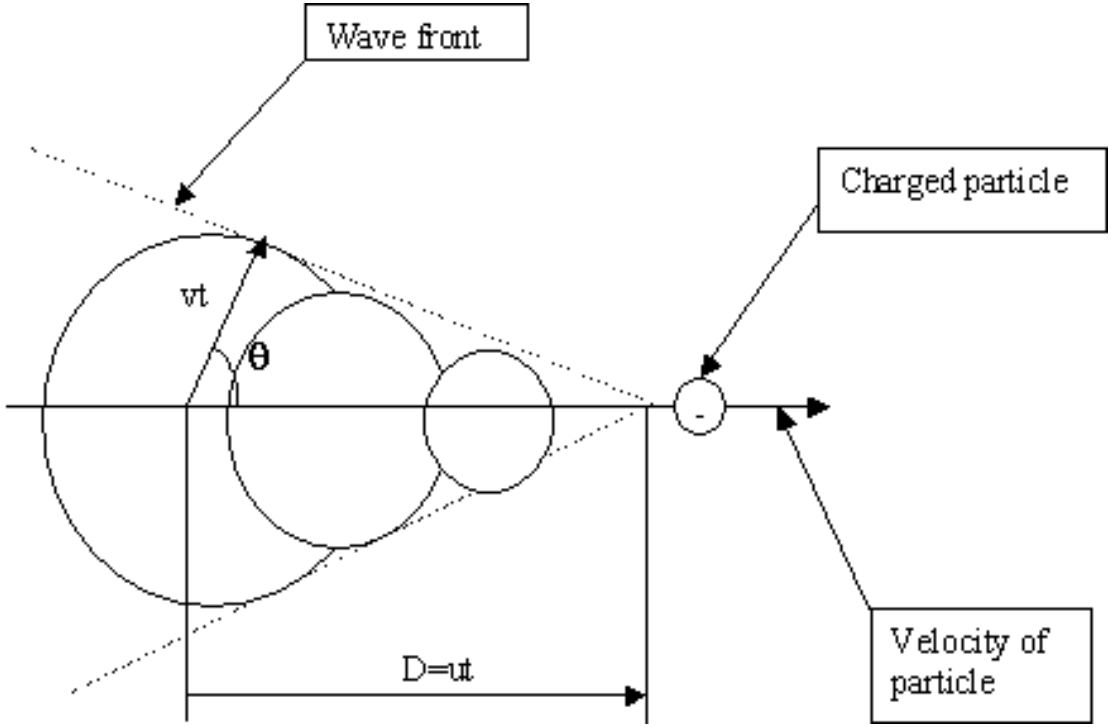




https://www.sciencedirect.com/topics/nursing-and-health-professions/linear-accelerator

Cerenkov radiation

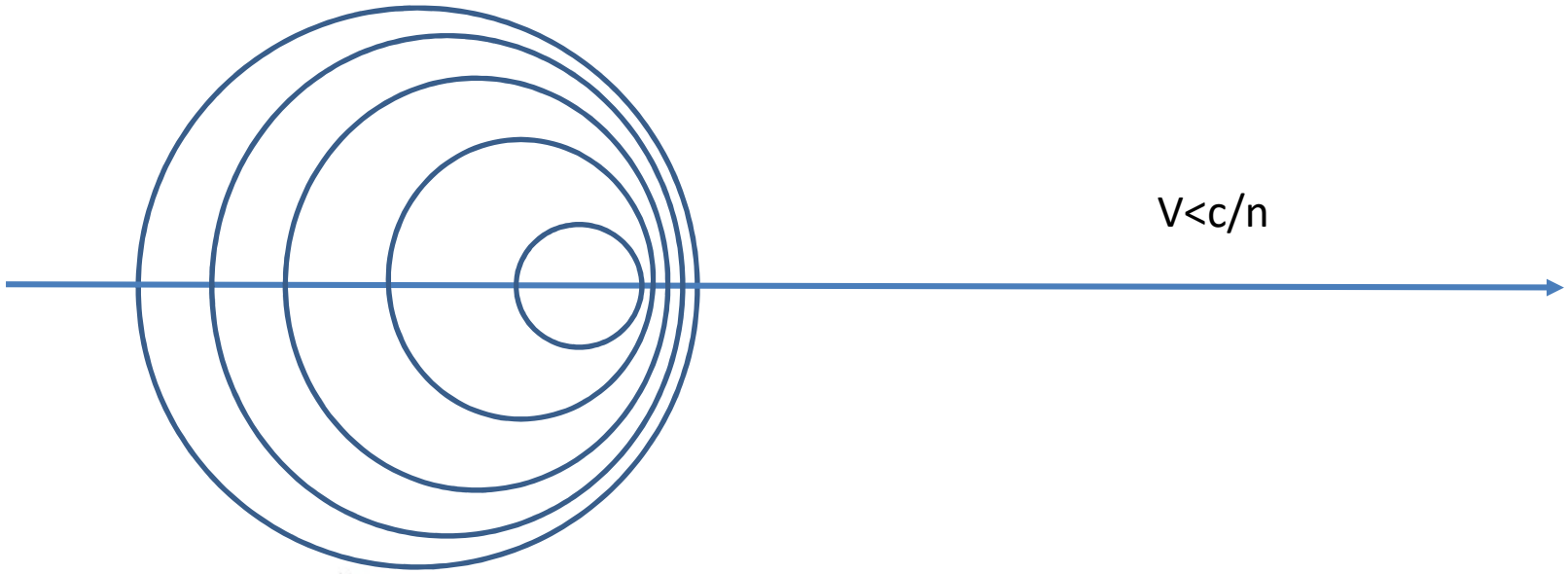
Can only happen when he charged particle travels faster than the speed of light in the material (c/n) n the index

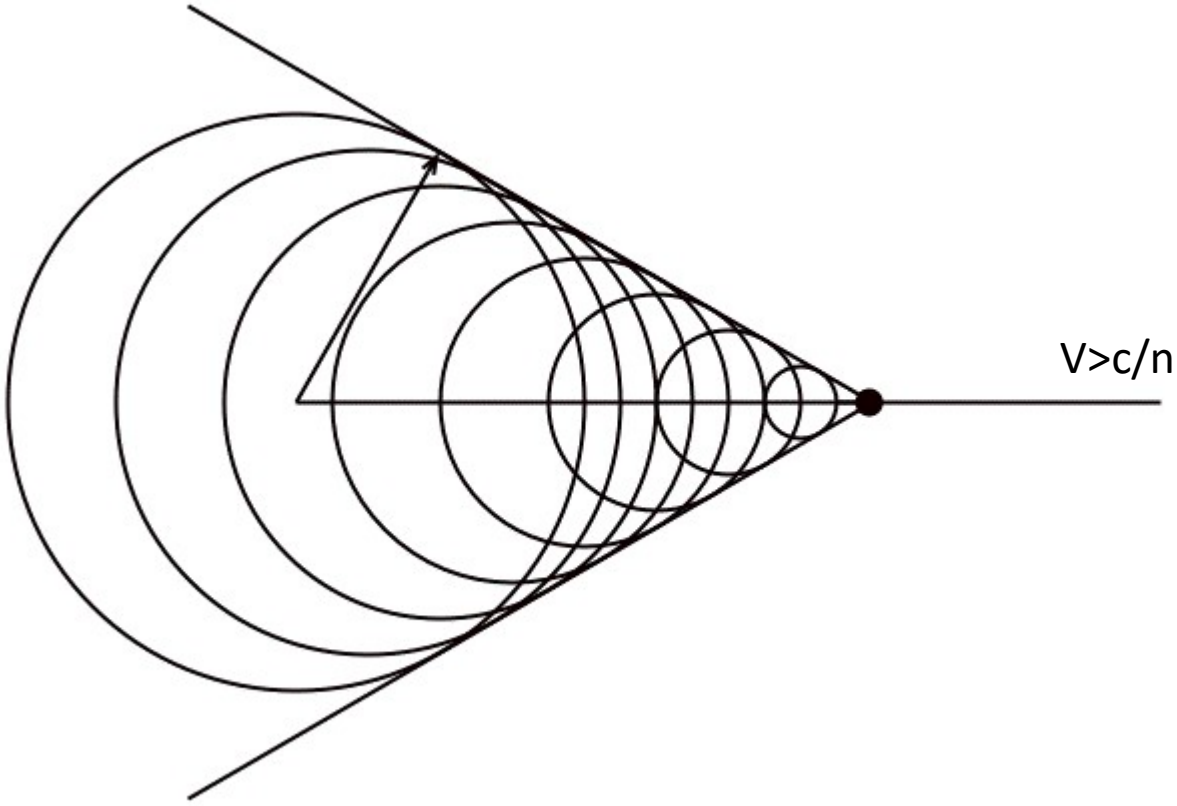


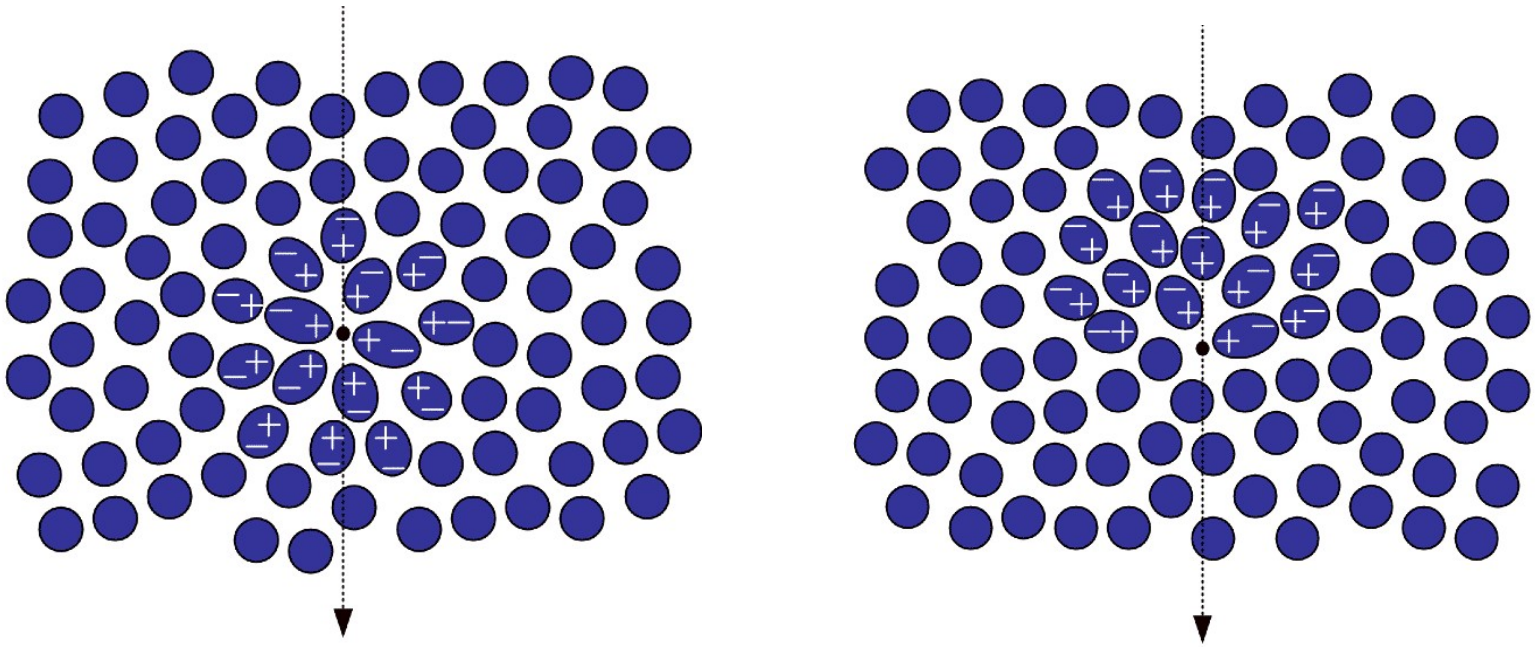
Nuclear reactor
Particle with velocity greater than spedd of light in the medium

Cos $\theta = 1/\beta n$

With the angle θ we can deduce the velocity


V<c/n


V>c/n



v<c/n

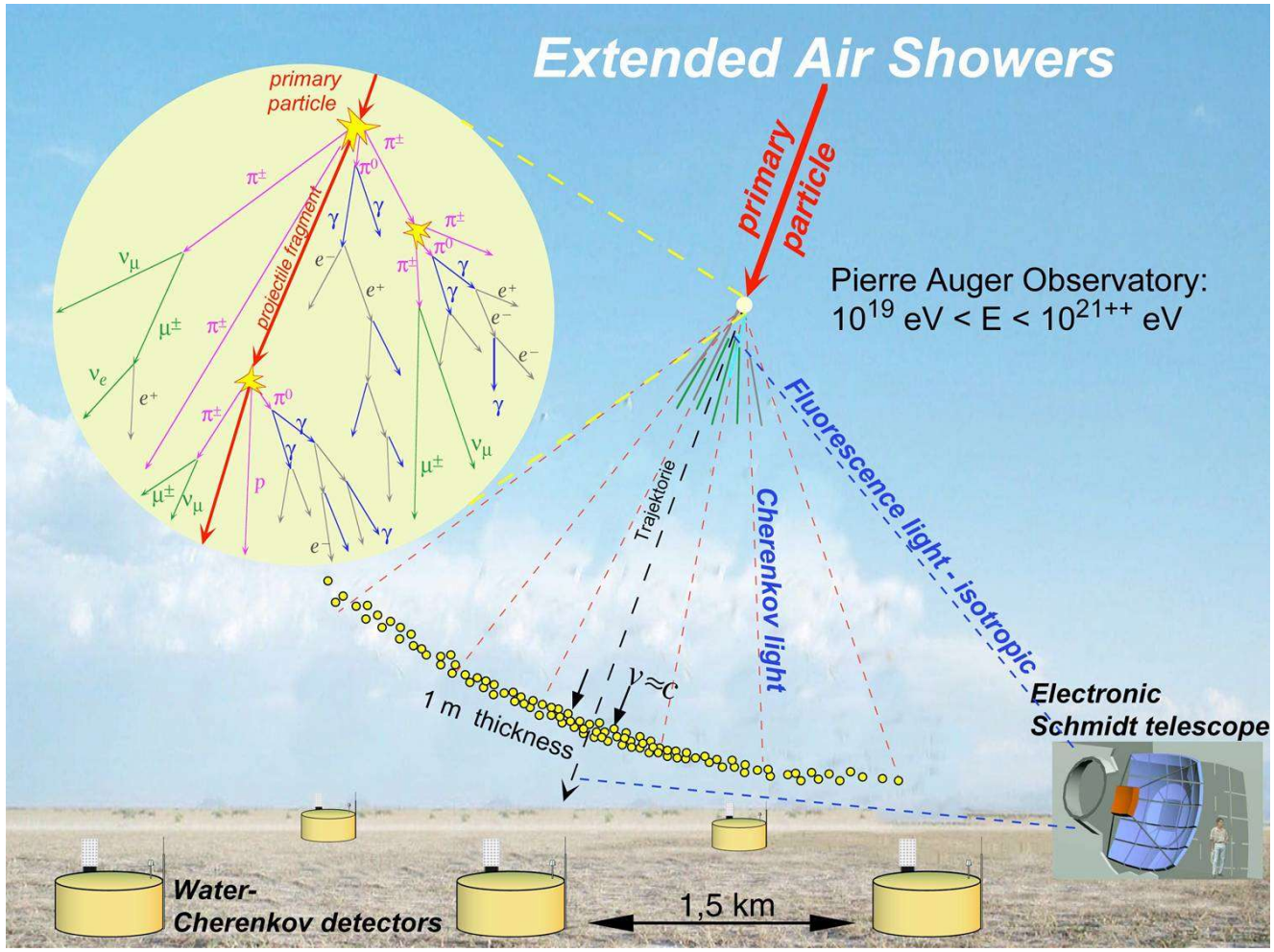
v>c/n

Univ Minn.

The light is in the visble to the UV domain

$$\frac{d^2N_{ph}}{dL\ d\lambda} = 2\pi\,\alpha\,Z^2\,\frac{\sin^2\hat{\theta}}{\lambda^2}$$

Loss around 1keV/cm
1% of ionization losses



Others

Noise radiations/scintillations see gammas

A few words again about electrons …

Due to their light mass they lose their energy with a cahotic behavior

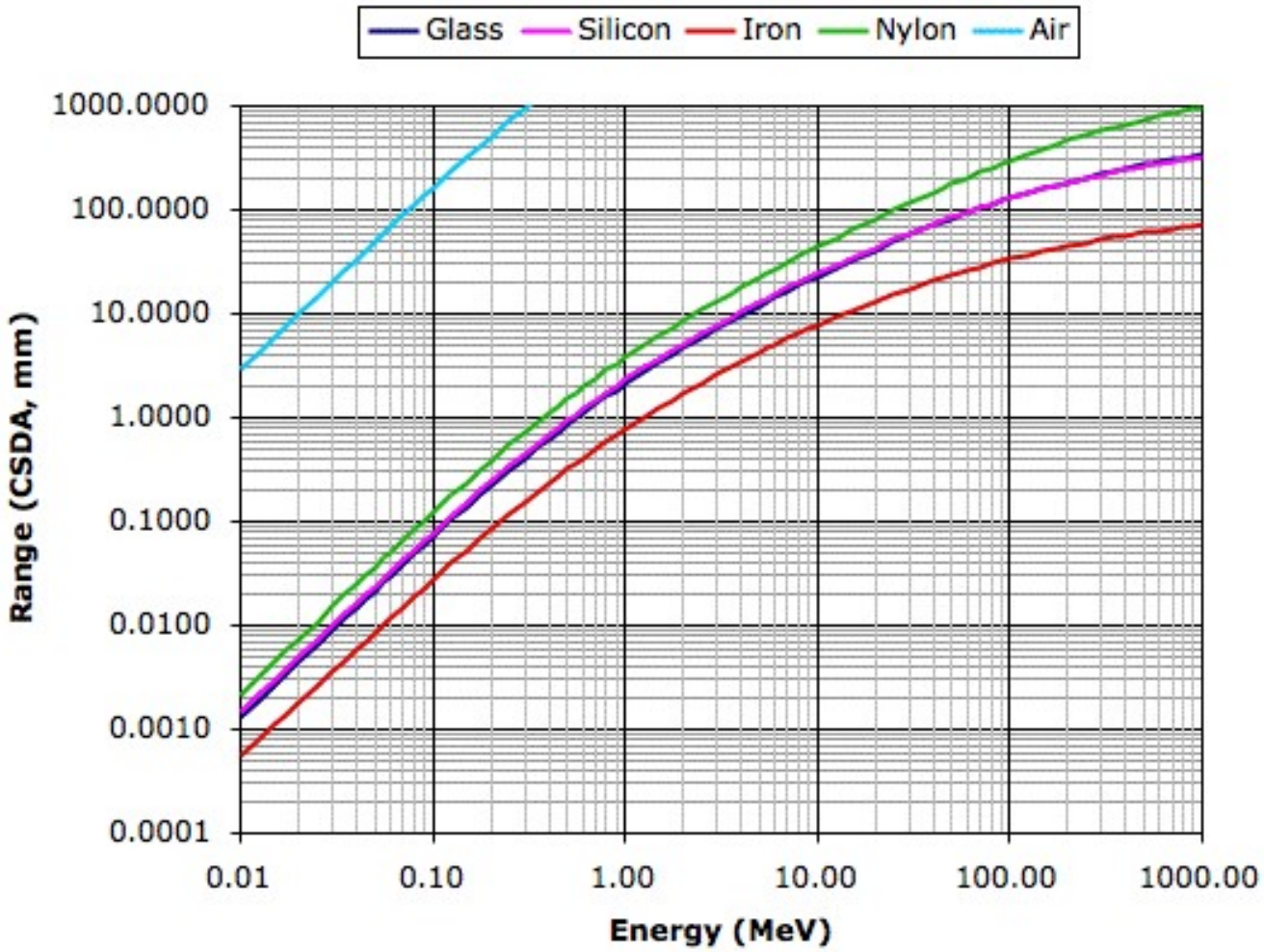
As a rule of thumb

For all solid materials

~1MeV/mm

The heavier shorter is the range

They are very often subject to Bremmstrhalung and cerenkov


Glass
Silicon
Iron
Nylon
Air
1000.0000
100.0000
10.0000
1.0000
0.1000
0.0100
0.0010
0.0001
Range (CSDA, mm)
0.01
0.10
1.00
10.00
100.00
1000.00
Energy (MeV)

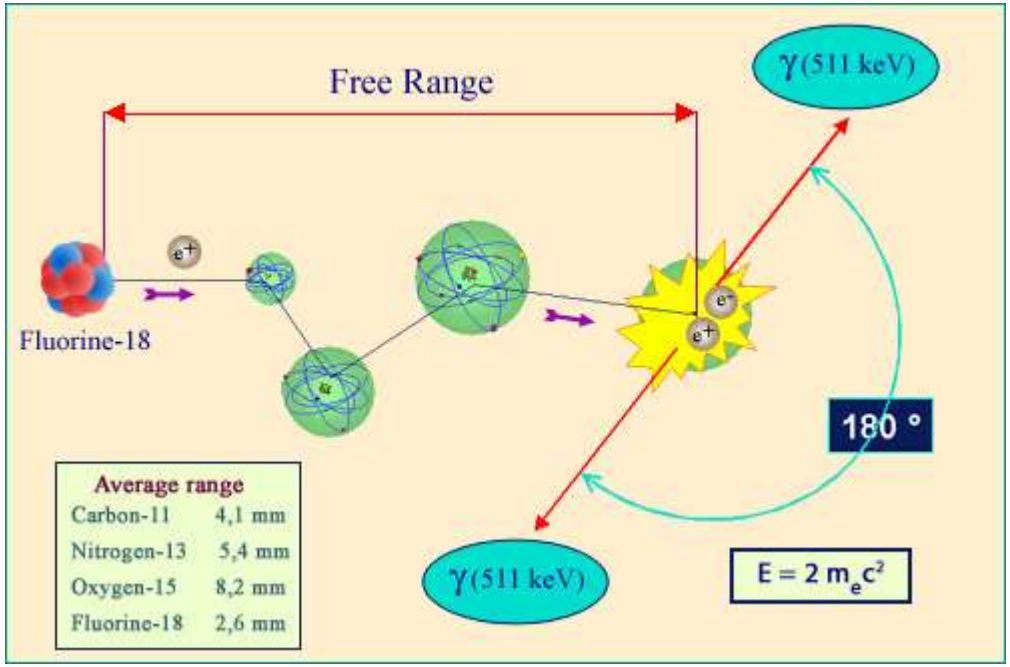
What about Positron β+ ??

They have also a modified bethe formula,,,

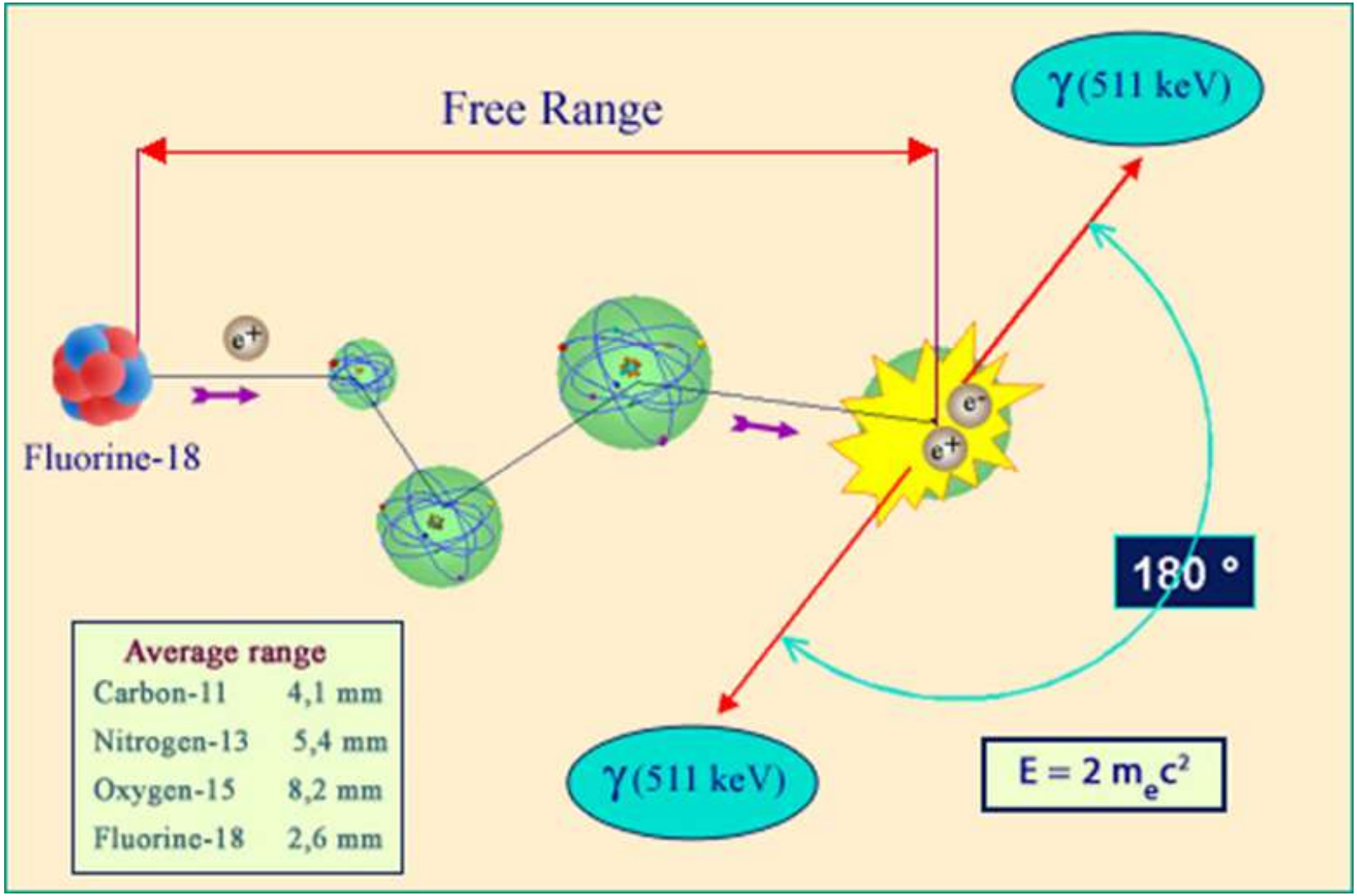
They lose their energy at about the same rate as electrons

There is a big difference at the end of their path

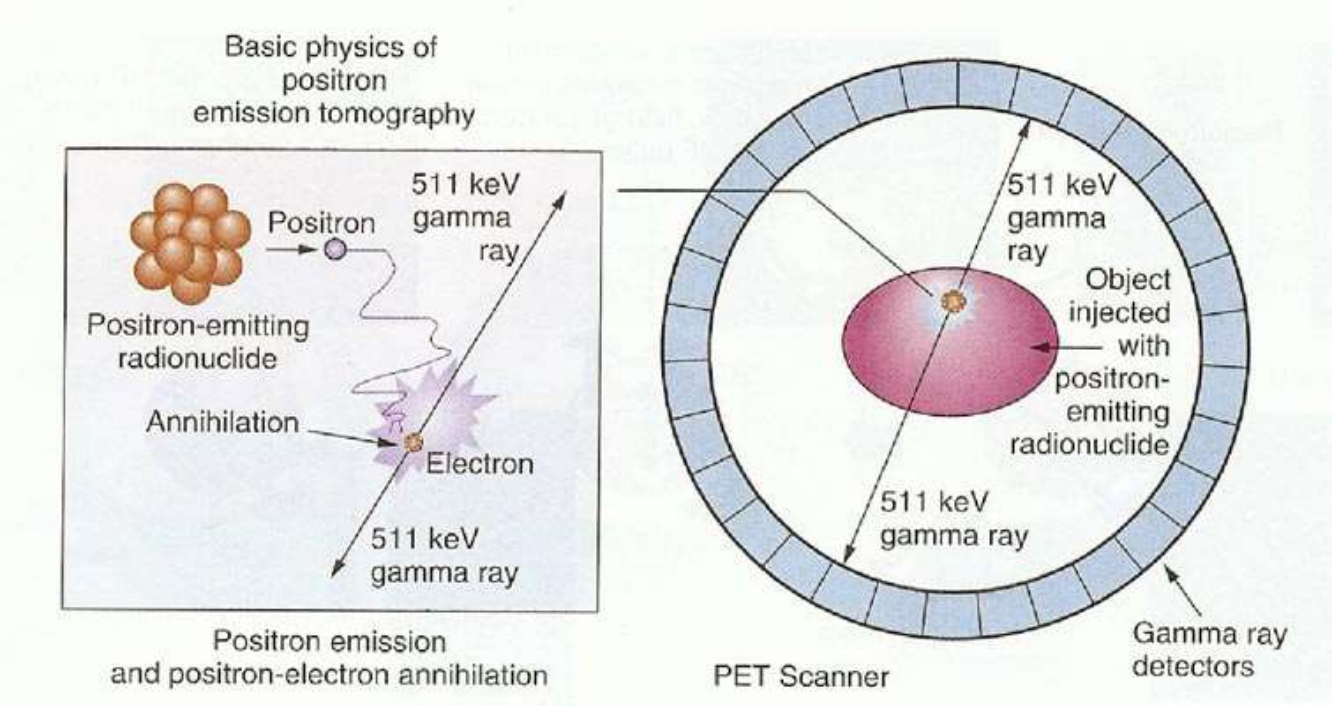
Since they are anti matter they cannot stay in our world an annihilates with an electron



La radioactivite.com


Free Range
γ(511 keV)
e+
Fluorine-18
e-
e+
180 °
Average range
Carbon-11 4,1 mm
Nitrogen-13 5,4 mm
Oxygen-15 8,2 mm
Fluorine-18 2,6 mm
γ(511 keV)
E = 2 m_e c²

Application nuclear pmedecine PET imaging
Positron emission tomography



IRM PET

Straggling

To straggle definition (dictionnary.com)
1. to stray from the road, course, or line of march.
2. to wander about in a scattered fashion; ramble.
3. to spread or be spread in a scattered fashion or at irregular intervals:
The trees straggle over the countryside.

Because of the large interaction number and probabilistic processes (cross section) each particle history will have some statistical fluctuations

The mean will be in accordance with the Bethe formula or other formulas

There will be fluctuation in energy, angle, range….

Energy straggling

As particles crossed a thin target their mean energy will be given by

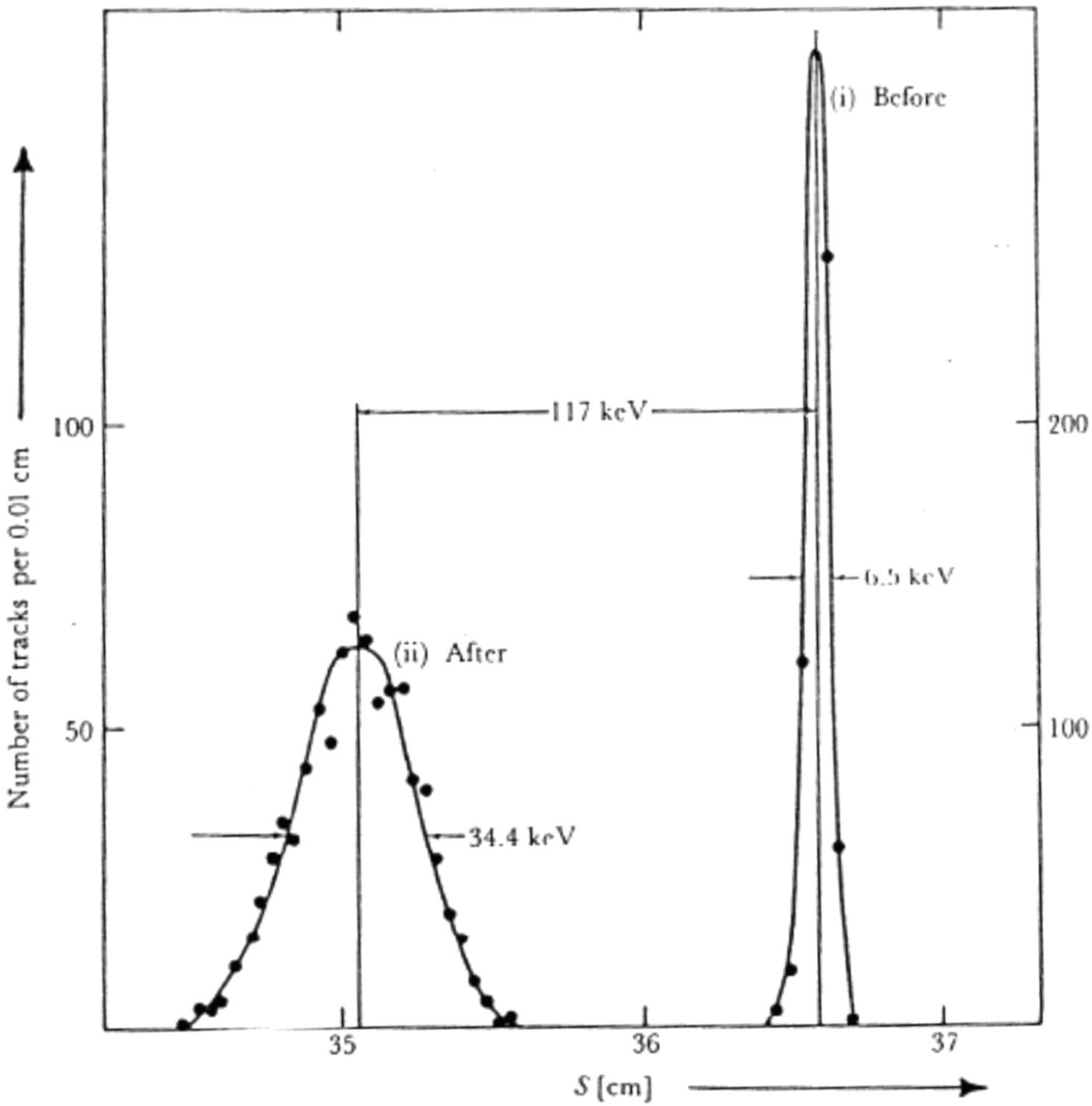
E=E0-dE/dx Δx

Even if the energy spread was null before the target it will broadened by straggling and the energy spread (sigma) will be given by

$$\frac{N(E)dE}{N} = \frac{1}{\alpha\pi^{1/2}} \exp\left[-\frac{(E_0-E)^2}{\alpha^2}\right]$$

$$\sigma^2 = 4\pi\ z^2 e^4 N Z x_0 \left[1 + \frac{kI}{m_e V^2} \ln \frac{2m_e V^2}{I}\right]$$

The broadening is larger as the particle is lighter (more subject to straggling) electrons



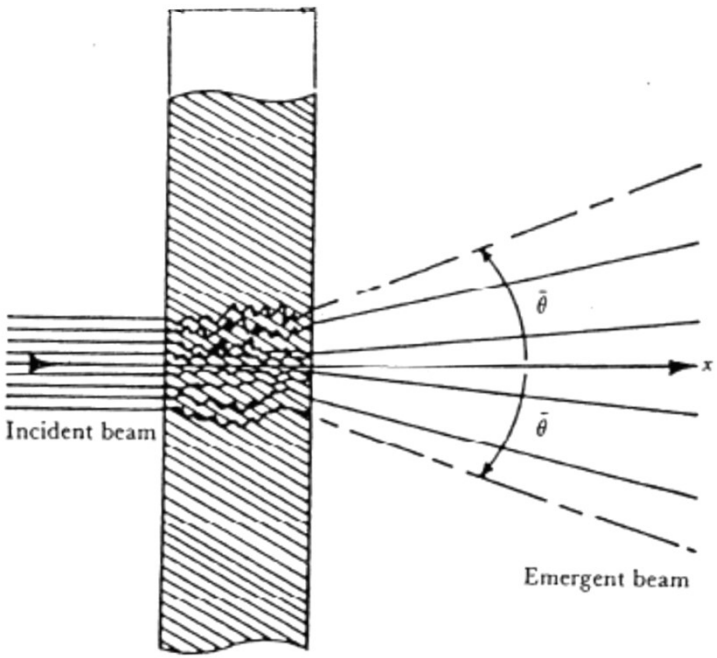
Straggling of 3 MeV Protons Through a 3.3 mg cm-2 gold foil

Angular Straggling

The same is true for the angular divergence of a beam

Even if the mean direction is the same before and after the thin traget there is some Angular opening in the beam

$$\theta_{rad} = \left[8{,}91 \frac{NZ\,(z+1)\,z^2}{E^2} \ln \frac{3{,}52 \times 10^{10}\, N\,(z+1)}{Z\,(Z^{2/3} + z^{2/3})} \right]^{9/2}$$



7 MeV protns going through a 55 mg/cm2
Thick aluminium foil are slow down to 4 MeV
The enrgy straggling is 70 keV and the angular Straggling 5°

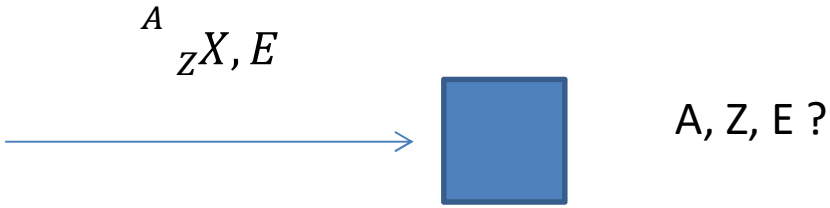
Any beam target interaction will modify the beam properties

Broadening in energy, direction, charge

These effect can limit the performances of detection system

Example telescope or ΔE E method

The is the only method to identify simultaneously the energy the charge and the mass of an ion



Photons

As neutral particle, photons will interact very rarely with matter. When they interact they interact individually with one particle

The attenuation law (Beer Lambert)

Is given by

$$I(x) = I_0 exp^{-\mu x}$$

I_0 is the initial intensity, I(x) is the intensity after x, μ is the linear attenuation coefficient

$\mu = N\sigma$

N the n umber of target per volume unit, σ the total cross section

Total cross section is the sum of all the cross section, ie all the interaction processes

$$\sigma = \sum_i \sigma_i$$

σi are the corresponding cross section for the i intercation

We will cover different interaction

Elastic scattering

Photo electric

Compton

Pair Production

Of course there are many others

Photo electric effect

The photon is giving all its energy to a bound electron

The electron energy Ee- after the photo electric effect is given by

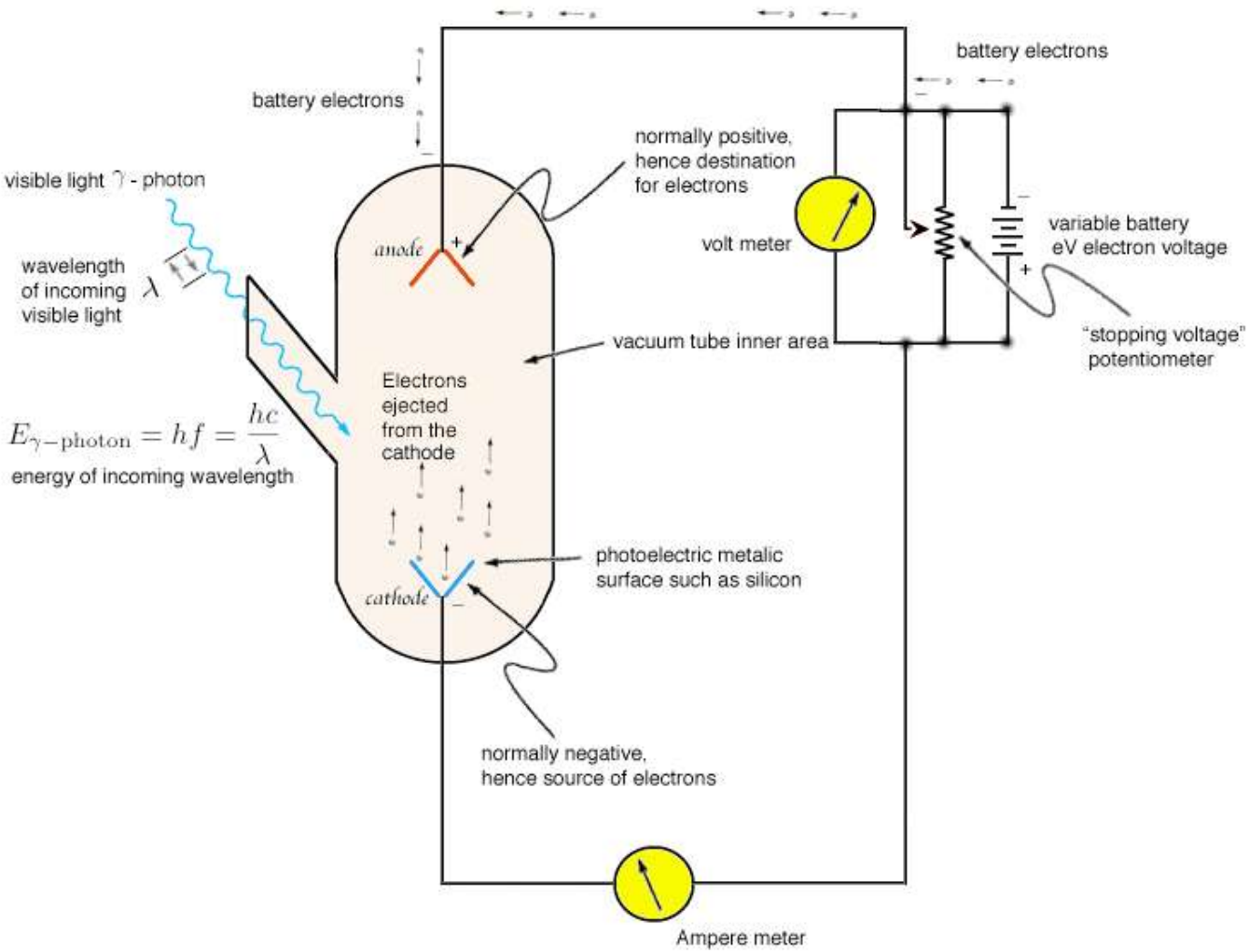
$$E_{e-} = E_0 - B_i$$

E0 is the initial photon energy
Bi is the electron binding energy

The photo electric effect has a threshold

Historically unexplained phenomenum ~1900

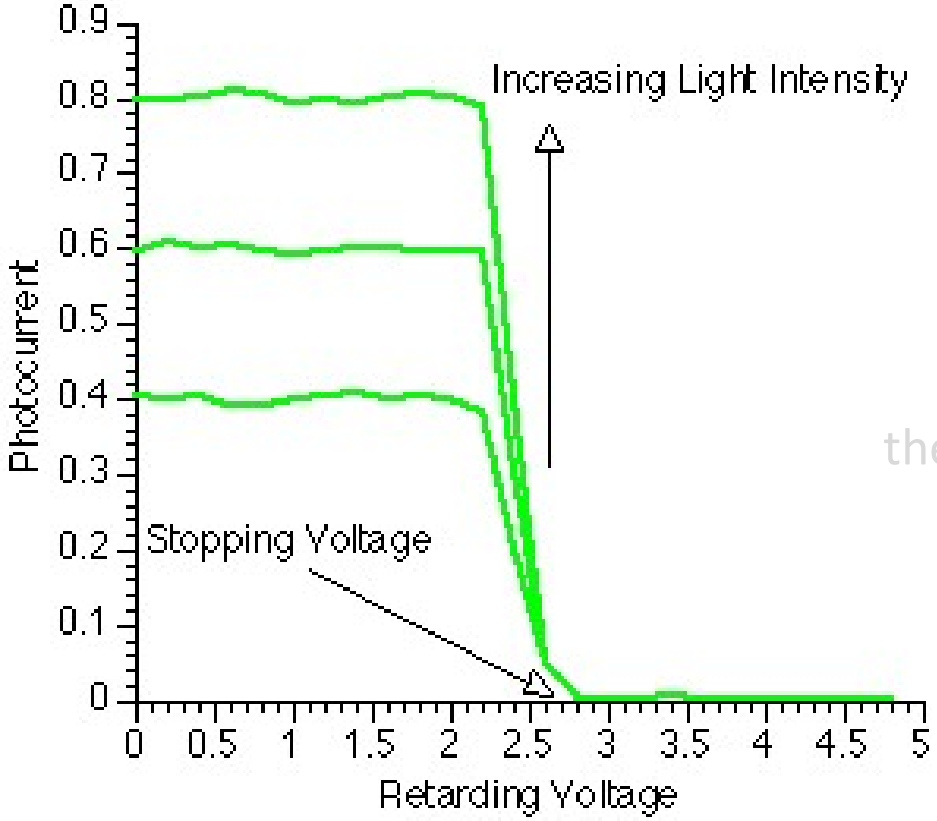
Experment : Electric curent when a metal plate is illuminated by light



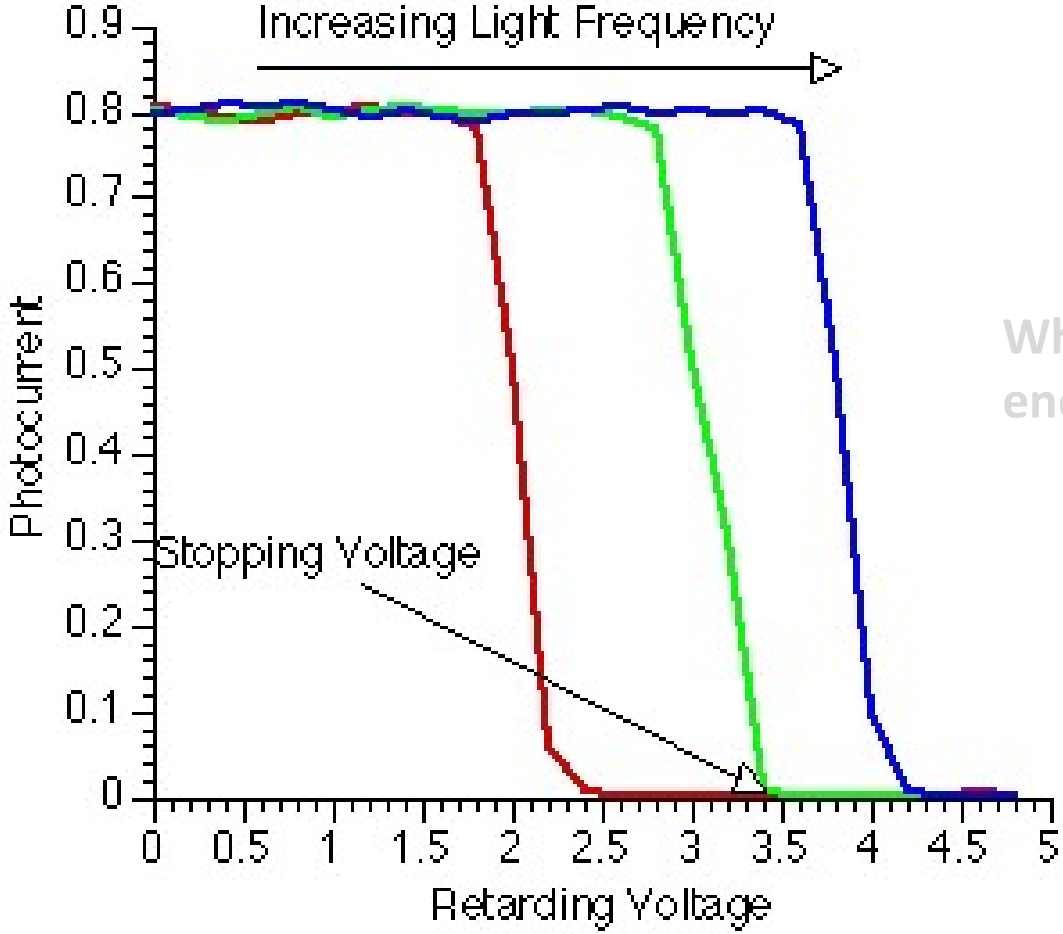
http://www.relativitycalculator.com/photoelectric_effect.shtml

Experimentally what can be vary

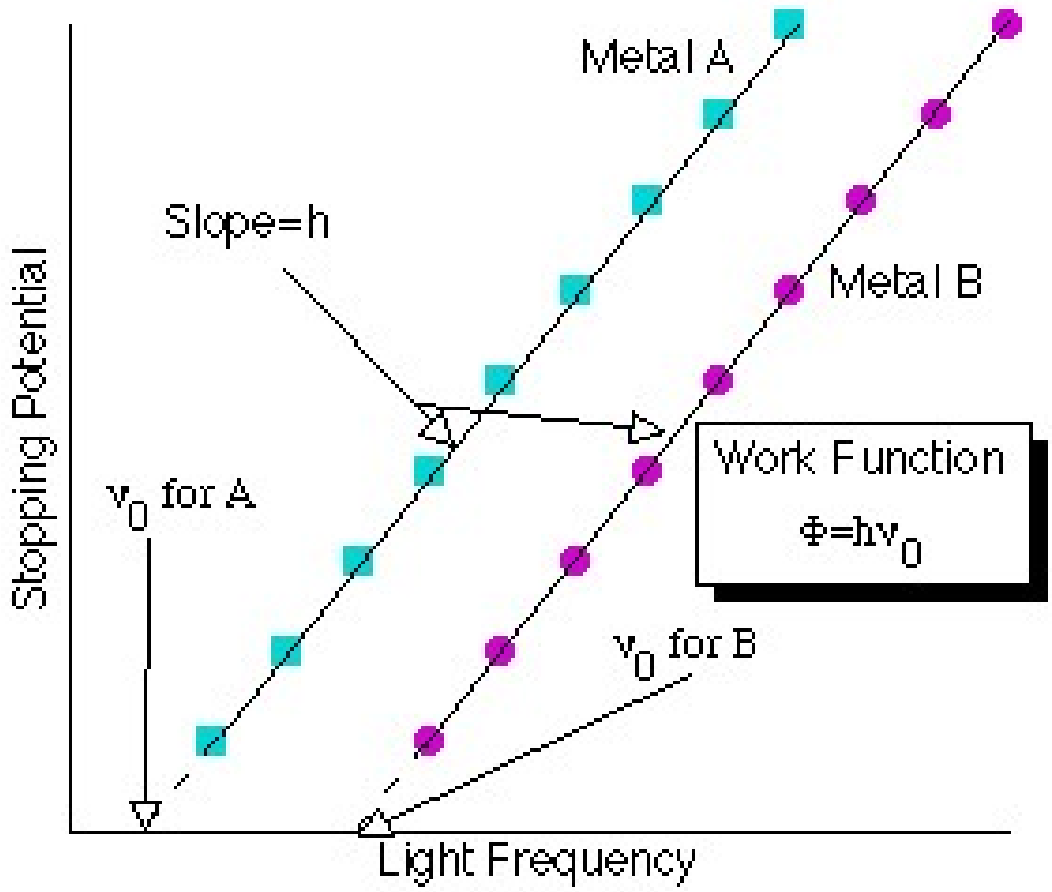
The light intensity
The light frequency
The stopping voltage
The cathode material



In the classical explanation
Intensity= EM Field intensity
→ How does it explain that
the electrons have more energy???



What links the electron energy and the frequency????



Different behavior
With different metals
???

Another unexplained experimental fact
Is the instantaneous curent
(no time needed to gain energy)

http://www.cobalt.chem.ucalgary.ca/ziegler/educmat/chm386/rudiment/tourexp/photelec.htm

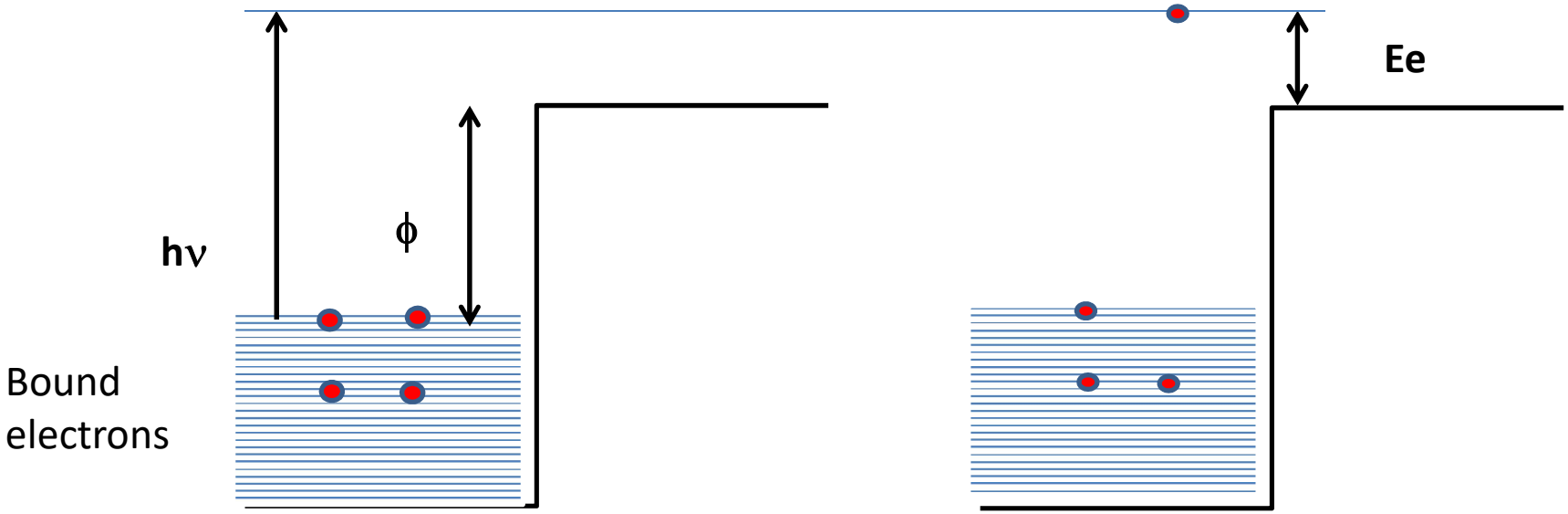
Quantum explanation

Albert Einstein 1905, using planck's idea of quantum particle (Photons)

quanta=photons=hν

No more EM wave

$$\boxed{Ee = h\nu - \phi}$$



Scaling Laws

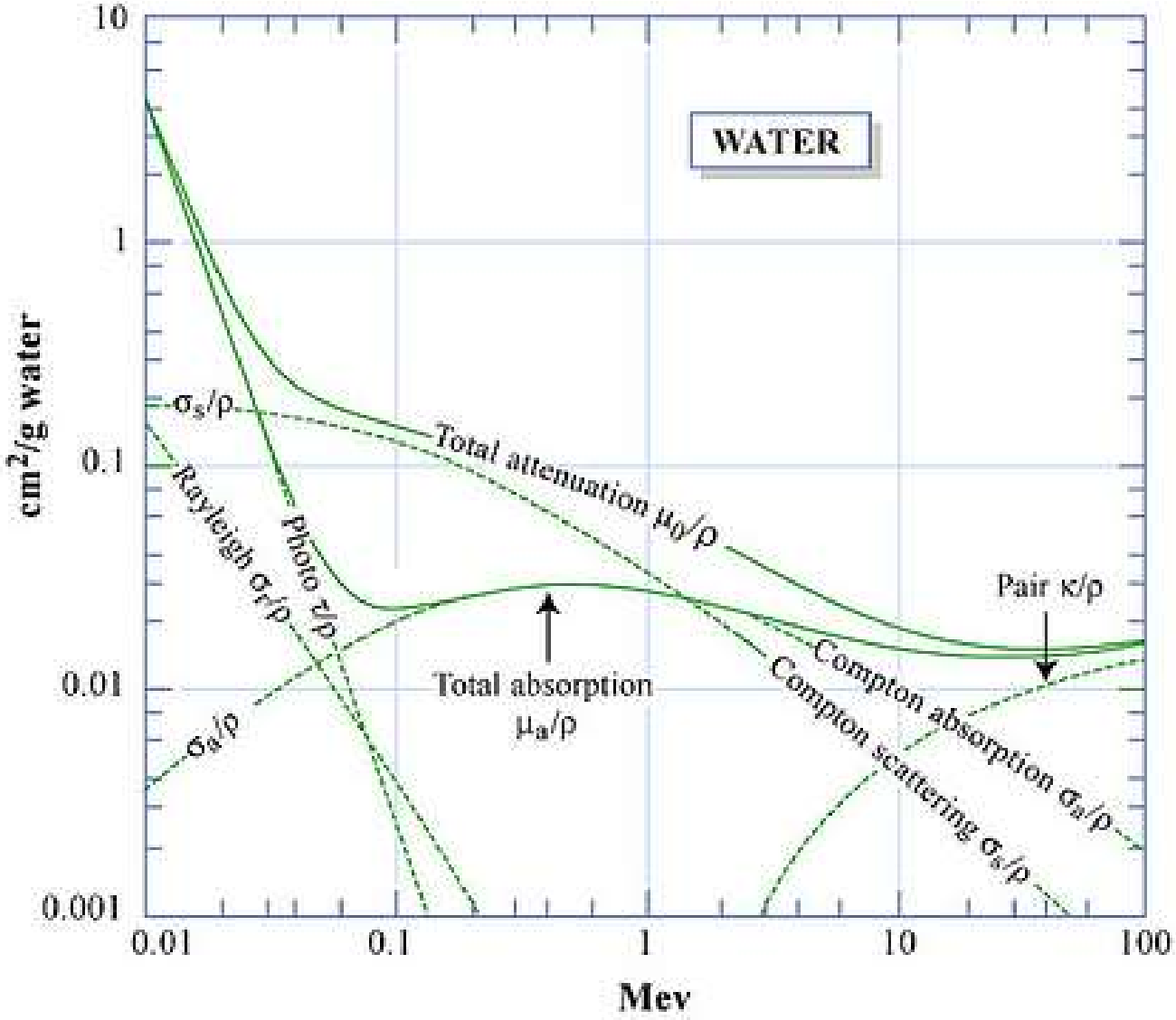
$$\sigma_{ph} \; \alpha \; \frac{Z^5}{E^{3,5}}$$

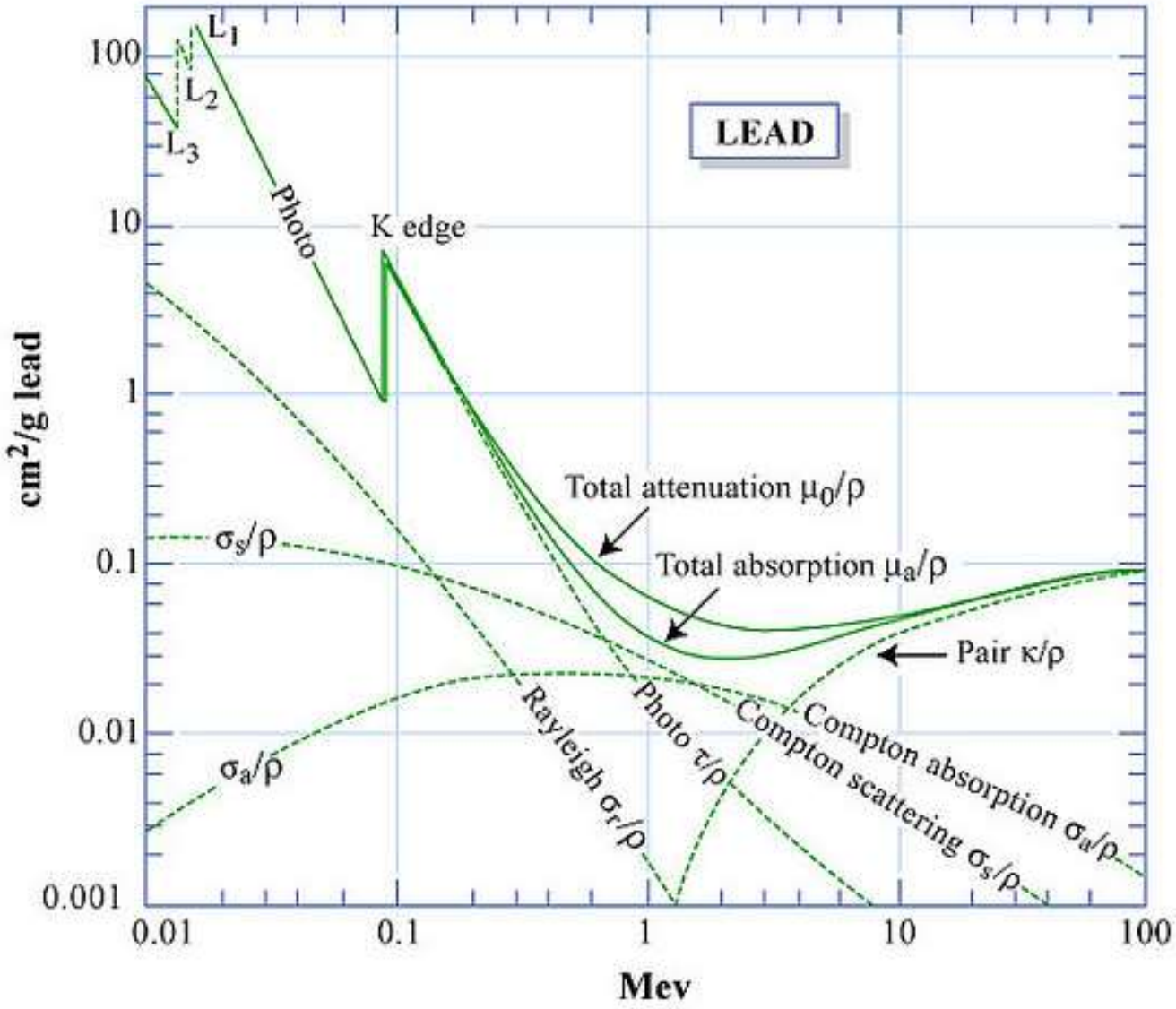
Outside the shell discontinuities

Varies strongly with Z and with E

The denser the material the higher the absorption
The higher the energy the more transparent is the absorber

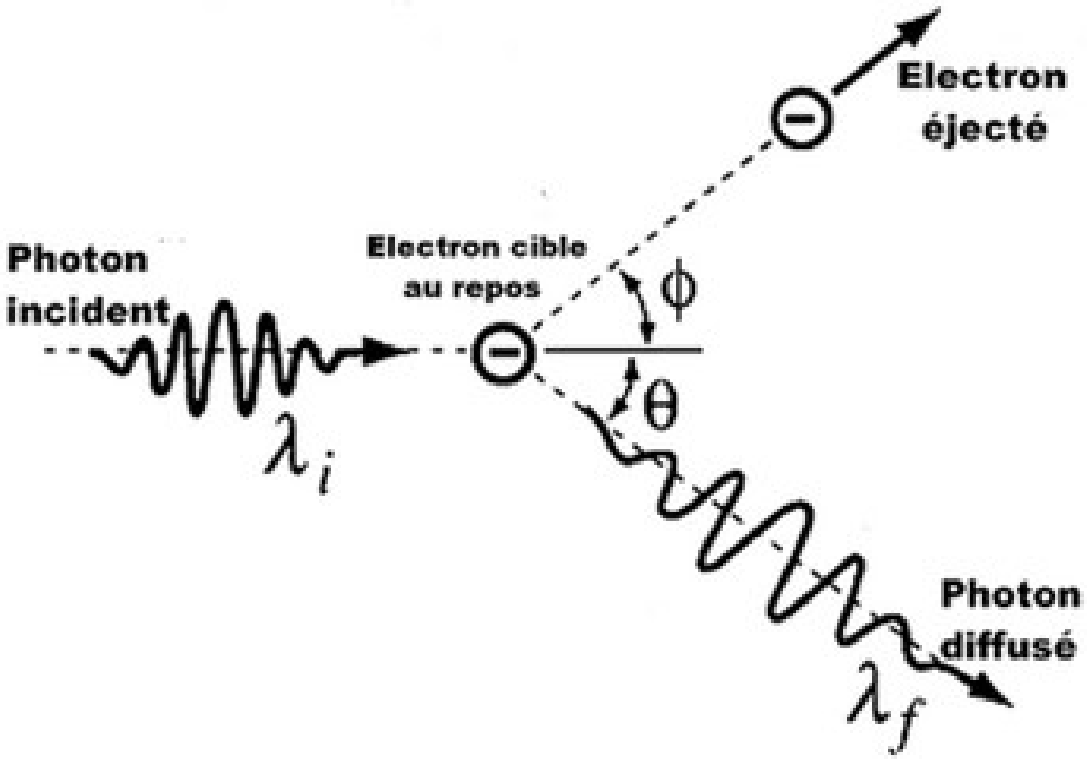
One can represent
μ/ρ
with $\mu = N\sigma$ and ρ the specific mass in g/cm^3


WATER
cm²/g water
Mev
10
1
0.1
0.01
0.001
0.01
0.1
1
10
100
σs/ρ
Total attenuation μ0/ρ
Rayleigh σr/ρ
Photo τ/ρ
Pair κ/ρ
Total absorption
μa/ρ
Compton absorption σa/ρ
Compton scattering σs/ρ
σa/ρ

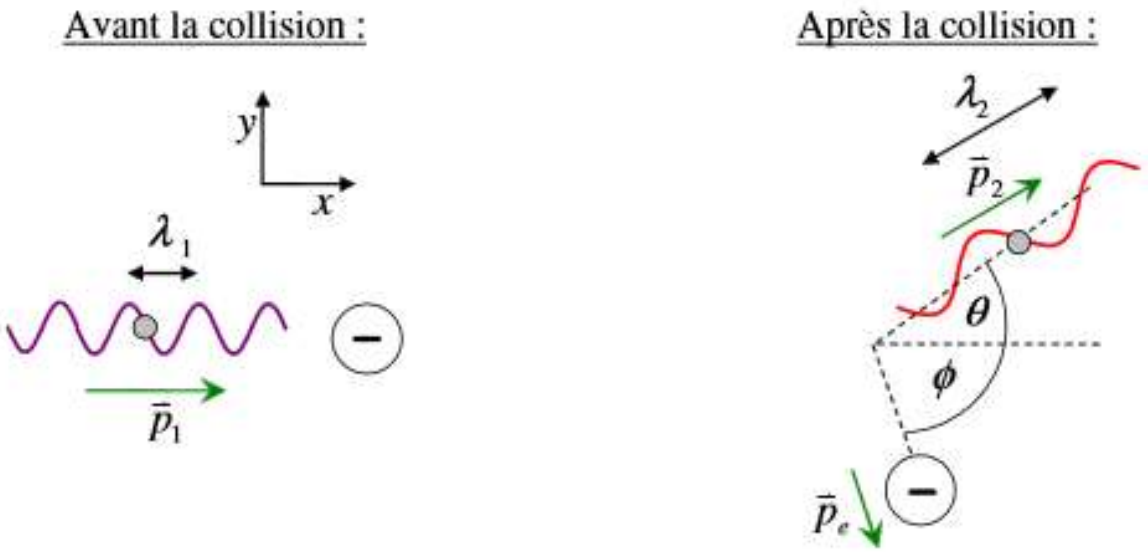

LEAD
L1
L2
L3
Photo
K edge
Total attenuation μ0/ρ
Total absorption μa/ρ
Pair κ/ρ
σs/ρ
σa/ρ
Rayleigh σr/ρ
Photo τ/ρ
Compton scattering σs/ρ
Compton absorption σa/ρ
cm2/g lead
Mev
100
10
1
0.1
0.01
0.001
0.01
0.1
1
10
100

Compton effect

Incoherent diffusion on an electron



Photon
E=hν
p=ħk



$$\sum p_{xf} = \sum p_{xi}$$

$$\Rightarrow \quad p_2 \cos(\theta) + p_e \cos(\phi) = p_1$$

$$\Rightarrow \quad p_e \cos(\phi) = p_1 - p_2 \cos(\theta)$$

$$\Rightarrow \quad \boxed{p_e^{\,2} \cos^2(\phi) = p_1^{\,2} - 2 p_1 p_2 \cos(\theta) + p_2^{\,2} \cos^2(\theta)}$$

Momentum

$$\sum p_{yf} = \sum p_{yi}$$

$$\Rightarrow \quad p_2 \sin(\theta) + p_e \sin(\phi) = 0$$

$$\Rightarrow \quad p_e \sin(\phi) = -p_2 \sin(\theta)$$

$$\Rightarrow \quad \boxed{p_e^{\,2} \sin^2(\phi) = p_2^{\,2} \sin^2(\theta)}$$

$$\left[p_e^{\,2} \cos^2(\phi)\right] + \left[p_e^{\,2} \sin^2(\phi)\right] = \left[p_1^{\,2} - 2p_1 p_2 \cos(\theta) + p_2^{\,2} \cos^2(\theta)\right] + \left[p_2^{\,2} \sin^2(\theta)\right]$$

$$\Rightarrow \quad p_e^{\,2}\left(\cos^2(\phi) + \sin^2(\phi)\right) = p_1^{\,2} - 2p_1 p_2 \cos(\theta) + p_2^{\,2}\left(\cos^2(\theta) + \sin^2(\theta)\right)$$

$$\Rightarrow \quad \boxed{p_e^{\,2} = p_1^{\,2} - 2p_1 p_2 \cos(\theta) + p_2^{\,2}}$$

Energy

$$\sum E_f = \sum E_i$$

$$\Rightarrow \quad E_{\gamma 2} + E_{ef} = E_{\gamma 1} + E_{ei}$$

$$\Rightarrow \quad p_2 c + E_{ef} = p_1 c + E_{ei}$$

$$\Rightarrow \quad p_2 c + \sqrt{p_{ef}{}^2 c^2 + m_e{}^2 c^4} = p_1 c + \sqrt{p_{ei}{}^2 c^2 + m_e{}^2 c^4}$$

$$\Rightarrow \quad p_2 c + \sqrt{p_e{}^2 c^2 + m_e{}^2 c^4} = p_1 c + m_e c^2$$

$$\Rightarrow \quad \sqrt{p_e{}^2 c^2 + m_e{}^2 c^4} = p_1 c - p_2 c + m_e c^2$$

$$\Rightarrow \quad \sqrt{p_e{}^2 c^2 + m_e{}^2 c^4} = c(p_1 - p_2) + m_e c^2$$

$$\Rightarrow \quad p_e{}^2 c^2 + m_e{}^2 c^4 = \left(c(p_1 - p_2) + m_e c^2\right)^2$$

$$\Rightarrow \quad p_e{}^2 c^2 + m_e{}^2 c^4 = c^2 (p_1 - p_2)^2 + 2 m_e c\ (p_1 - p_2) + m_e{}^2 c^4$$

$$\Rightarrow \quad \boxed{p_e{}^2 = (p_1 - p_2)^2 + 2 m_e c (p_1 - p_2)} \quad \textbf{(4)}$$

$$\left\lfloor p_e^{\,2}\right\rfloor - \left\lfloor p_e^{\,2}\right\rfloor = \left\lfloor p_1^{\,2} - 2p_1p_2\cos(\theta) + p_2^{\,2}\right\rfloor - \left\lfloor (p_1 - p_2)^2 + 2m_ec(p_1 - p_2)\right\rfloor$$

$$\Rightarrow \quad 0 = p_1^{\,2} - 2p_1p_2\cos(\theta) + p_2^{\,2} - (p_1 - p_2)^2 - 2m_ec(p_1 - p_2)$$

$$\Rightarrow \quad 0 = p_1^{\,2} - 2p_1p_2\cos(\theta) + p_2^{\,2} - \left(p_1^{\,2} - 2p_1p_2 + p_2^{\,2}\right) - 2m_ec(p_1 - p_2)$$

$$\Rightarrow \quad 0 = -2p_1p_2\cos(\theta) + 2p_1p_2 - 2m_ec(p_1 - p_2)$$

$$\Rightarrow \quad 0 = 2p_1p_2(1 - \cos(\theta)) - 2m_ec(p_1 - p_2)$$

$$\Rightarrow \quad 2m_ec(p_1 - p_2) = 2p_1p_2(1 - \cos(\theta))$$

$$\Rightarrow \quad p_1 - p_2 = \frac{p_1p_2}{m_ec}(1 - \cos(\theta))$$

$$\Rightarrow \quad \frac{h}{\lambda_1} - \frac{h}{\lambda_2} = \frac{(h/\lambda_1)(h/\lambda_2)}{m_ec}(1 - \cos(\theta))$$

$$\Rightarrow \quad \frac{1}{\lambda_1} - \frac{1}{\lambda_2} = \frac{h}{m_ec}\frac{1}{\lambda_1\lambda_2}(1 - \cos(\theta))$$

$$\Rightarrow \quad \lambda_2 - \lambda_1 = \frac{h}{m_ec}(1 - \cos(\theta))$$

$$\Rightarrow \quad \lambda_f - \lambda_i = \frac{h}{m_ec}(1 - \cos(\theta)) \quad \blacksquare$$

And

$$\mathbf{h\nu' =} = \frac{\mathbf{h\nu}}{(1 + \frac{\mathbf{h\nu}}{\boldsymbol{mc^2(1 - cos\theta)}})}$$

$h\nu'$ energy of the scatterred phton
$h\nu$ energy of the initial photon
mc^2 electron energy mass
θ scattering angle

Ee =$h\nu$-$h\nu'$

Electron energy

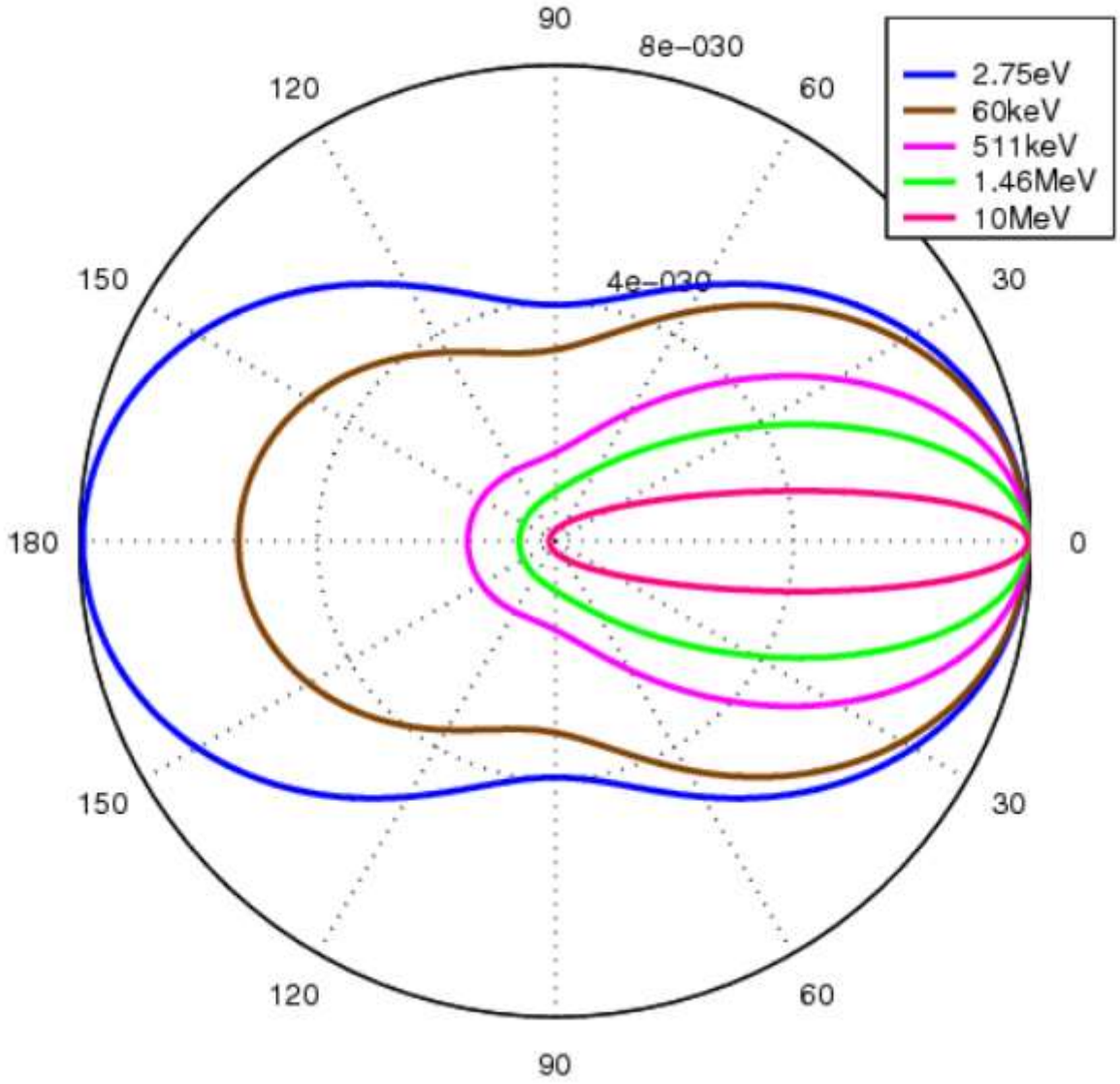
REMEMBER the CP ionize the matter not the NP

The cross section is given by the Klein Nishina formula

$$\frac{d\sigma}{d\Omega} = \frac{1/2 r_0^2 \left[1 + \cos^2 \Theta\right]}{\left[1 + 2\varepsilon \sin^2 \Theta / 2\right]^2} \left\{1 + \frac{4\varepsilon^2 \sin^4 \Theta / 2}{\left[1 + \cos^2 \Theta\right]\left[1 + 2\varepsilon \sin^2 \Theta / 2\right]}\right\}$$

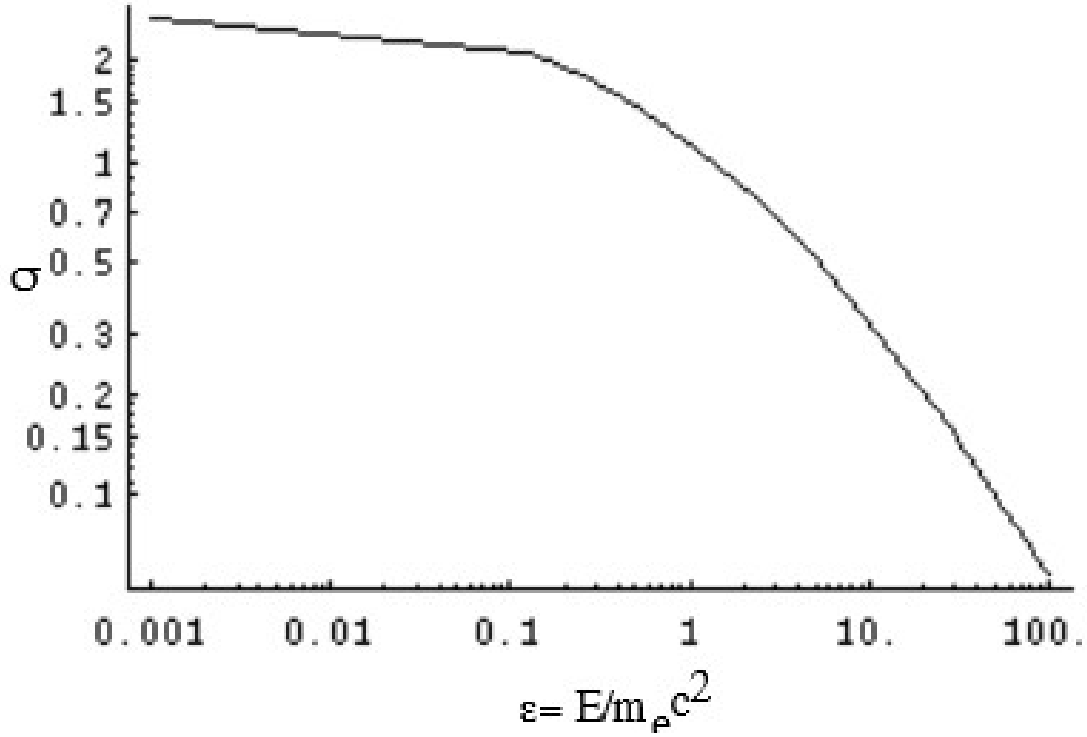
With r_0 the classical radius of the electron

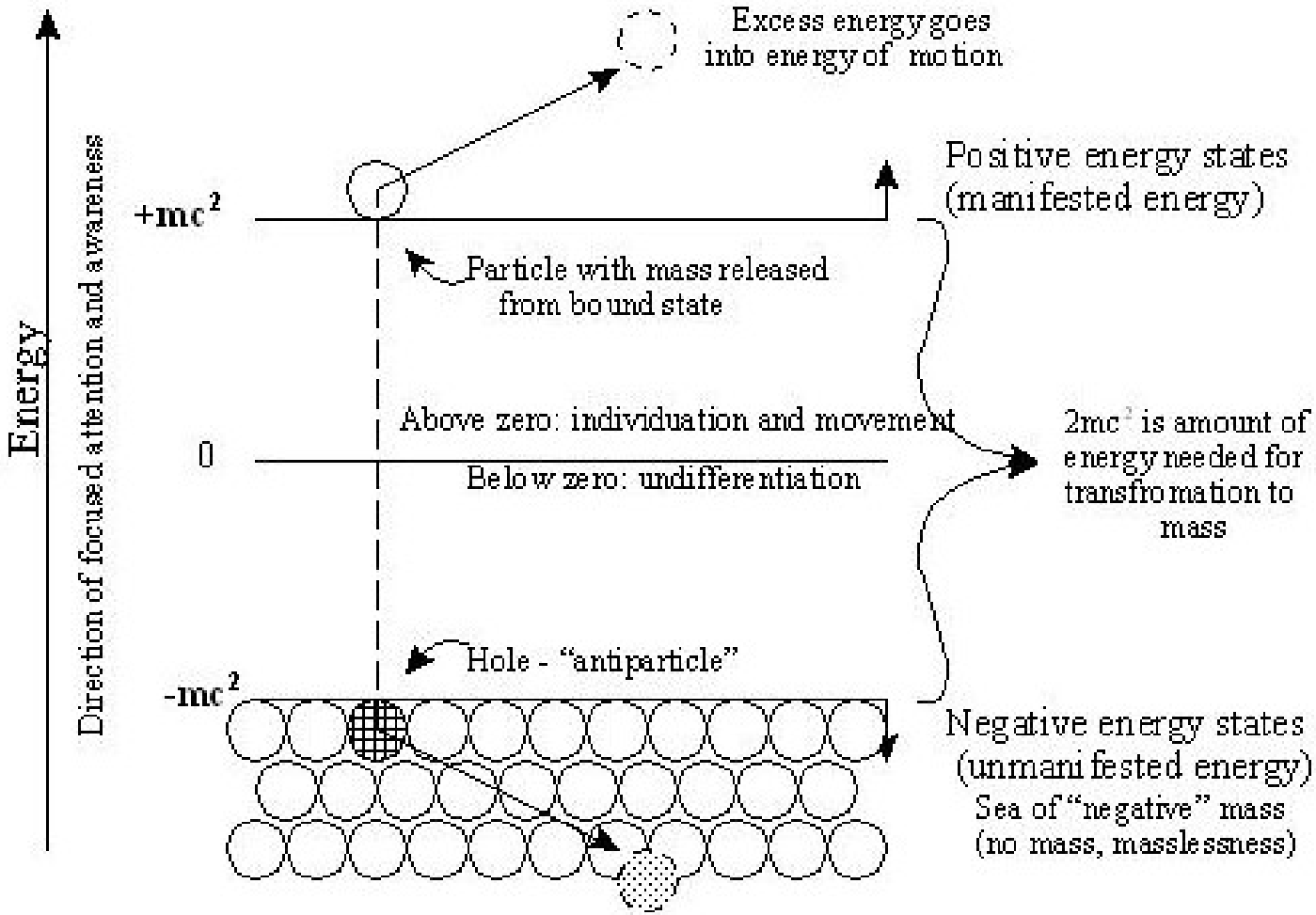
e^2/mc^2~2,8 10^{-13} cm and ε the ratio between the energy and the rest mass mc^2


90
8e−030
120
60
150
4e−030
30
180
0
150
30
120
60
90
2.75eV
60keV
511keV
1.46MeV
10MeV

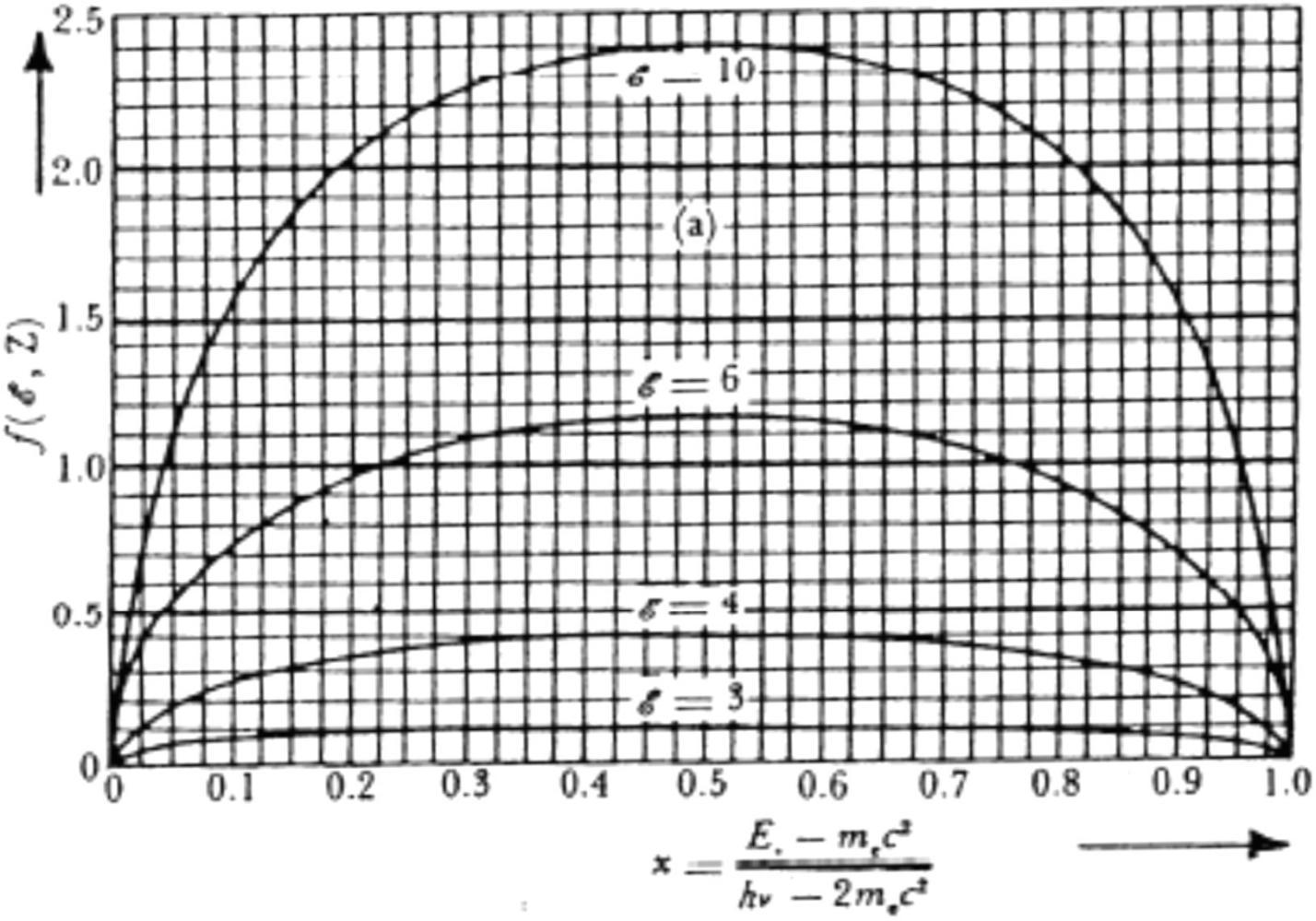
By integrating over al angles the total cross section is given by

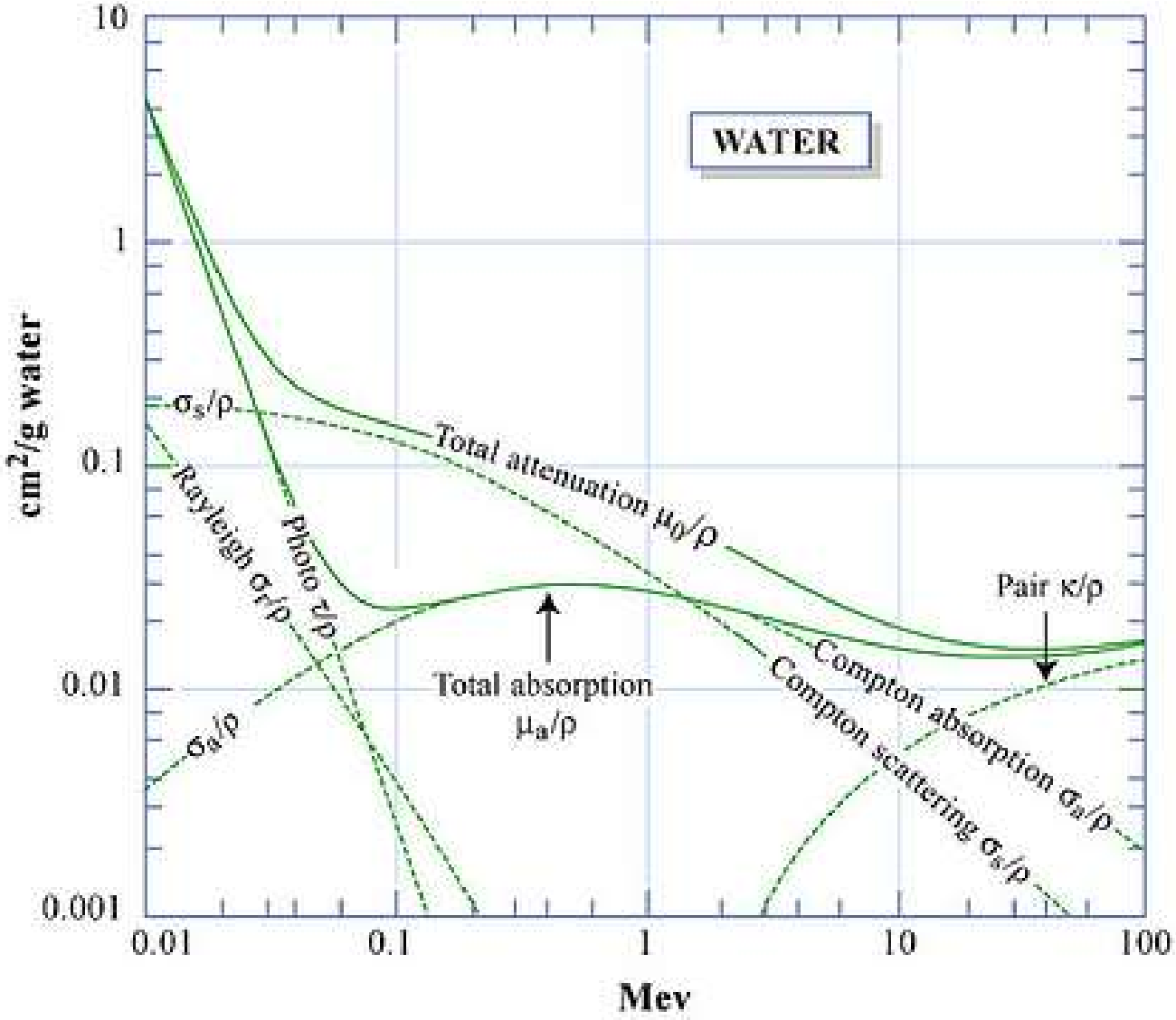
$$\sigma = 2\pi \cdot r_0^2 \left\{ \frac{1+\varepsilon}{\varepsilon} \left[\frac{2+2\varepsilon}{1+2\varepsilon} - \frac{\ln(1+2\varepsilon)}{\varepsilon} \right] + \frac{\ln(1+2\varepsilon)}{2\varepsilon} - \frac{1+3\varepsilon}{(1+2\varepsilon)^2} \right\}$$

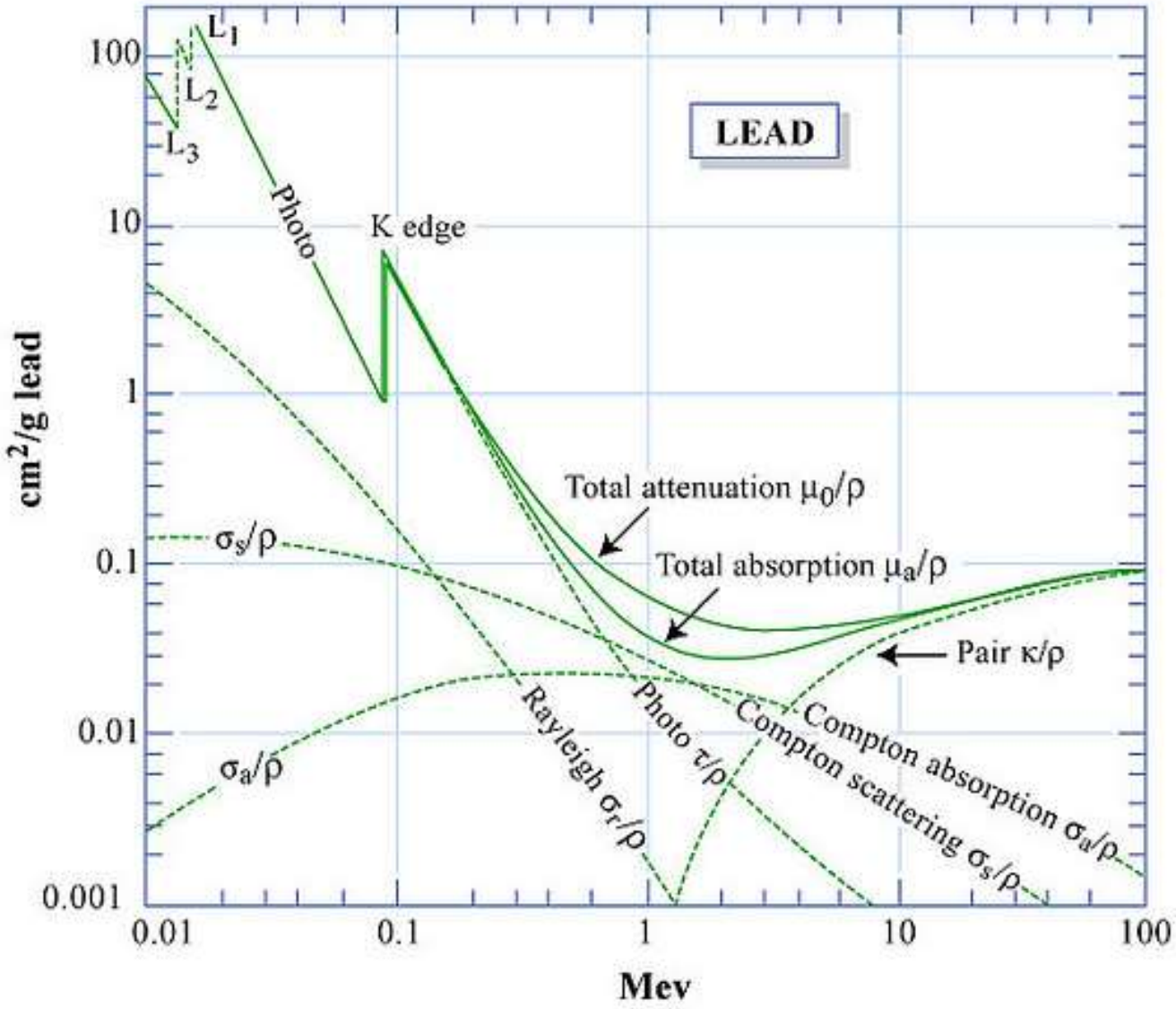


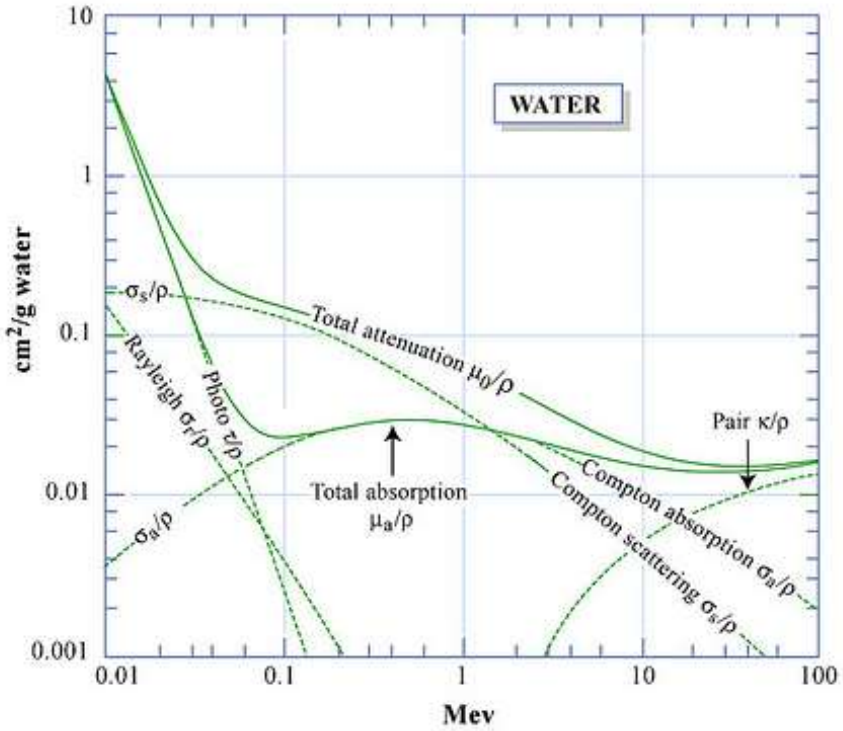


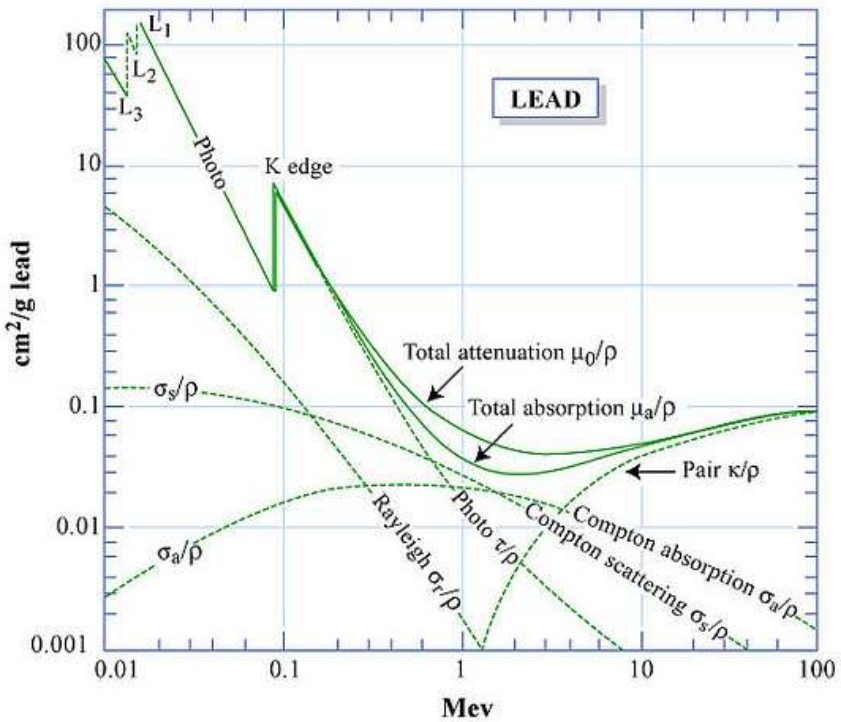
Pair Production from sea of "negative" mass


2.5
2.0
1.5
1.0
0.5
0
$f(\epsilon, Z)$
$\epsilon = 10$
(a)
$\epsilon = 6$
$\epsilon = 4$
$\epsilon = 3$
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
$x = \frac{E_e - m_e c^2}{h\nu - 2m_e c^2}$

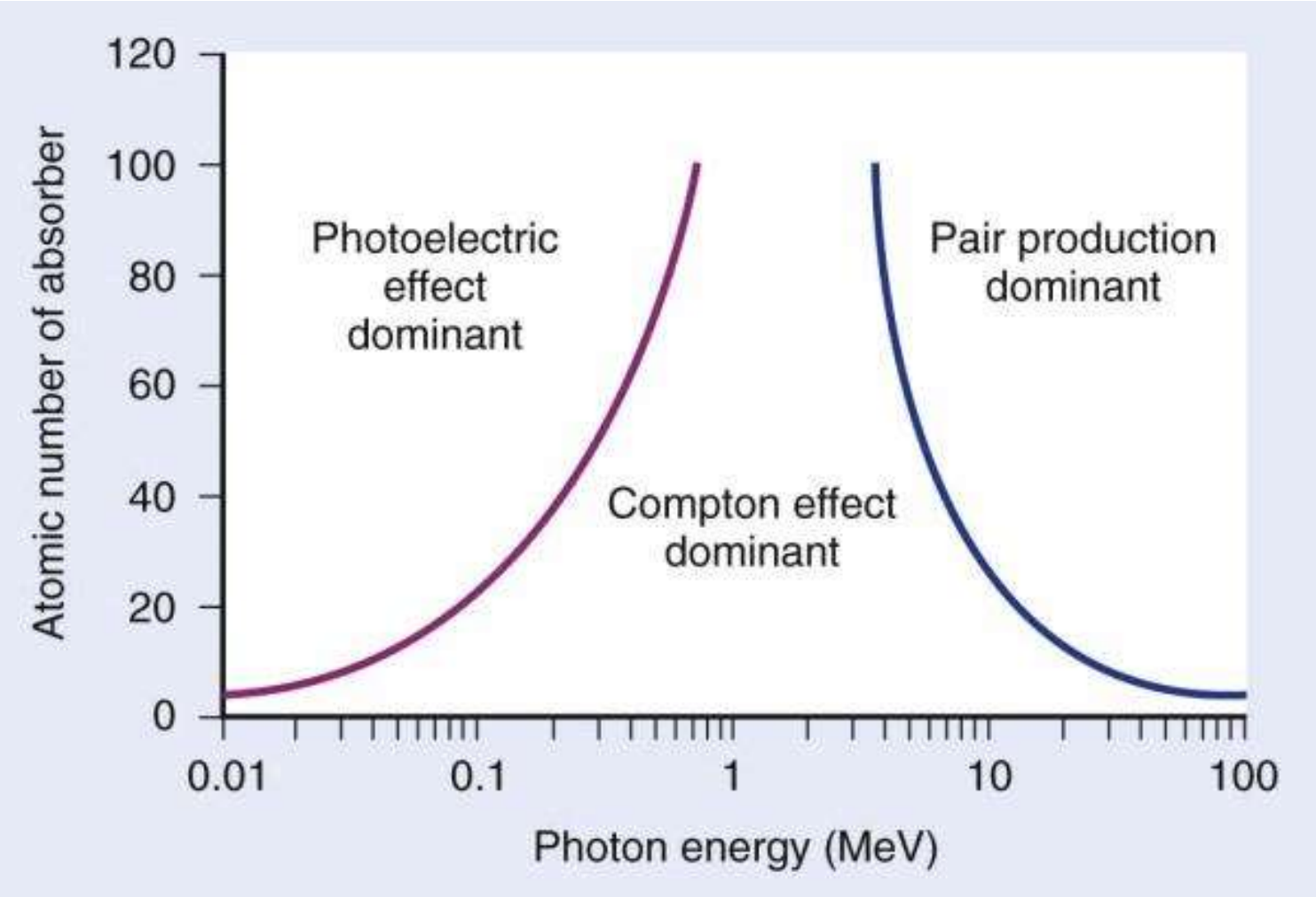

WATER
cm²/g water
Mev
10
1
0.1
0.01
0.001
0.01
0.1
1
10
100
σs/ρ
Total attenuation μ0/ρ
Rayleigh σr/ρ
Photo τ/ρ
Pair κ/ρ
Total absorption
μa/ρ
Compton absorption σa/ρ
Compton scattering σs/ρ
σa/ρ


LEAD
L1
L2
L3
Photo
K edge
Total attenuation μ0/ρ
Total absorption μa/ρ
Pair κ/ρ
σs/ρ
σa/ρ
Rayleigh σr/ρ
Photo τ/ρ
Compton scattering σs/ρ
Compton absorption σa/ρ
cm2/g lead
Mev
100
10
1
0.1
0.01
0.001
0.01
0.1
1
10
100


WATER
cm²/g water
Mev
Total attenuation μ0/ρ
Total absorption μa/ρ
Pair κ/ρ
Compton absorption σa/ρ
Compton scattering σs/ρ
Rayleigh σr/ρ
Photo τ/ρ
σs/ρ
σa/ρ


LEAD
cm²/g lead
Mev
L1
L2
L3
Photo
K edge
Total attenuation μ0/ρ
Total absorption μa/ρ
Pair κ/ρ
Compton absorption σa/ρ
Compton scattering σs/ρ
Rayleigh σr/ρ
Photo τ/ρ
σs/ρ
σa/ρ

Dominance domains



Cross sections and attenuation coefficient:

https://www.nist.gov/pml/x-ray-and-gamma-ray-data

Photons and medical applications

X Ray radiography
Contrast obtain by different absorption (µbone µtissue)
Low energy X rays = absorption =dose

Nuclear medecine
Single photon
Radio isotope with a biological molecule
Isotope concentration is imaged
Common isotope is 99Tcm (140 keV rather high)
High transmission
Low detection efficiency → dose

PET Positron+ 2 511 keV gammas
CP interaction (Blur) → annihilation→ Gammas (detection efficiency)

Radio therapy
Few MeV photons
No bragg peak continous attenuation still the main solution using radiations for cancer treatment

Neutrons matter interactions

Reminder

Mn=939 MeV/c2
Q=0
S=1/2
$T_{1/2}$= 12 minutes

Neutrons are name with their energy

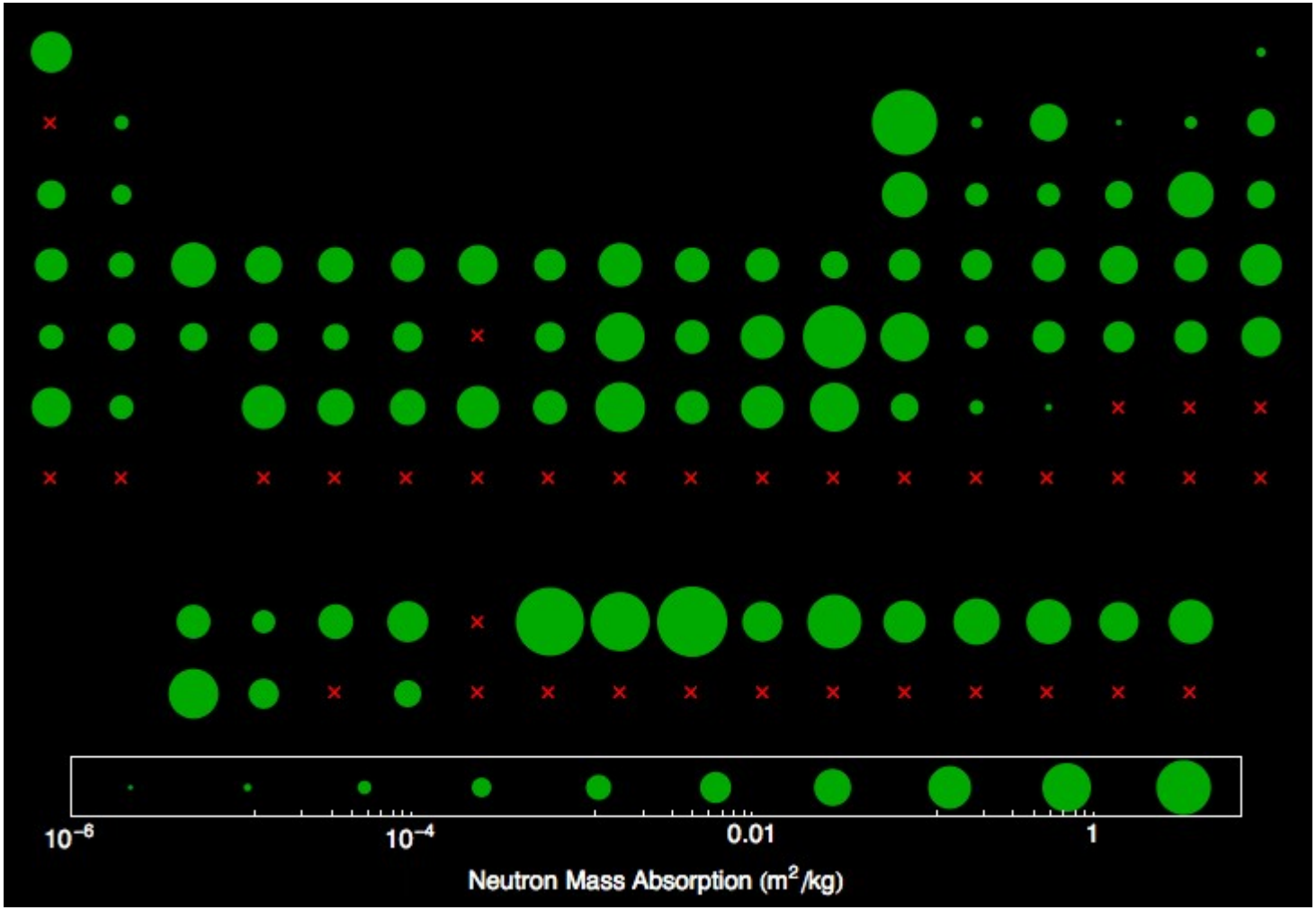
Cold, thermal, fast and so on

Neutron energy	Energy range
0.0 eV-0.025 eV	Cold neutrons
0.025 eV	Thermal neutrons
0.025 eV-0.4 eV	Epithermal neutrons
0.4 eV-0.6 eV	Cadmium neutrons
0.6 eV-1 eV	EpiCadmium neutrons
1 eV-10 eV	Slow neutrons
10 eV-300 eV	Resonance neutrons
300 eV-1 MeV	Intermediate neutrons
1 MeV-20 MeV	Fast neutrons
> 20 MeV	Relativistic neutrons

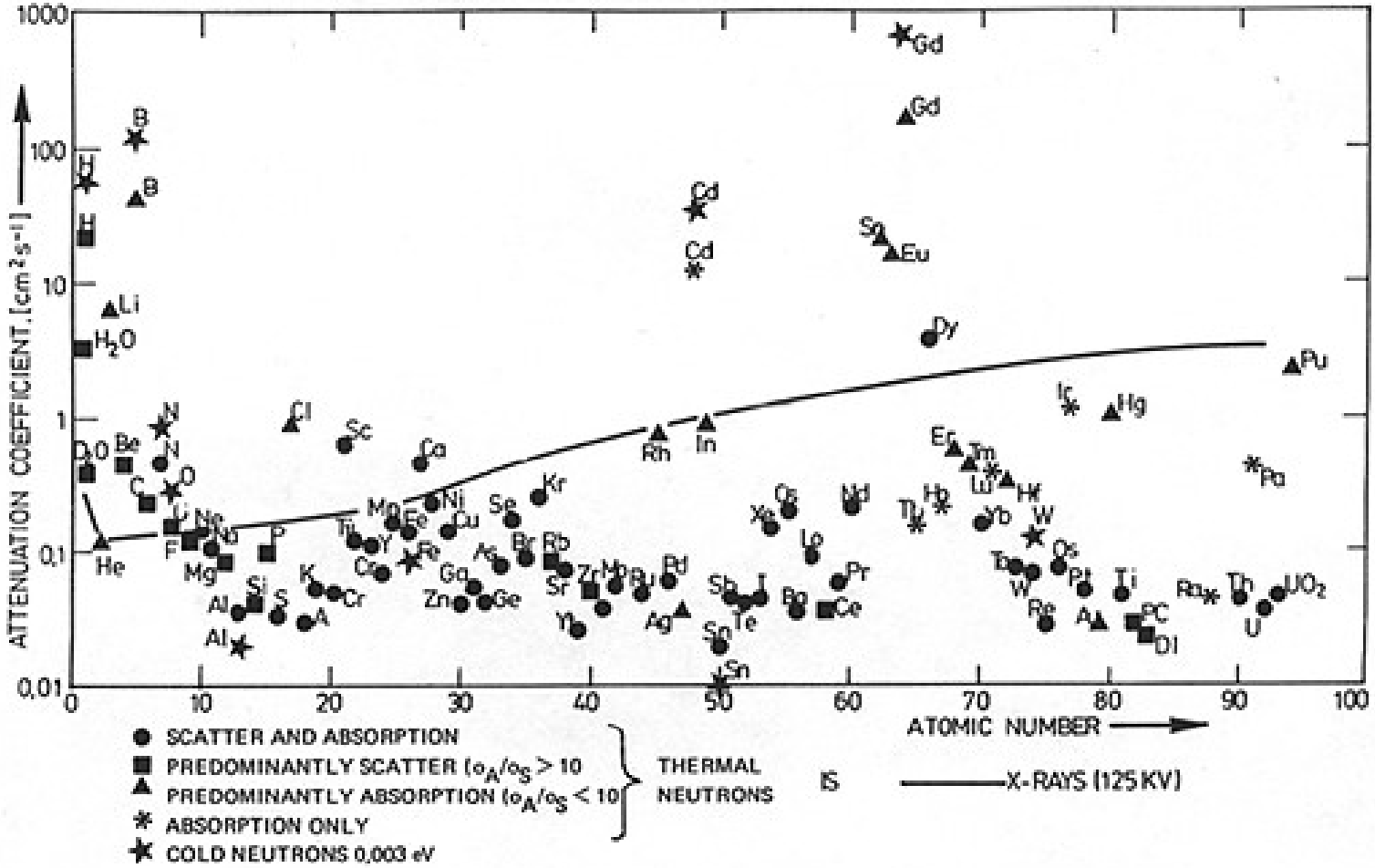
How to produce neutrons

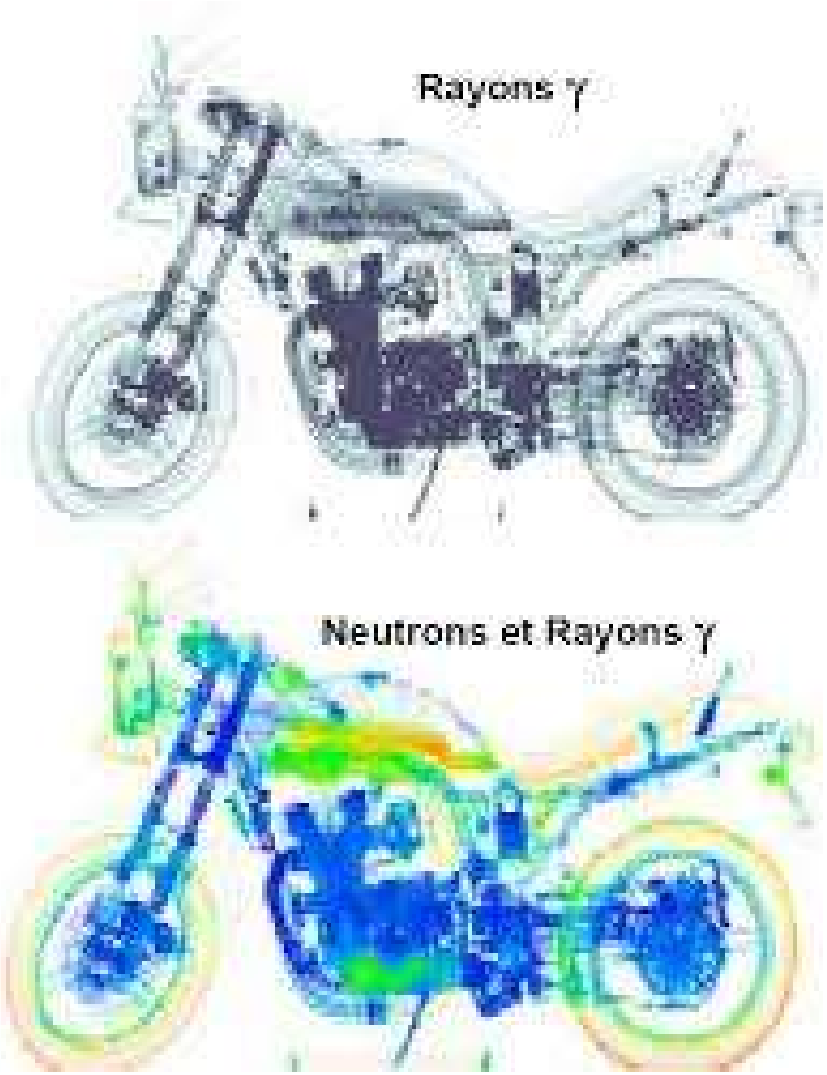
	Flux	price	pros	cons
Reactor	Up to 1014 n/cm2/s	Extremely high 10M€	High flux At any energy	Expensive Not easy to use safety
DT generator	Up to 109 n/s	100 k€	Moderate flux Easy to use cost	cost
Isotopique source	Up to 106 n/s	Few k€	Cost Easy to use	Low flux

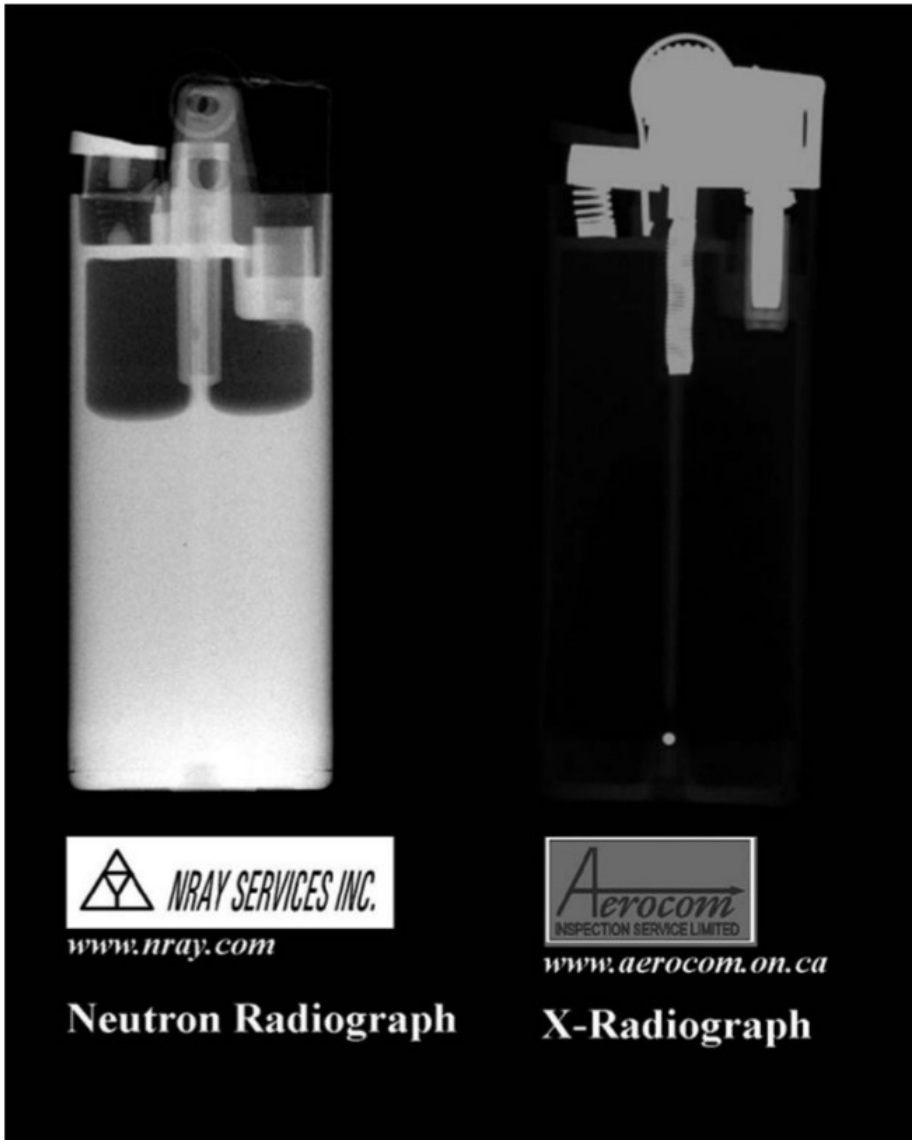
Absorption



The neutron interaction will depend only on the Nuclear Structure of the nucleus


ATTENUATION COEFFICIENT, [cm²s⁻¹]
ATOMIC NUMBER
SCATTER AND ABSORPTION
PREDOMINANTLY SCATTER (σA/σS > 10
PREDOMINANTLY ABSORPTION (σA/σS < 10
ABSORPTION ONLY
COLD NEUTRONS 0,003 eV
THERMAL NEUTRONS
IS
X-RAYS (125 KV)


Rayons γ
Neutrons et Rayons γ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www.nray.com
Neutron Radiograph
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Elastic Scattering

A neutron interacts with a nucleus and lose some energy

$$E_n = E_0 \frac{A^2+1+2A\cos\theta}{(A+1)^2}$$

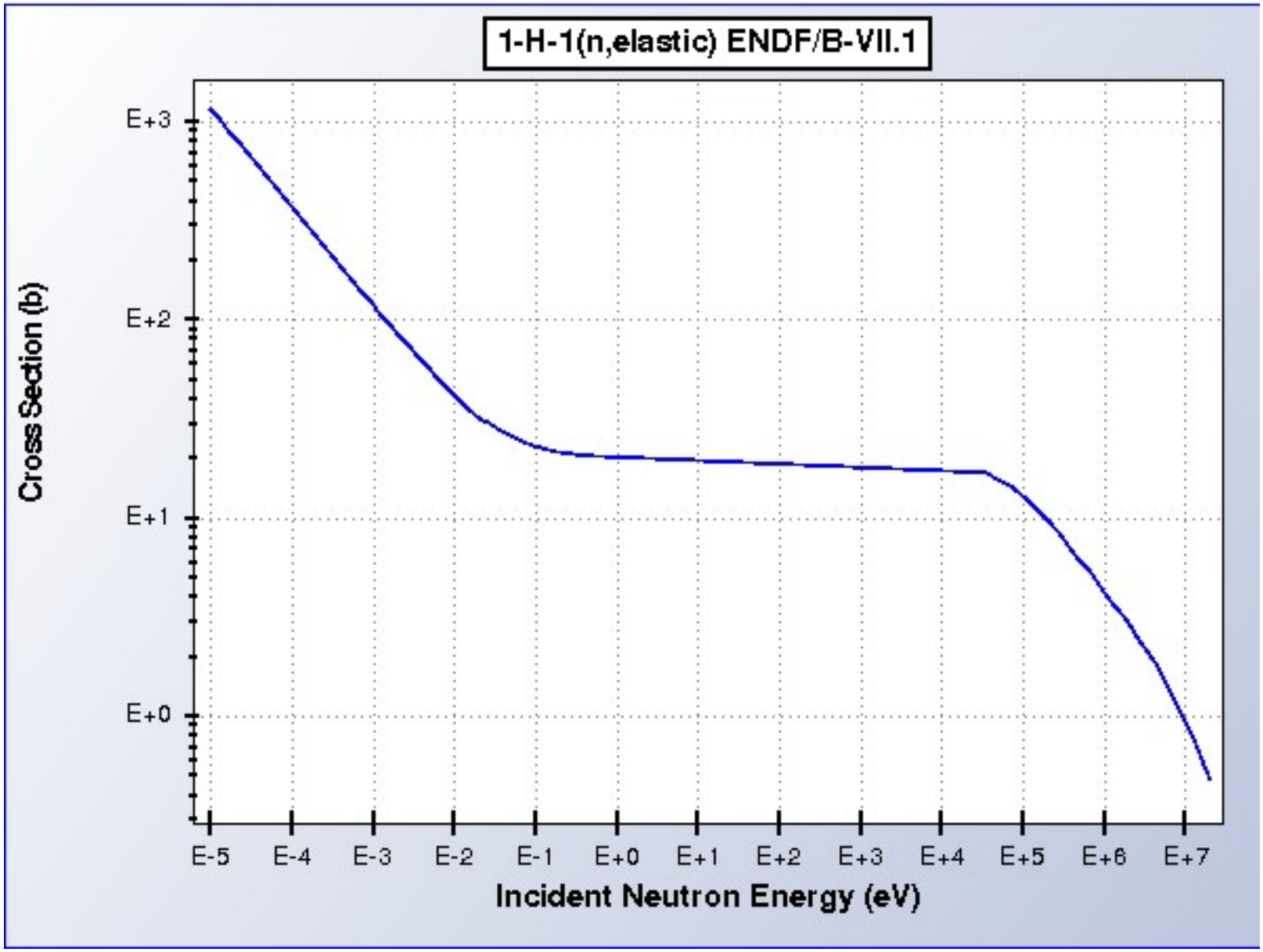
The recoil nucleus gains E_0-E_n

This the process to slow down neutrons
It is called moderation

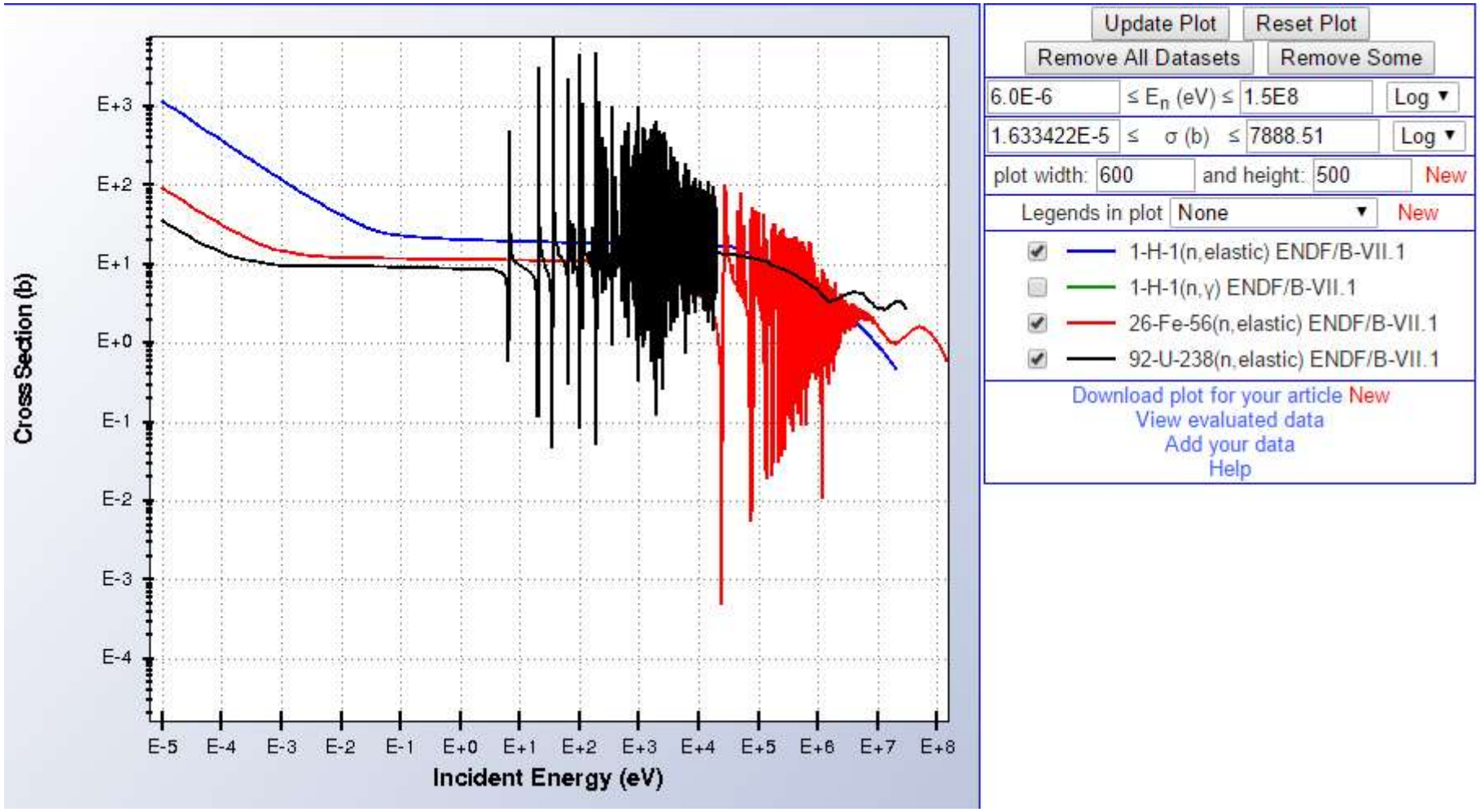
The medium where the moderation takes place is called a moderator

Kinematically the lower the A the more efficient could be the moderation

Example a few cm of water is enough to slow down fast neutron to thermal energies.



More or less constant in our energy domain



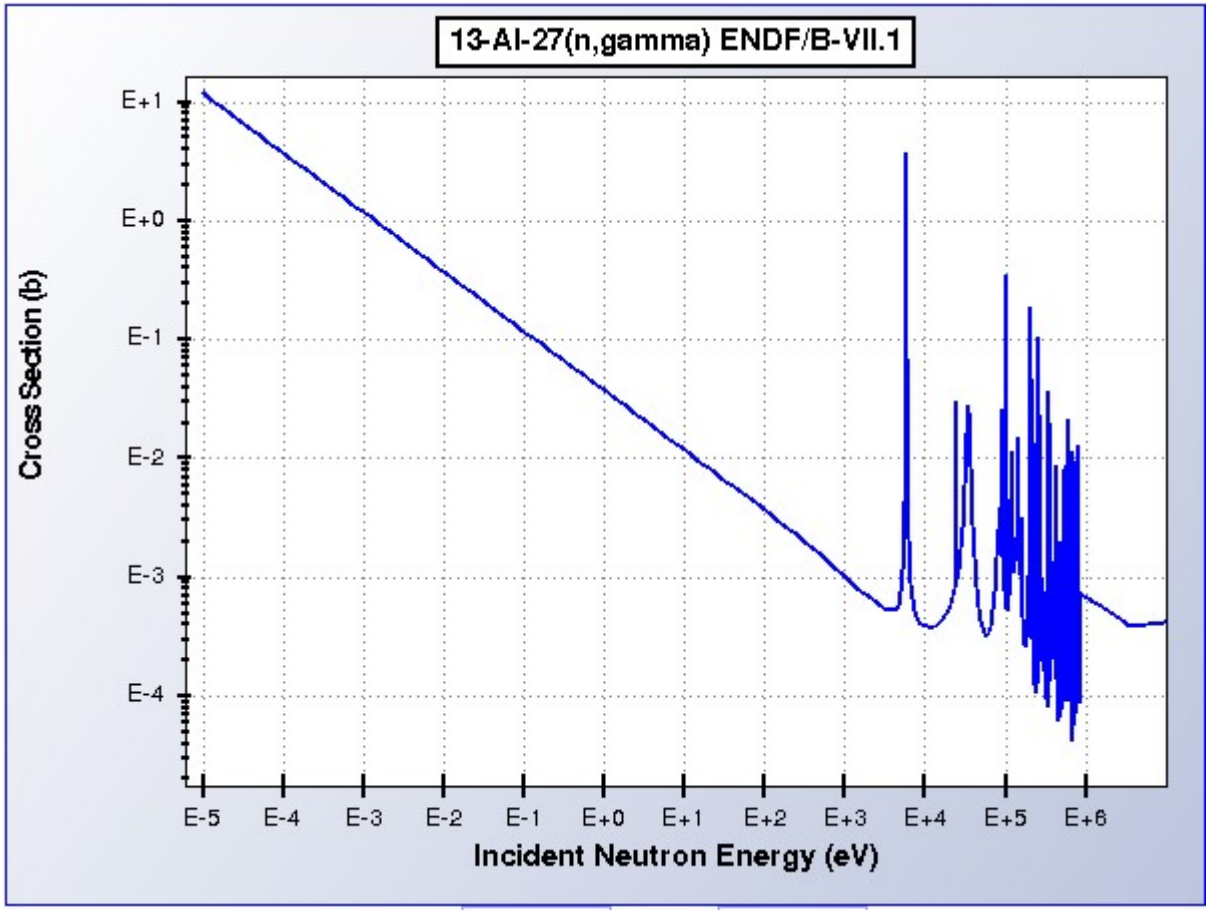
Hydrogen, Iron, Uranium elastic cross section
more or less constant except in the resonances region

Radiative capture (n, γ)

The neutron is capture by the nucleus (A), the (A+1) nucleus emits a gamma

This the process called activation and this how materail in a nuetron environment get activated

The cross section varies as 1/V



Nuclear reactions

Charge particles

$$^{3}He + n \longrightarrow {}^{3}H + p + 765\ KeV \quad (19)$$

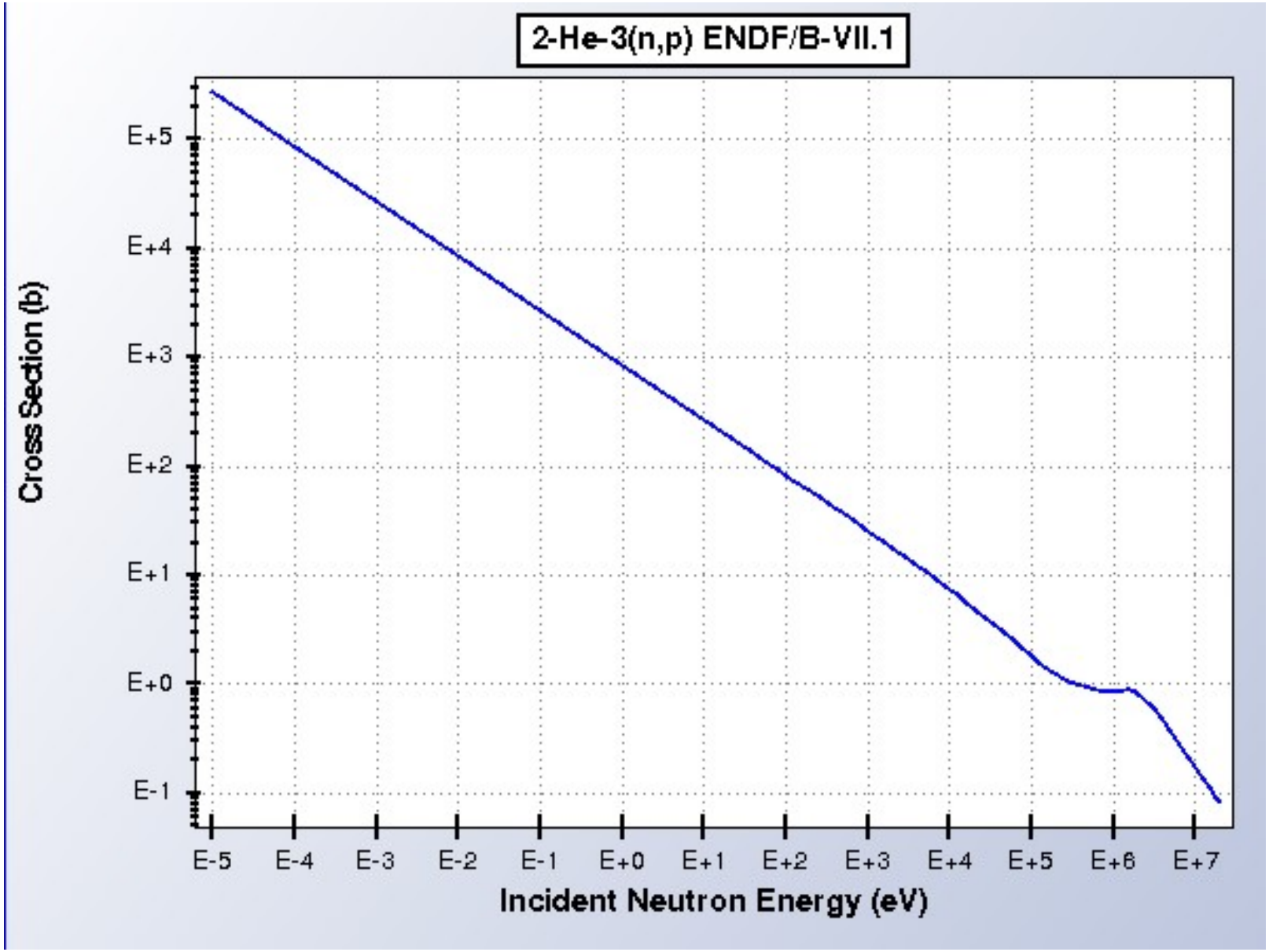
$$^{10}B + n \longrightarrow {}^{7}Li + \alpha + 2{,}78\ MeV \quad (20)$$

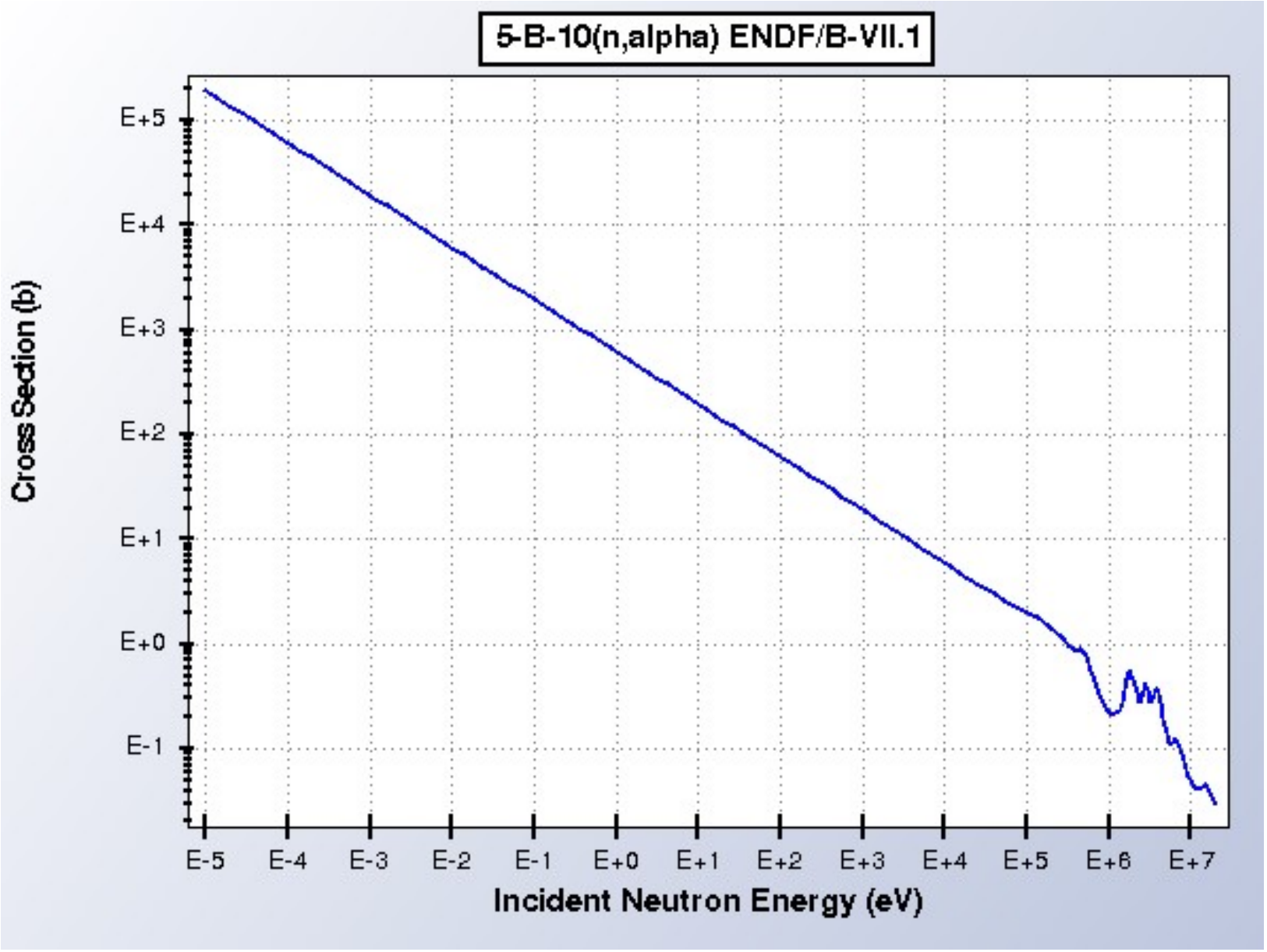
$$^{6}Li + n \longrightarrow {}^{3}H + \alpha + 4{,}78\ MeV \quad (21)$$

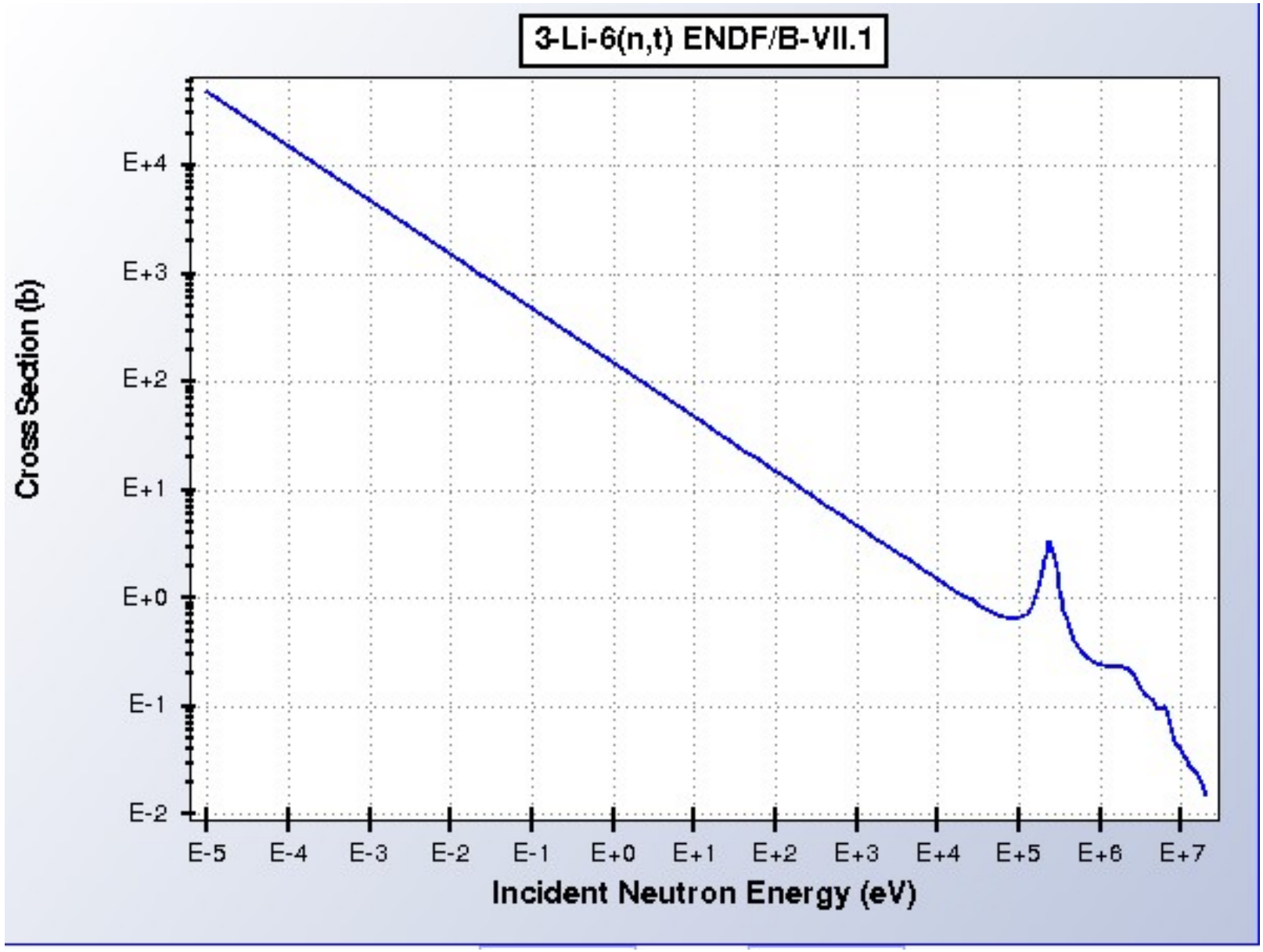
$$^{235}U + n \longrightarrow \text{fission products} + \sim 160\ MeV \quad (22)$$

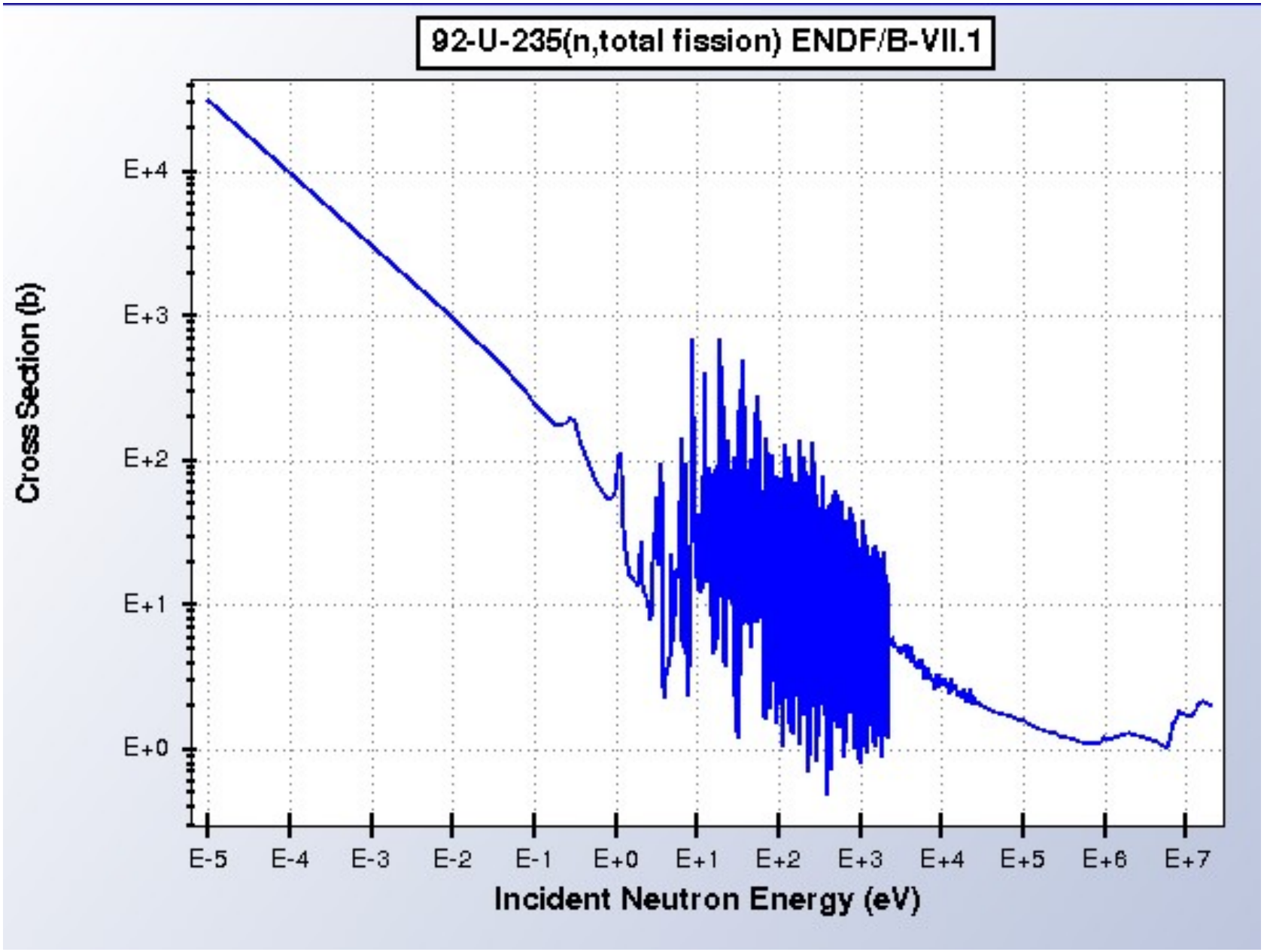
The reaction energy is release as kinetic energy

Cross section is varying like 1/V
the slower the neutrons the higher the reaction rate


2-He-3(n,p) ENDF/B-VII.1
Cross Section (b)
E+5
E+4
E+3
E+2
E+1
E+0
E-1
E-5
E-4
E-3
E-2
E-1
E+0
E+1
E+2
E+3
E+4
E+5
E+6
E+7
Incident Neutron Energy (eV)

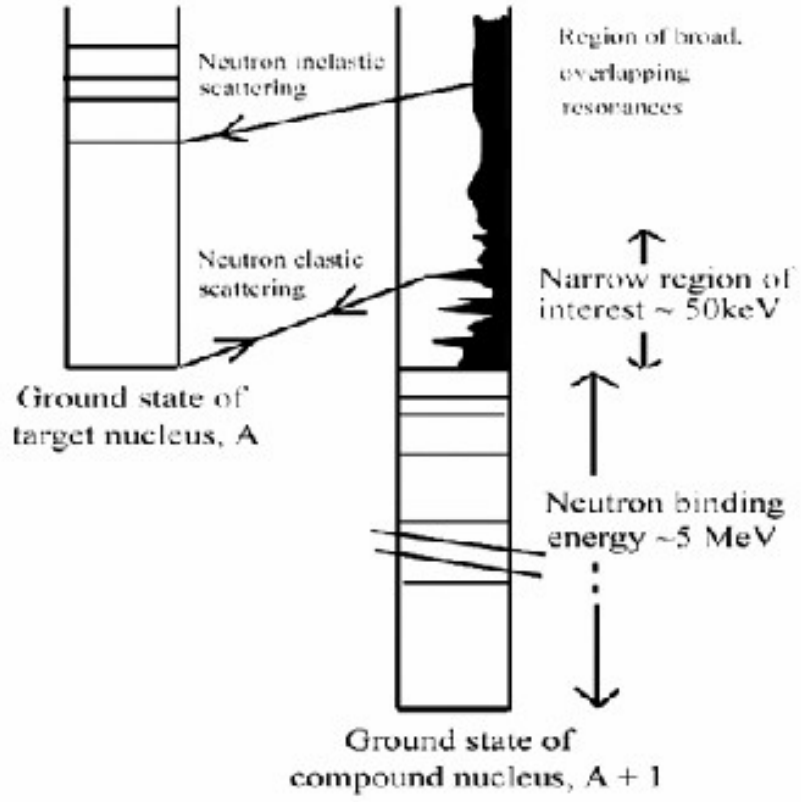

5-B-10(n,alpha) ENDF/B-VII.1
Cross Section (b)
E+5
E+4
E+3
E+2
E+1
E+0
E-1
E-5
E-4
E-3
E-2
E-1
E+0
E+1
E+2
E+3
E+4
E+5
E+6
E+7
Incident Neutron Energy (eV)

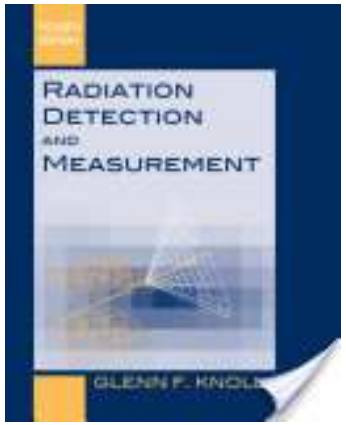

3-Li-6(n,t) ENDF/B-VII.1
Cross Section (b)
E+4
E+3
E+2
E+1
E+0
E-1
E-2
E-5
E-4
E-3
E-2
E-1
E+0
E+1
E+2
E+3
E+4
E+5
E+6
E+7
Incident Neutron Energy (eV)


92-U-235(n,total fission) ENDF/B-VII.1
Cross Section (b)
E+4
E+3
E+2
E+1
E+0
E-5
E-4
E-3
E-2
E-1
E+0
E+1
E+2
E+3
E+4
E+5
E+6
E+7
Incident Neutron Energy (eV)

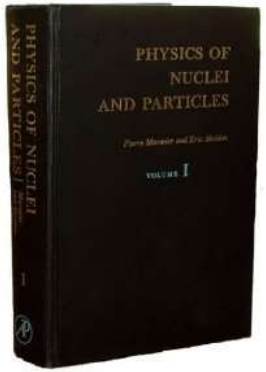
Resonance

Resonance occur when the neutron energy is exactly the difference between the Energy level of the initial nucleus A plus the neutron binding energy Sn
and one of the energy level of the A+1 nuclei





Glenn F Knoll.
Wiley



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