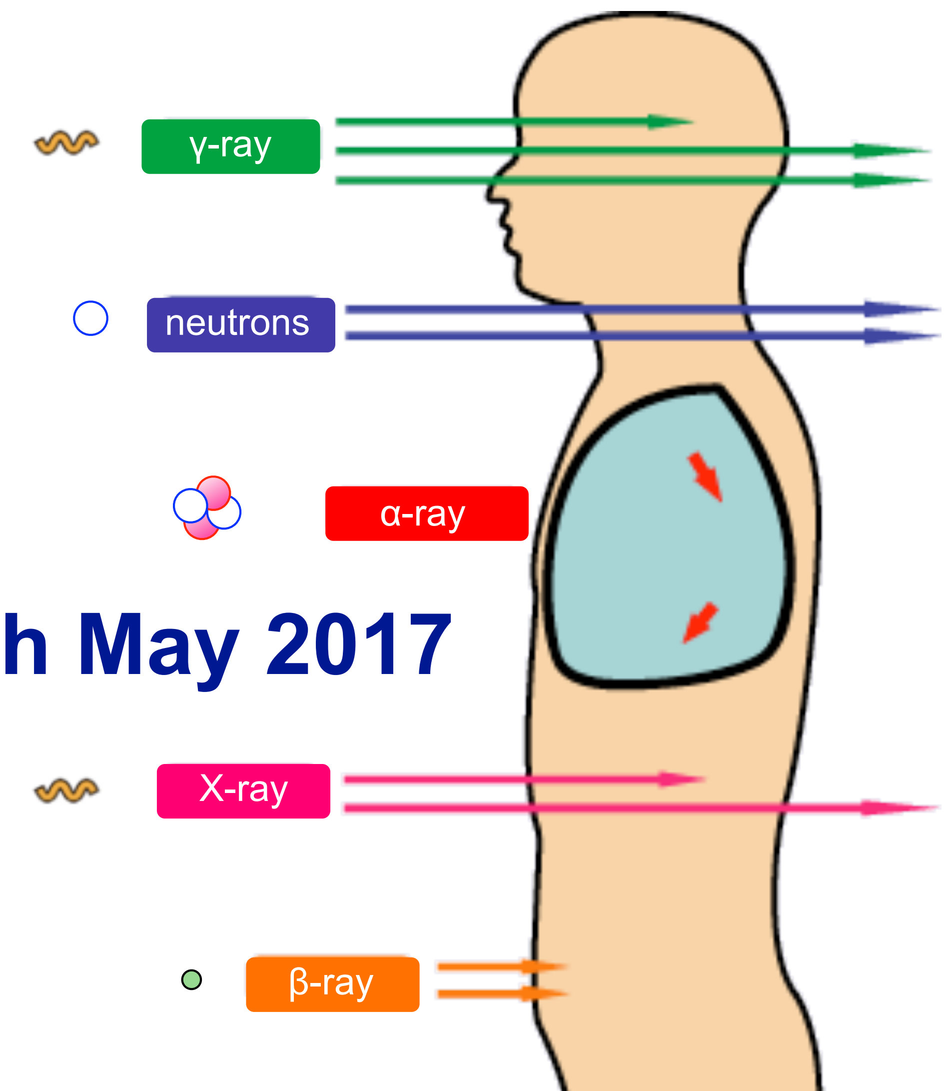
Lecture for 3rd-year students, Chemistry dept.



Wed. 24th May 2017

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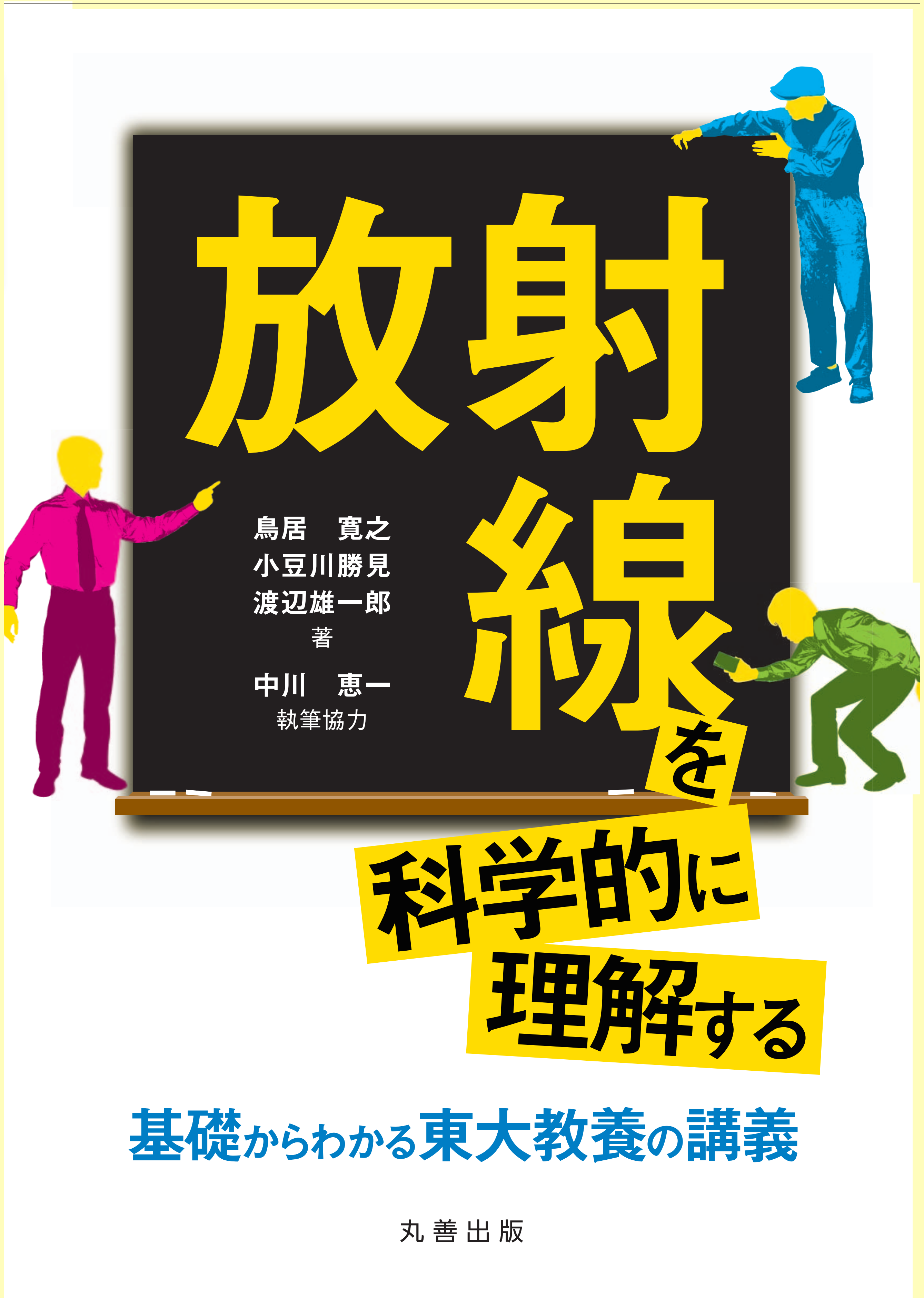


「放射線を科学的に理解する
― 基礎からわかる東大教養の講義 ―」

鳥居寛之・小豆川勝見・渡辺雄一郎 著

中川恵一 執筆協力

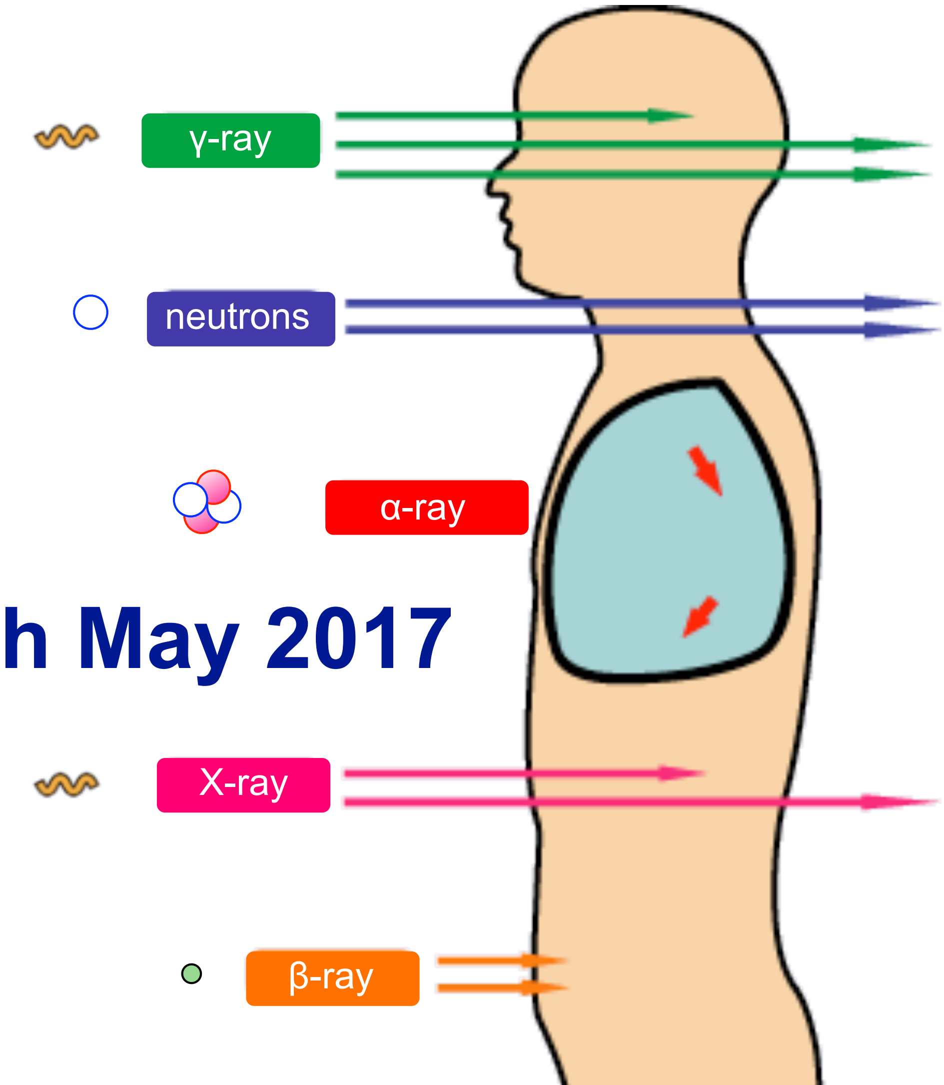
丸善出版　　本体 2500円＋税

放射線を理解するには、物理学・化学・生物学・医学・工学など多くの分野の知識が必要です。しかしこれらすべてを網羅することは難しく、系統立てて学べる機会は非常に少ないのが実情です。

本書は東京大学教養学部で行われた講義をもとに、放射線について多角的に学べるよう配慮しています。日常生活や原発事故にかかわる具体的な例を引きながらやさしくていねいに解説しましたので高校生や一般の方にも広く読んでいただきたいと願っています。

http://radphys4.c.u-tokyo.ac.jp/~torii/lecture/radiolect-kn.html

Lecture for 3rd-year students, Chemistry dept.

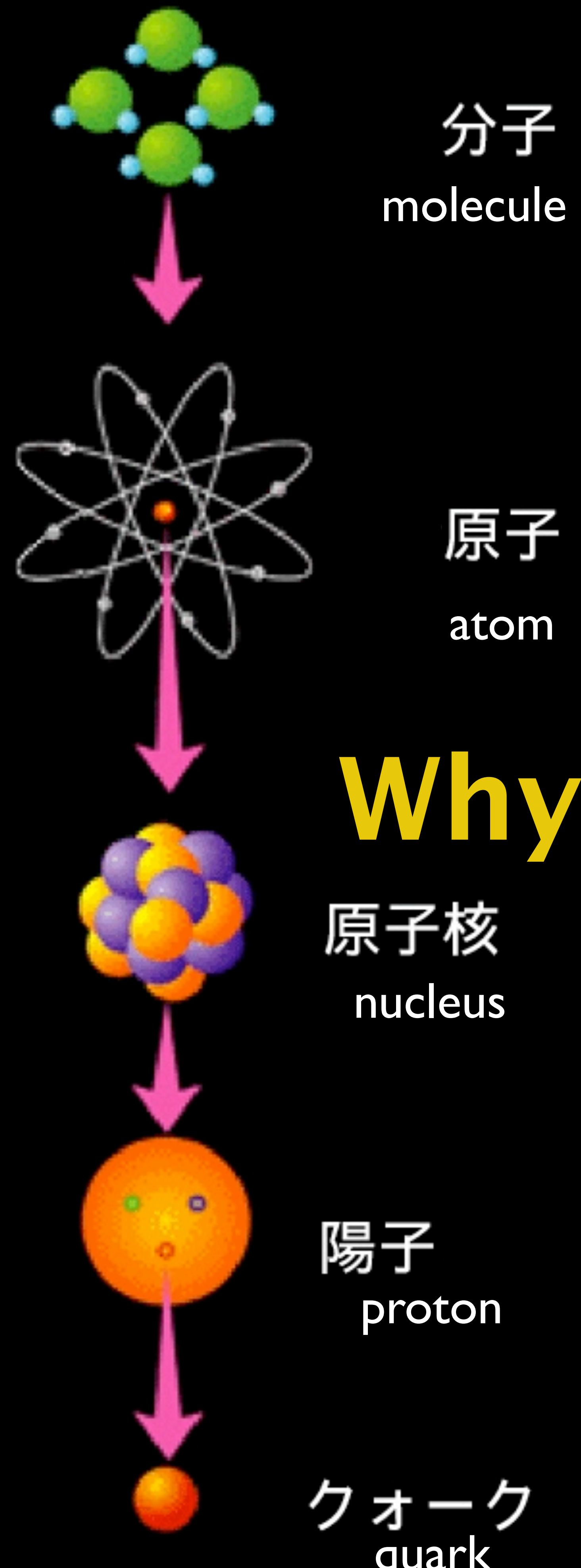


Wed. 24th May 2017

5th lecture

Interaction between radiation & matter (I)

鳥居 寛之 (Hiroyuki A. TORII)
RI Lab., Dept. of Chemistry, School of Science, Univ. of Tokyo



nm (10^{-9} m) — nanometer

Chemistry

eV — electronvolt

atom < atomus < ατομος < a- + témnein + -os (cannot be cut)

Atomic Physics

Å (10^{-10} m) — Ångström

eV – keV — several electronvolts – kiloelectronvolt

Why did alchemy fail?

Nuclear Physics

fm (10^{-15} m) — femtometer

MeV — megaelectronvolt

Particle Physics

am (10^{-18} m) — attometer

GeV — gigaelectronvolt

Billet de 500 Francs Français
en circulation: 1993–1999

α-ray **helium nucleus**

β-ray **electron**

γ-ray **photon** (EM wave)

X-ray **photon** (EM wave)

Radiations

- radiation
  - particle beam
    - beta ray (electron)
    - proton beam
    - neutron beam
    - alpha ray
    - ion beam
  - photon (EM wave)
    - X ray
    - gamma ray

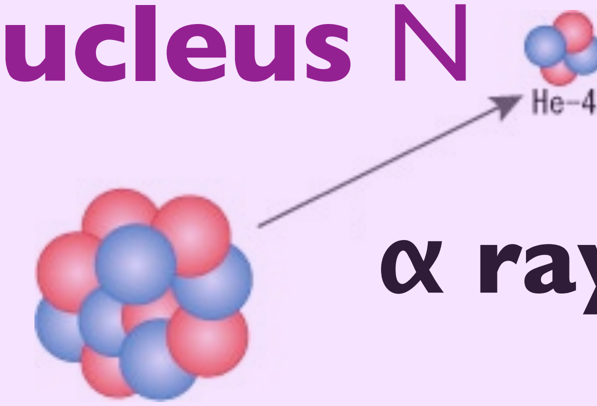
Typical energies of radiation
☞ **10 keV 〜 several MeV**
(α,β,γ)

Cf. Atomic binding energies
☞ **around 10 eV for outermost-shell electrons**
(1 eV = 96 kJ/mol)

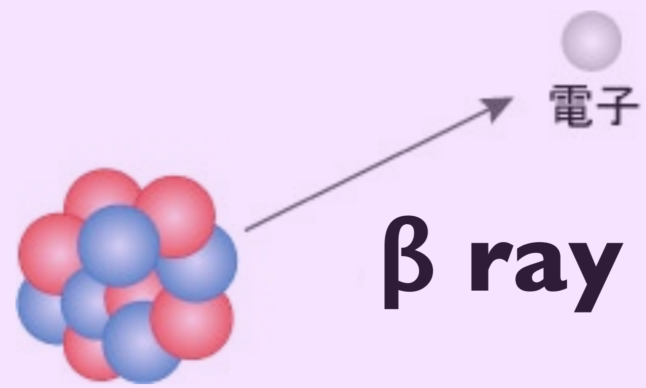
Speed of radiation
☞ **few〜100% of light speed**

Nucleus N

MeV order
high energy



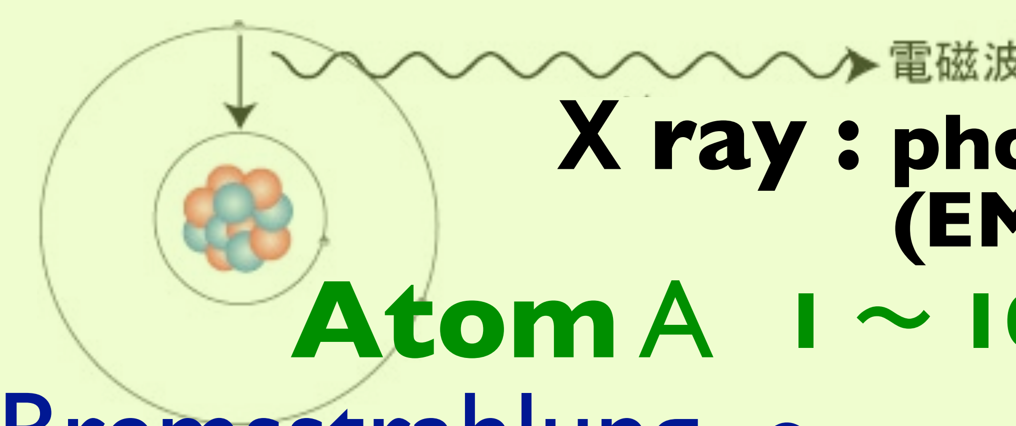
α ray : He nucleus
several MeV



10 keV 〜 MeV
β ray : electron at high speed

10 keV 〜 MeV

γ ray : photon (EM wave)

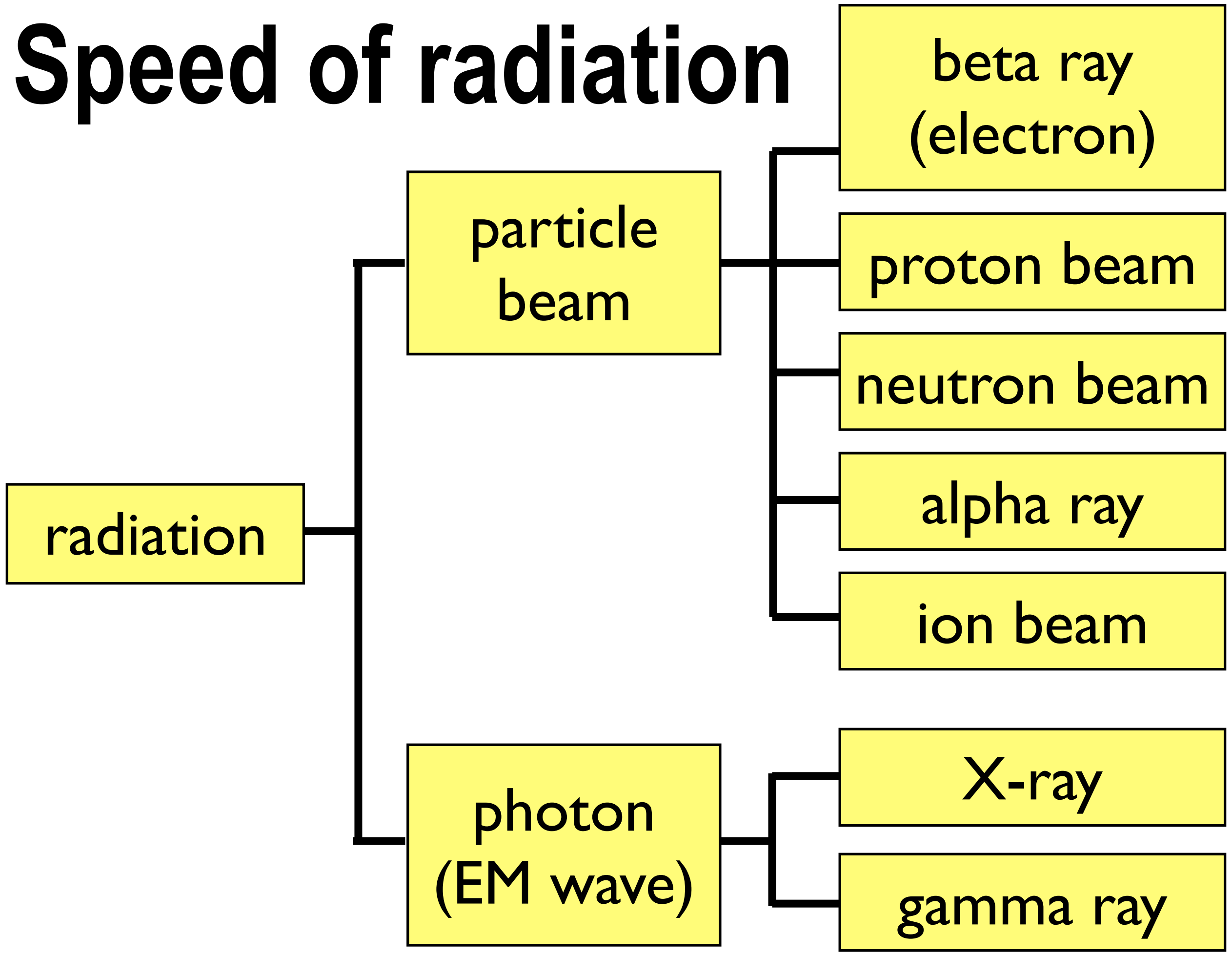


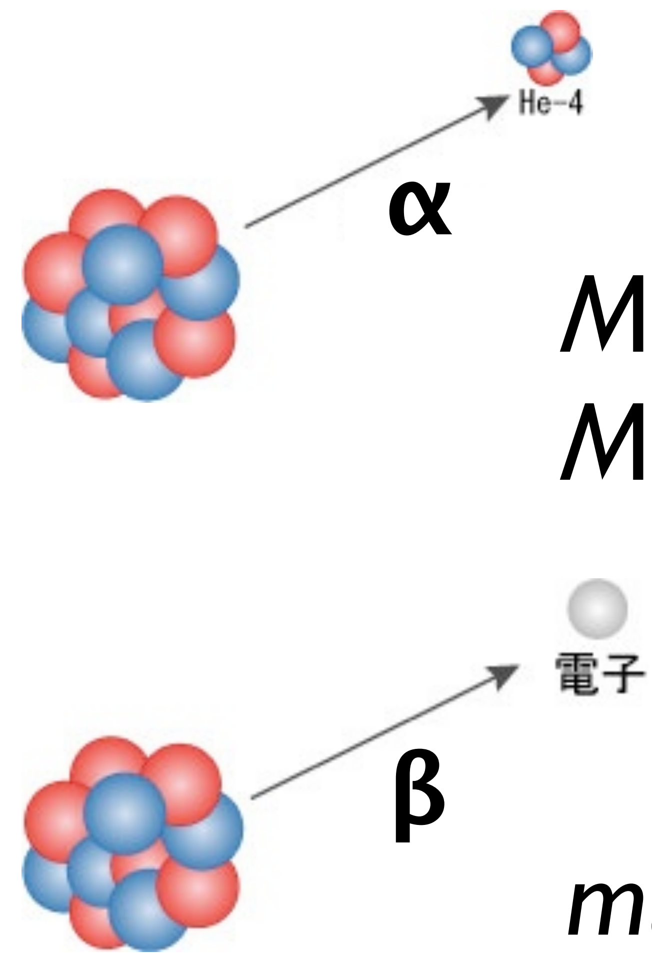
X ray : photon (EM wave)

Atom A **1 〜 100 keV**

Bremsstrahlung 〜 several **MeV**

Speed of radiation





$M_\alpha \approx 4\ \mathrm{GeV}/c^2$

~~1.67×10^{-27} kg x 4~~

$M_p = 938\ \mathrm{MeV}/c^2$

$M_n = 940\ \mathrm{MeV}/c^2$

~~9.11×10^{-31} kg~~

$m_e = 511\ \mathrm{keV}/c^2$

$\approx 0.5\ \mathrm{MeV}/c^2$

Mass of charged particles ?

in the unit of **MeV/c²**

Speed of charged particles ?

relative to the **speed of light**

$$E = mc^2\gamma = mc^2 \frac{1}{\sqrt{1-\beta^2}}$$

$$\beta = v/c$$

$$T = E - mc^2$$

$$\approx \frac{1}{2} mv^2 = \frac{1}{2} mc^2 \beta^2 \quad (v \ll c)$$

Calculate the speed of a 5-MeV α ray.

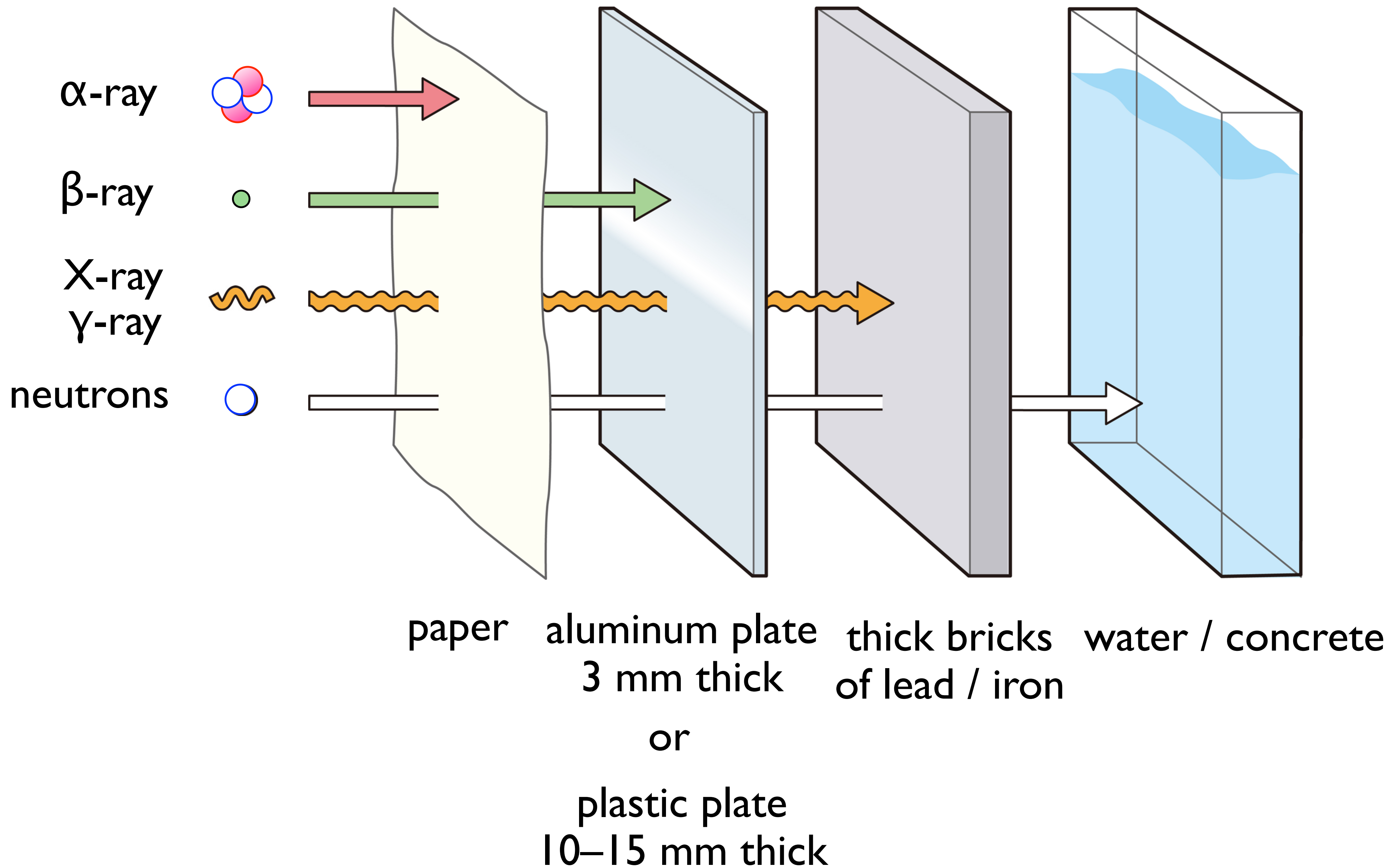
Calculate the speed of a 1-MeV β ray.

Interaction between radiation and matter

Slowing-down of charged particles

放射線と物質との相互作用
荷電粒子の減速

Penetration of radiation



Slowing-down and energy loss of charged particles (α-ray, β-ray etc.)

荷電粒子の減速（エネルギー損失）

Step-by-step energy loss due to ionization and excitation of atoms / molecules.

Fixed range of the same heavy particles for a given energy. (with a slight deviation)

Stopping power = energy loss per unit length = $-\left\langle \frac{dE}{dx} \right\rangle$

Attenuation of photons (X-ray, γ-ray)

光子の減衰（減弱）

Photons are lost by stochastic processes of absorption or scattering, but the rest remain intact through.

☞ **Exponential decrease of photon number**

reaction cross section σ is proportional to the reaction probability per unit length.

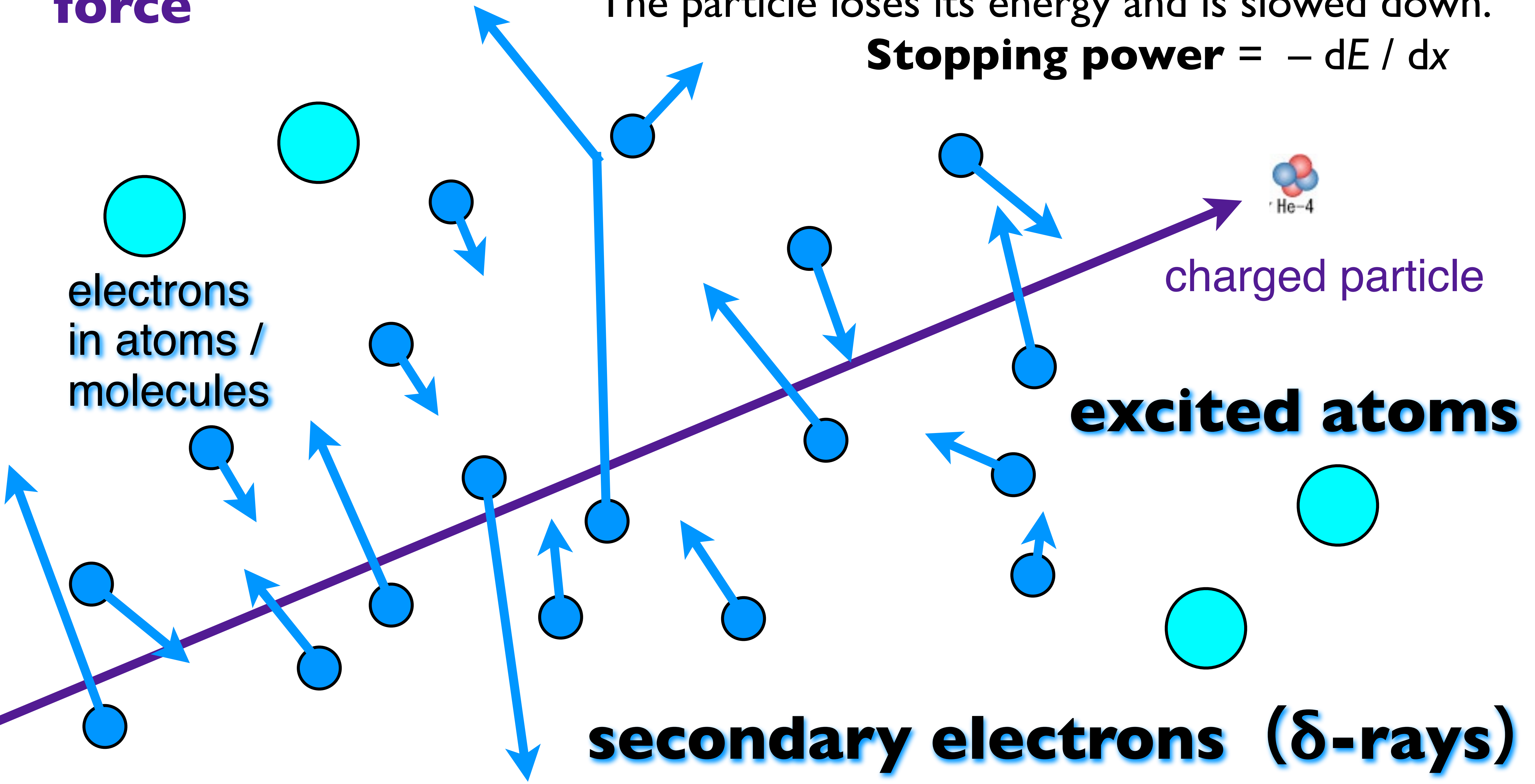
Energy loss of charged particles

electric charge: **Coulomb force**

Kinetic energy of the particle is transferred to electrons through **ionization** or **excitation** of atoms and molecules in the matter.

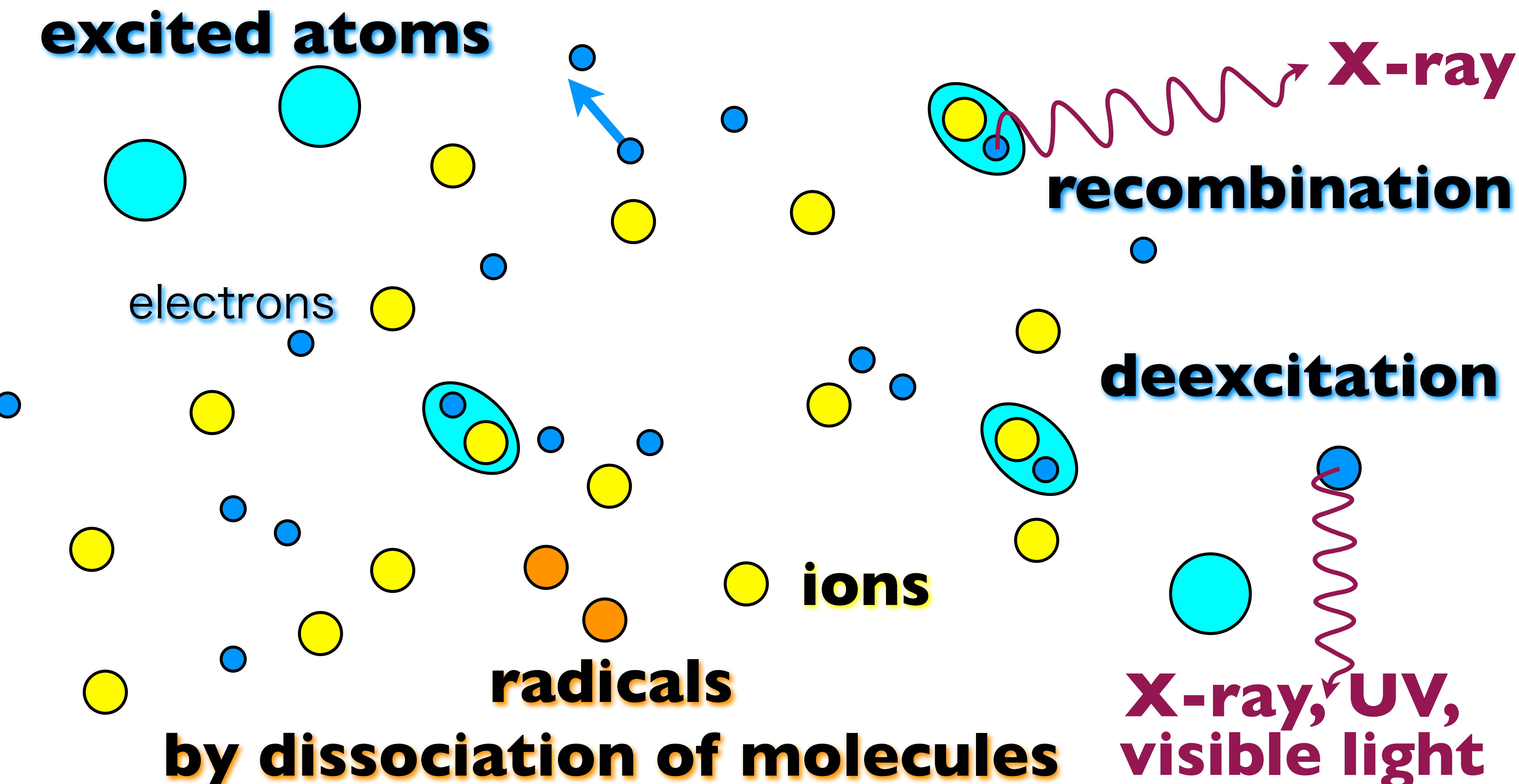
The particle loses its energy and is slowed down.

Stopping power = $-\,\mathrm{d}E\,/\,\mathrm{d}x$

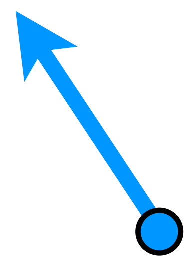


Along the track after passage of charged particles

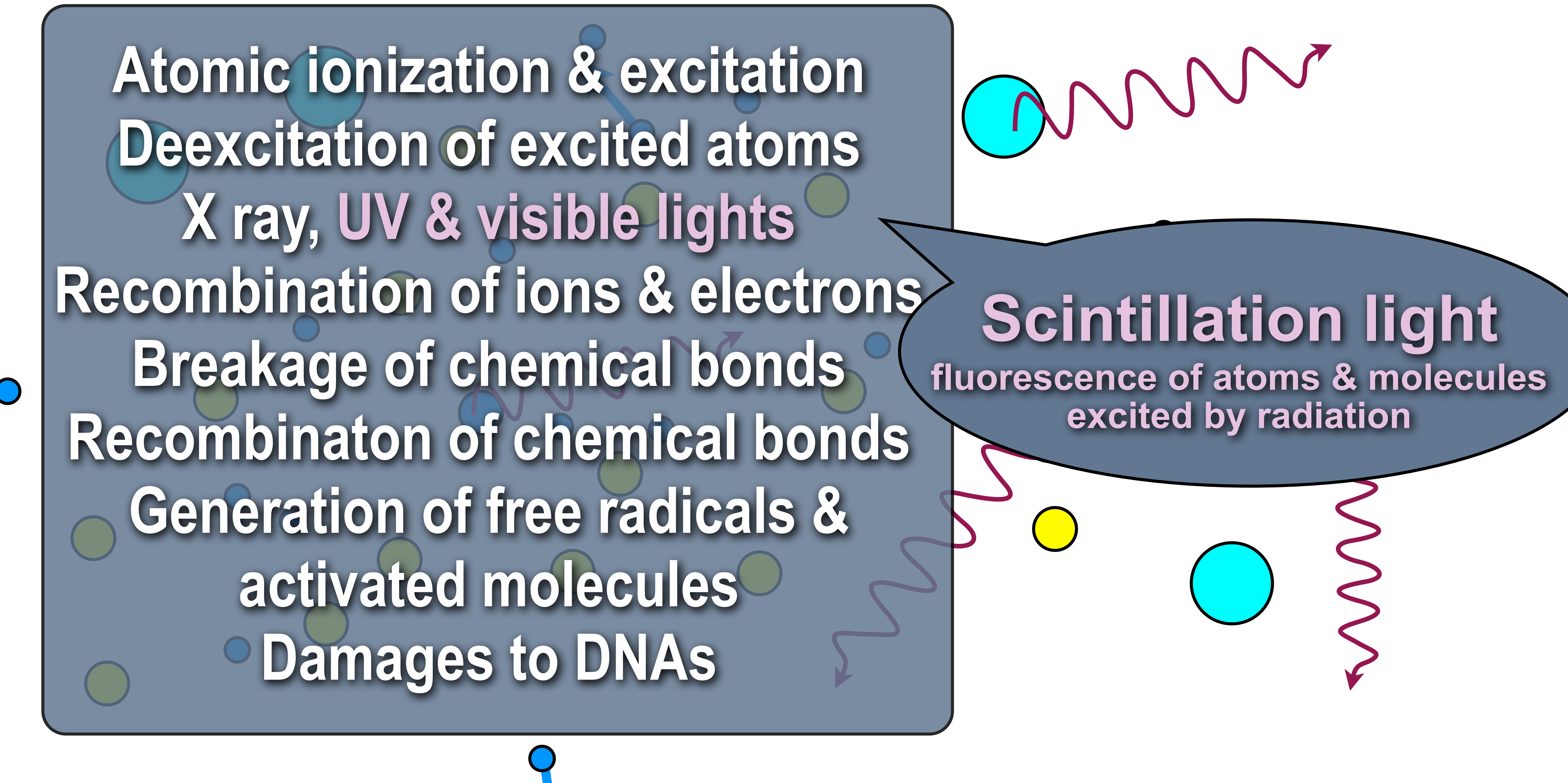
Ions and **excited atoms** are produced, while energetic **secondary electrons** can ionize other atoms.
Molecules are **dissociated** to form free **radicals**.
X-rays are emitted after atomic **recombination** or **deexcitation**.



Along the track after passage of charged particles



Ions and **excited atoms** are produced, while energetic **secondary electrons** can ionize other atoms. **X-rays** are emitted after atomic **recombination** or **deexcitation**.



Stopping power（Energy loss, Linear Energy Transfer : LET）

阻止能　（エネルギー損失、線エネルギー付与）

$$-\left\langle \frac{dE}{dx} \right\rangle$$

Charged particle : Coulomb force

Kinetic energy of the particle is transferred to a number of electrons (**secondary electrons**) scattered via **ionization** or **excitation** of atoms and molecules in the matter.
The particle loses its energy and is slowed down (**electron collision stopping power**).

- **heavy particles** : proton beams, α-rays, heavy ions, pions, muons
  Small energy transfer to each single electron.
  Slowed down via **scattering of many electrons**.
  Small momentum transfer results in almost **linear trajectory**.
- light particles : **electrons (e^-),** positrons (e^+)
  Large energy transfer per single collision.
  Sometimes **zig-zag trajectories**.
  Can generate secondary electrons with large kinetic energy (**δ-rays**).

Tracks of Radiation

observed by
cloud chambers

α-ray

7.7 MeV

0.2 MeV

β⁻-ray

0.056 MeV

γ-ray

0.047 MeV

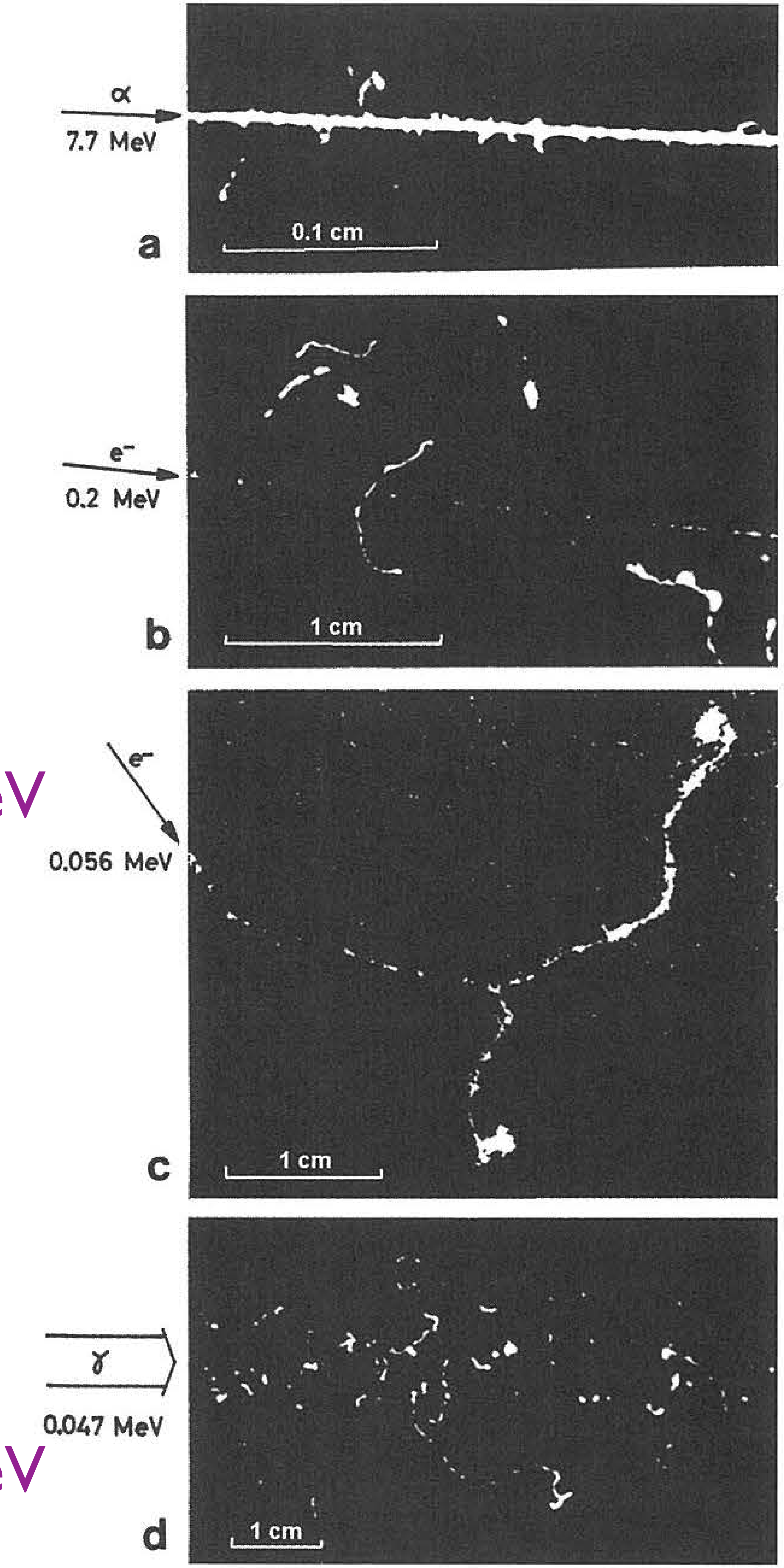


Figure 7.5 Cloud chamber tracks of α, β, (e⁻), and γ-rays at 1 bar in air ((a), (b), and (c)) and in methane (d). *(From W. Gentner, H. Maier-Leibnitz, and H. Bothe.)*

$$-\left\langle \frac{dE}{dx} \right\rangle$$

Stopping power

energy loss

Charged particle : Coulomb force

Kinetic energy of the particle is transferred to a number of electrons (**secondary electrons**) scattered via **ionization** or **excitation** of atoms and molecules in the matter.
The particle loses its energy and is slowed down (**electron collision stopping power**).

Energies transferred to nuclei are relatively small, because they are heavy.
(Nuclear collision stopping power is usually negligible.)

Among secondary particles (mostly **secondary electrons**), those with rather high energy and capable of ionizing atoms and molecules are sometimes called **δ-rays**.

Number of ionizations (electron-ion pairs) per unit length = **Specific ionization**

Stopping power / Specific ionization = *W*-value

***W*-value** : Average energy required to produce 1 ion pair.
Does not depend on species or energy of charged particles.
Value larger than the ionization energy (due to loss by excitation).
***W* ~ 30 eV** not depending on the material.

阻止能

$-\left\langle\frac{dE}{dx}\right\rangle$ **Stopping power** for charged particles

energy loss Linear Energy Transfer : LET

（エネルギー損失、線エネルギー付与）

Bohr's calculation

Equation modified along with the SI units

$$-\left\langle\frac{dE}{dx}\right\rangle = \frac{z^2 e^4}{4\pi \varepsilon_0^2 m_e v^2} n_e \ln \frac{b_{max}}{b_{min}}$$

on blackboard

$$n_e = Z n_a = \rho N_A Z / A$$

Bethe-Bloch equation

$$-\left\langle\frac{dE}{dx}\right\rangle = K z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

$$K = 4\pi N_A r_e^2 m_e c^2 \rho$$

$Z/A \approx 1/2$ except for hydrogen.

Does not depend very much on the material.

mass stopping power

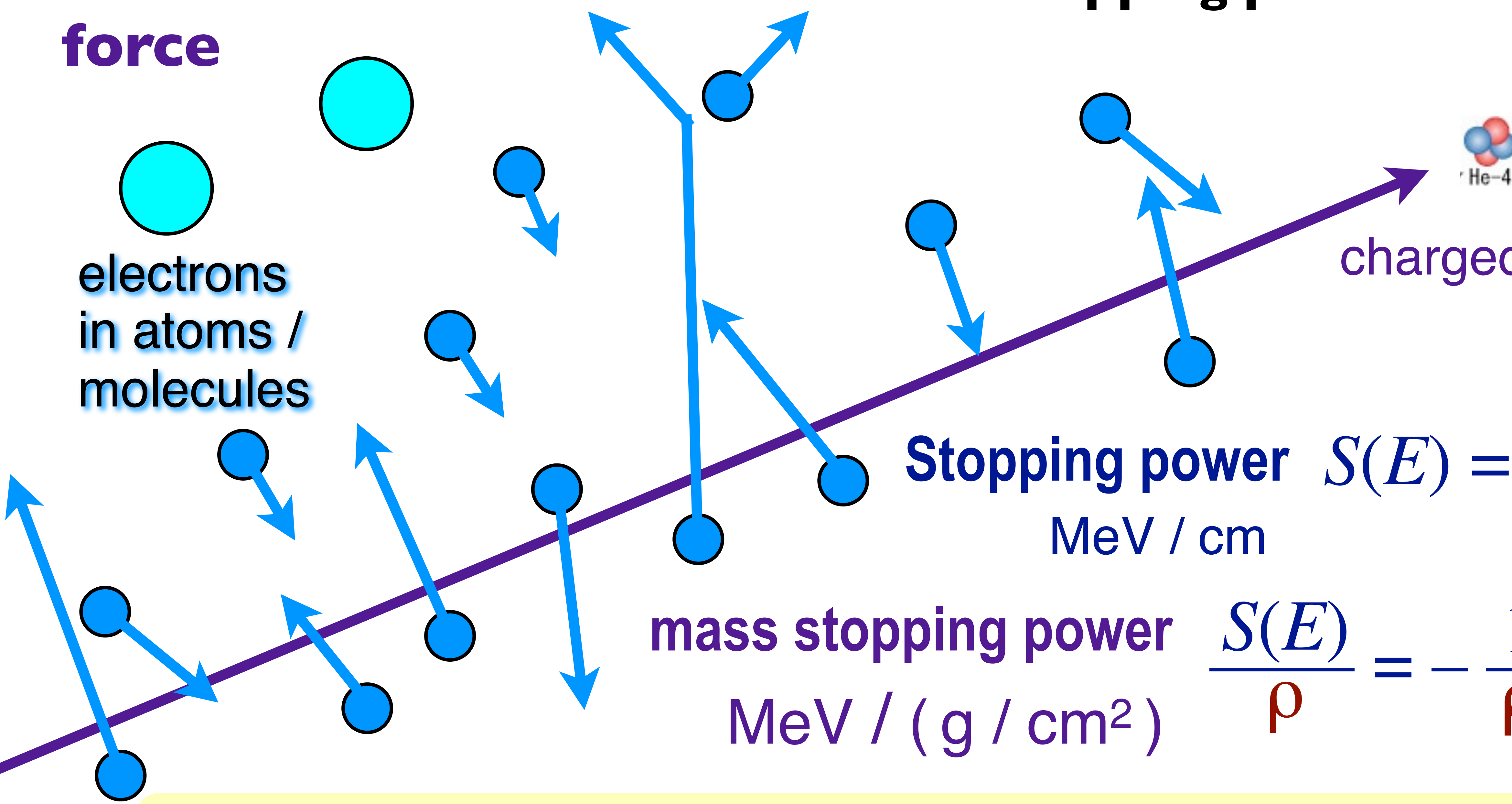
MeV / (g / cm^2)

$$-\frac{1}{\rho}\left\langle\frac{dE}{dx}\right\rangle \propto \frac{z^2}{v^2} = \frac{z^2 M/2}{Mv^2/2} \propto \frac{z^2 M}{T}$$

Stopping power of materials for charged particles

electric charge:
Coulomb force

Kinetic energy of the particle is transferred to **electrons**.
The ionizing particle loses its energy and is slowed down.
Stopping power = $-\mathrm{d}E\,/\,\mathrm{d}x$



Stopping power $S(E) = -\dfrac{\mathrm{d}E}{\mathrm{d}x}$

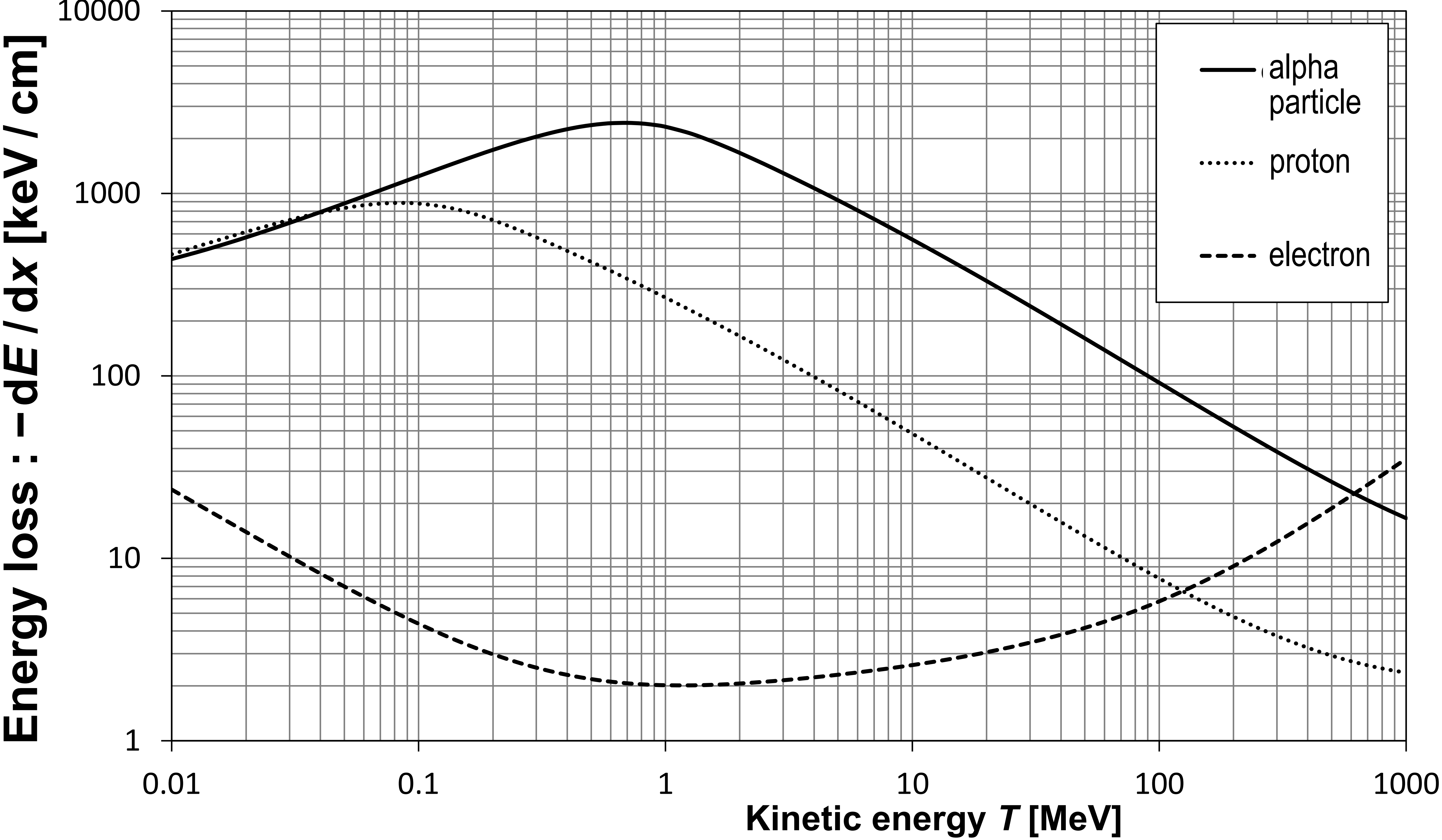
MeV / cm

mass stopping power $\dfrac{S(E)}{\rho} = -\dfrac{1}{\rho}\dfrac{\mathrm{d}E}{\mathrm{d}x}$

MeV / (g / cm^2)

Stopping power is proportional to the **density of electrons** scattered.
Mass stopping power does not depend very much on the material.

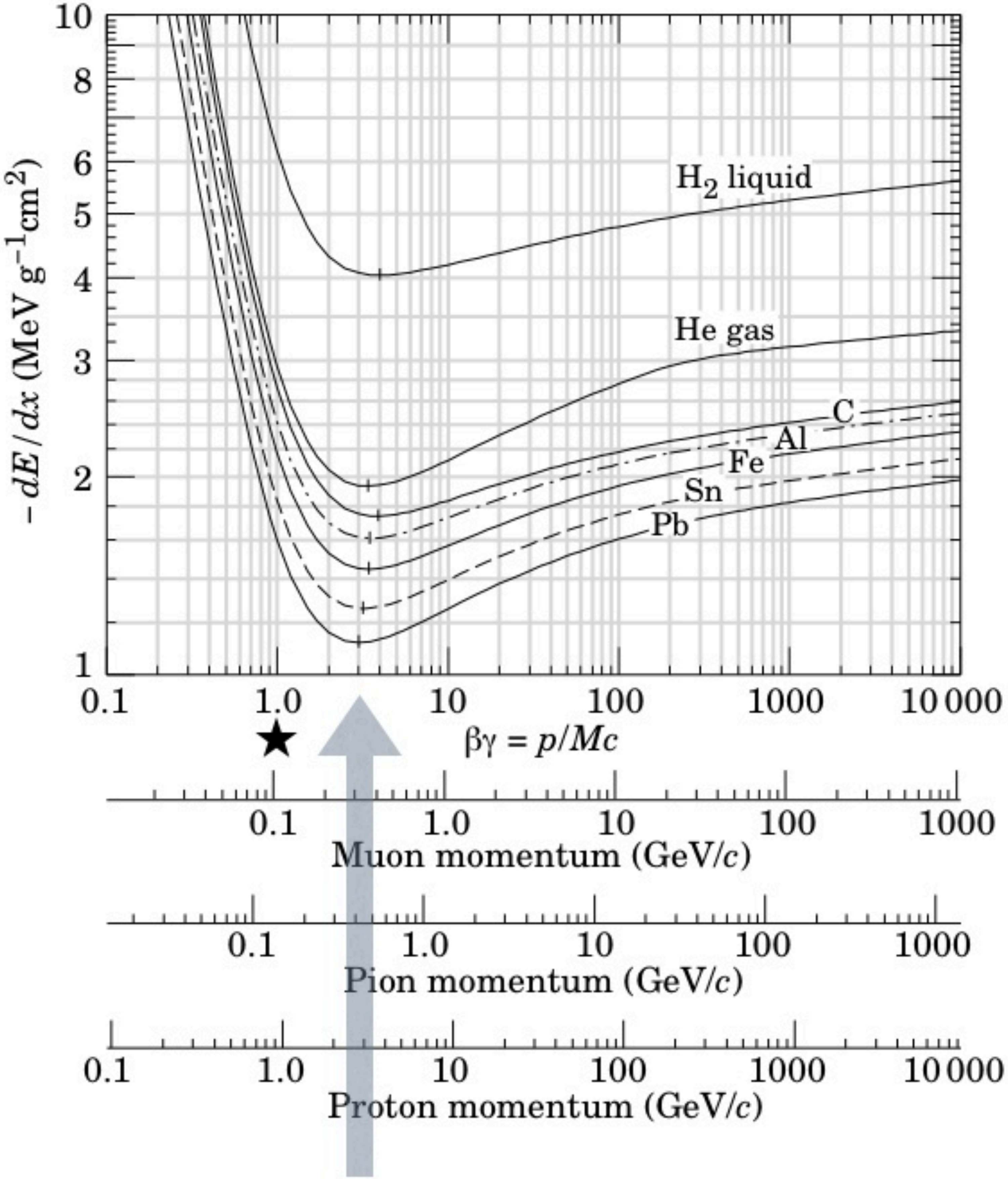
Stopping power for various charged particles in air



mass stopping power

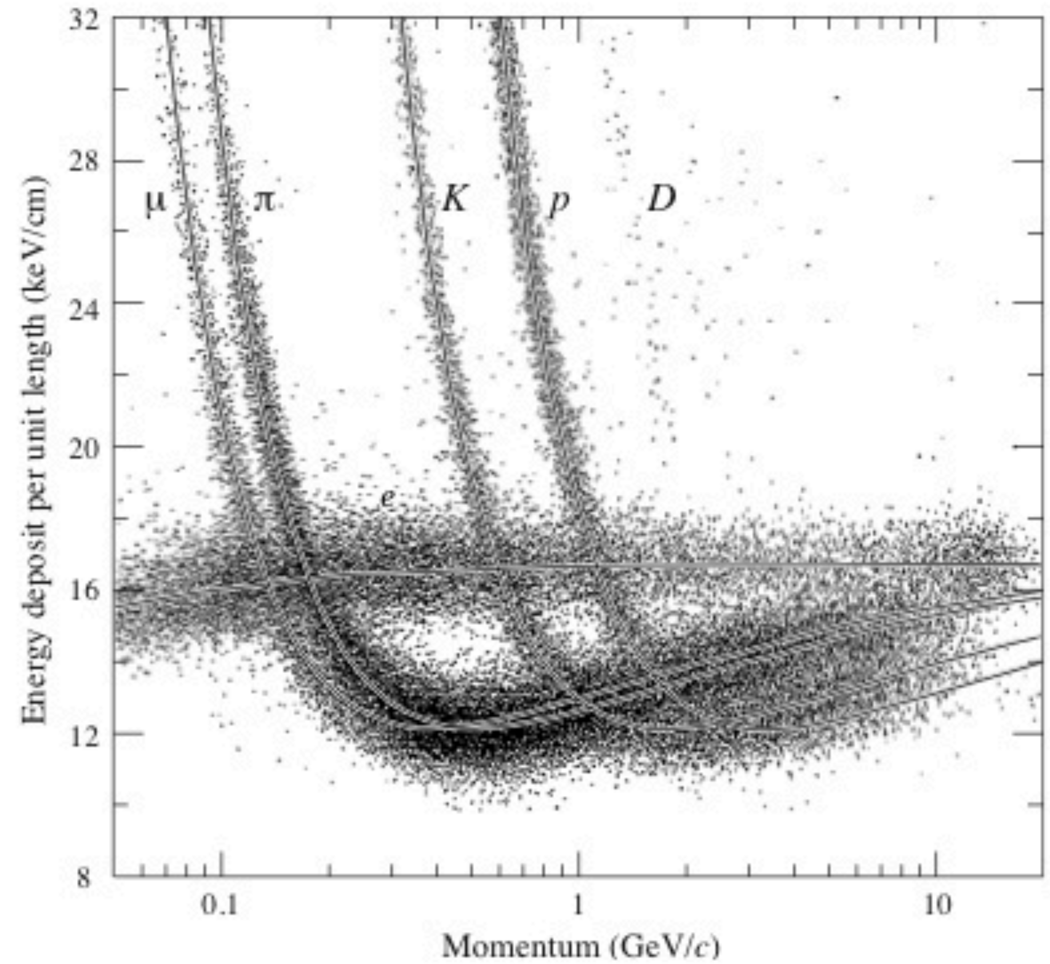
MeV / (g / cm²)

$$-\frac{1}{\rho}\left\langle\frac{dE}{dx}\right\rangle \propto \frac{z^2}{v^2} = \frac{z^2\,M/2}{Mv^2/2} \propto \frac{z^2 M}{T}$$



minimum ionizing ≈ 2 MeV / (g/cm^2)

particle identification



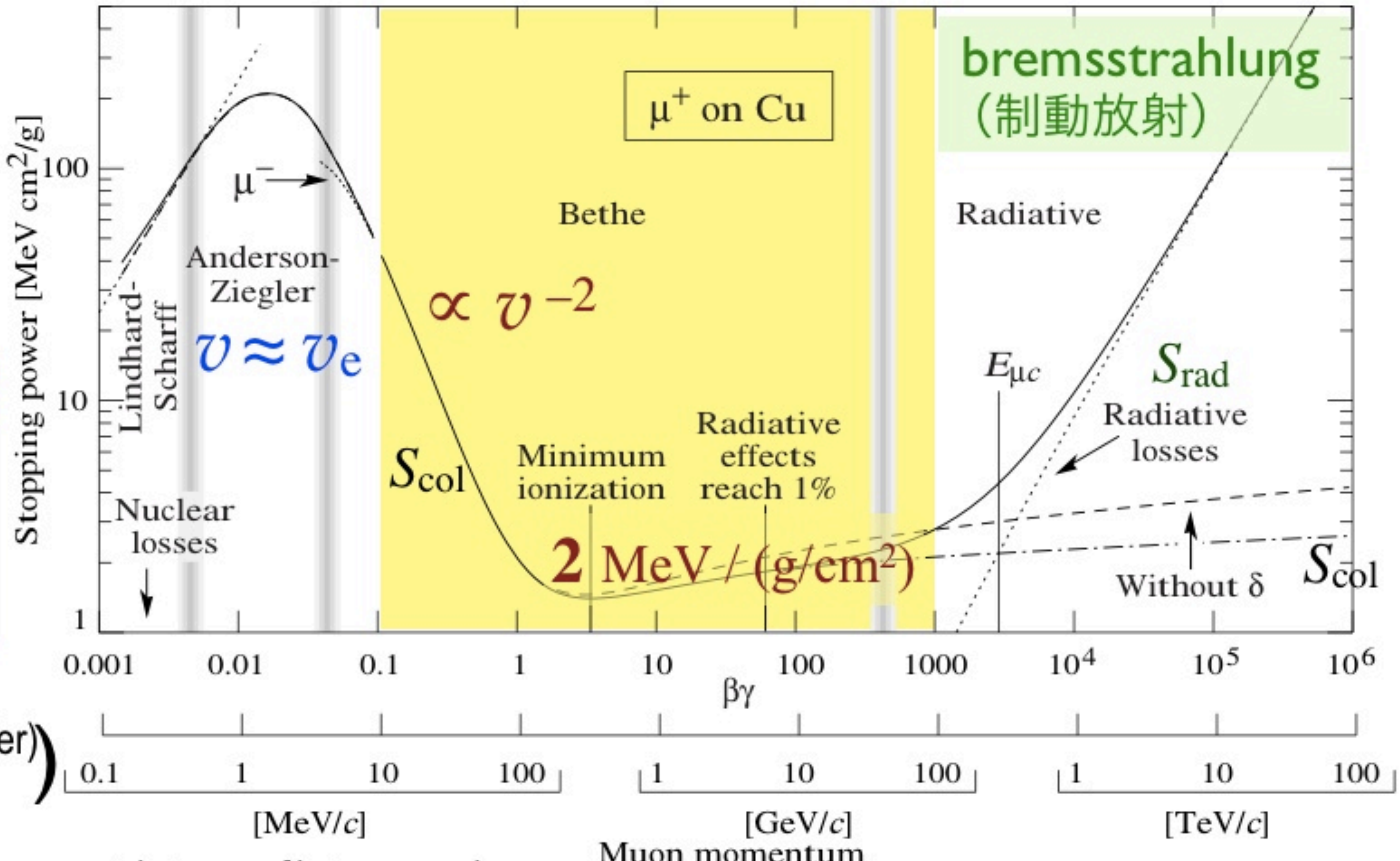
(8.5 atm Ar-CH_4 80:20)

★ $\beta\gamma = 1 \Leftrightarrow \beta = 1/\sqrt{2}$

$T = 1546$ MeV for α

$$-\frac{1}{\rho}\left\langle\frac{dE}{dx}\right\rangle$$

- non-adiabatic
- Barkas effect
- ions capture electrons



(**LET** (linear energy transfer) keV / μm)

27.2.2. ***Stopping power at intermediate energies*** :

The mean rate of energy loss by moderately relativistic charged heavy particles, $M_1/\delta x$, is well-described by the "Bethe" equation,

$$S_{col} = -\left\langle\frac{dE}{dx}\right\rangle_{col} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right].$$

bremsstrahlung

$$\frac{S_{rad}}{S_{col}} = \frac{(E+mc^2)\,Z}{1600\,mc^2}$$

mass stopping power

MeV / (g / cm²)

$$-\frac{1}{\rho}\left\langle\frac{dE}{dx}\right\rangle \propto \frac{z^2}{v^2} = \frac{z^2\,M/2}{Mv^2/2} \propto \frac{z^2\,M}{T}$$

Stopping power (Energy loss, Linear Energy Transfer : LET)

阻止能　（エネルギー損失、線エネルギー付与）

proton beams, α-rays, heavy ions : high-LET radiation

neutron beams : give **high LET** by kicking out protons in media.

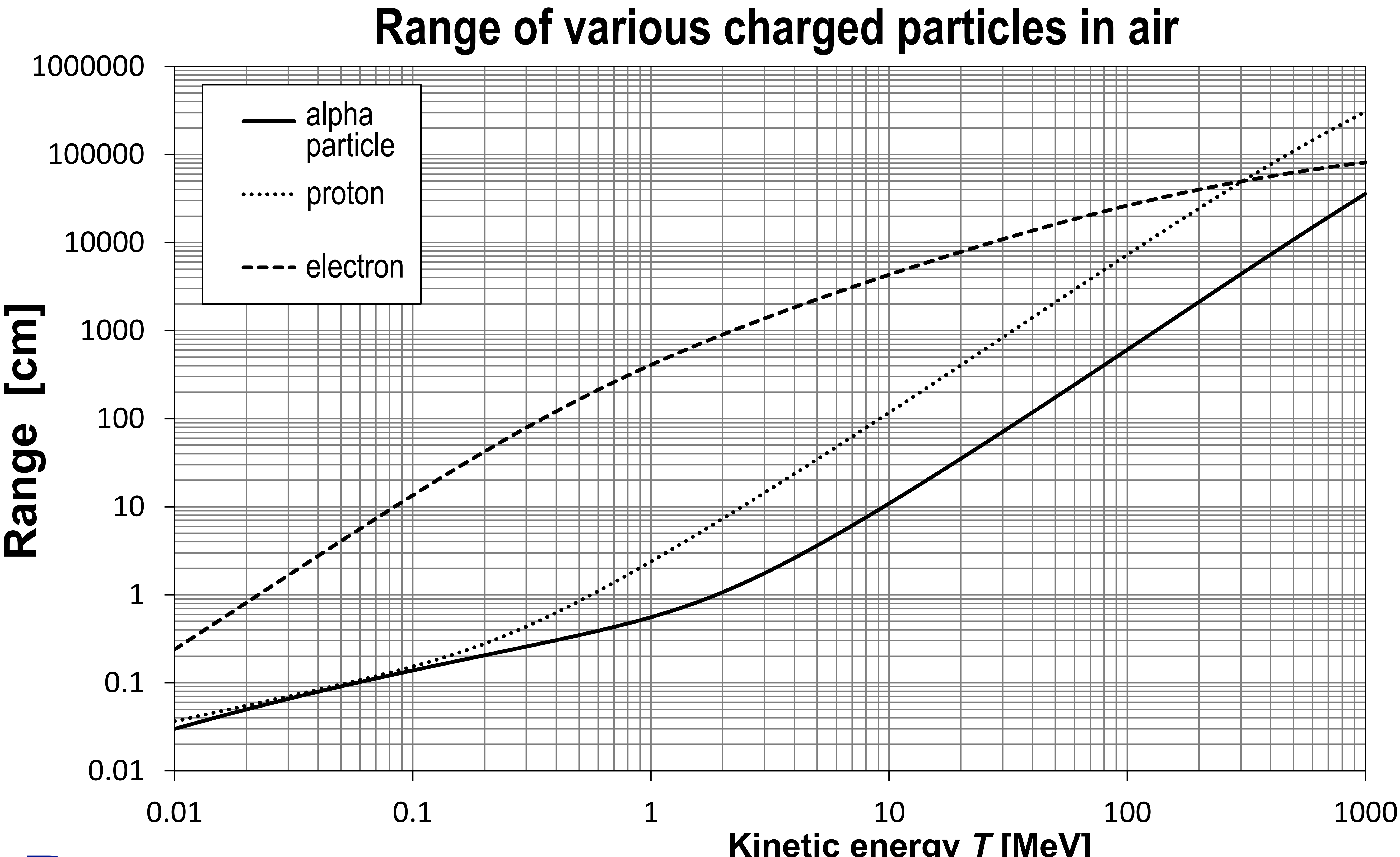
β-rays (electron beams) : low-LET radiation

photons (X-rays, γ-rays) : kick out electrons in media.
or create electron-positron pairs at high energies,
giving **low LET**.

Does not depend very much on the material.

mass stopping power
MeV / (g / cm^2)

$$-\frac{1}{\rho}\left\langle\frac{dE}{dx}\right\rangle \propto \frac{z^2}{v^2} = \frac{z^2\, M/2}{Mv^2/2} \propto \frac{z^2 M}{T}$$



Range 飛程

Integral of the reciprocal of the stopping power.

$$R\,(E_0) = \int_{E_0}^{0} \left\langle \frac{dE}{dx} \right\rangle^{-1} dE$$

Range Integral of the reciprocal of the stopping power.

proton beams, α-rays, heavy ions : short range
Shielding is easy against external exposure.

neutron beams : penetrate deep into matter.
do not interact with electrons.
drastic deceleration by collision with protons in media.
(but the cross section / reaction probability is small.)
Long range. Shielding by materials including H atoms.

β-rays (electron beams) : longer range than p, α, ions.
easily scattered by electrons in media.

Does not depend very much on the material.

mass stopping power

MeV / (g / cm^2)

$$-\frac{1}{\rho}\left\langle\frac{dE}{dx}\right\rangle \propto \frac{z^2}{v^2} = \frac{z^2 M/2}{Mv^2/2} \propto \frac{z^2 M}{T}$$

Transmission (number) vs. **thickness**

lin.

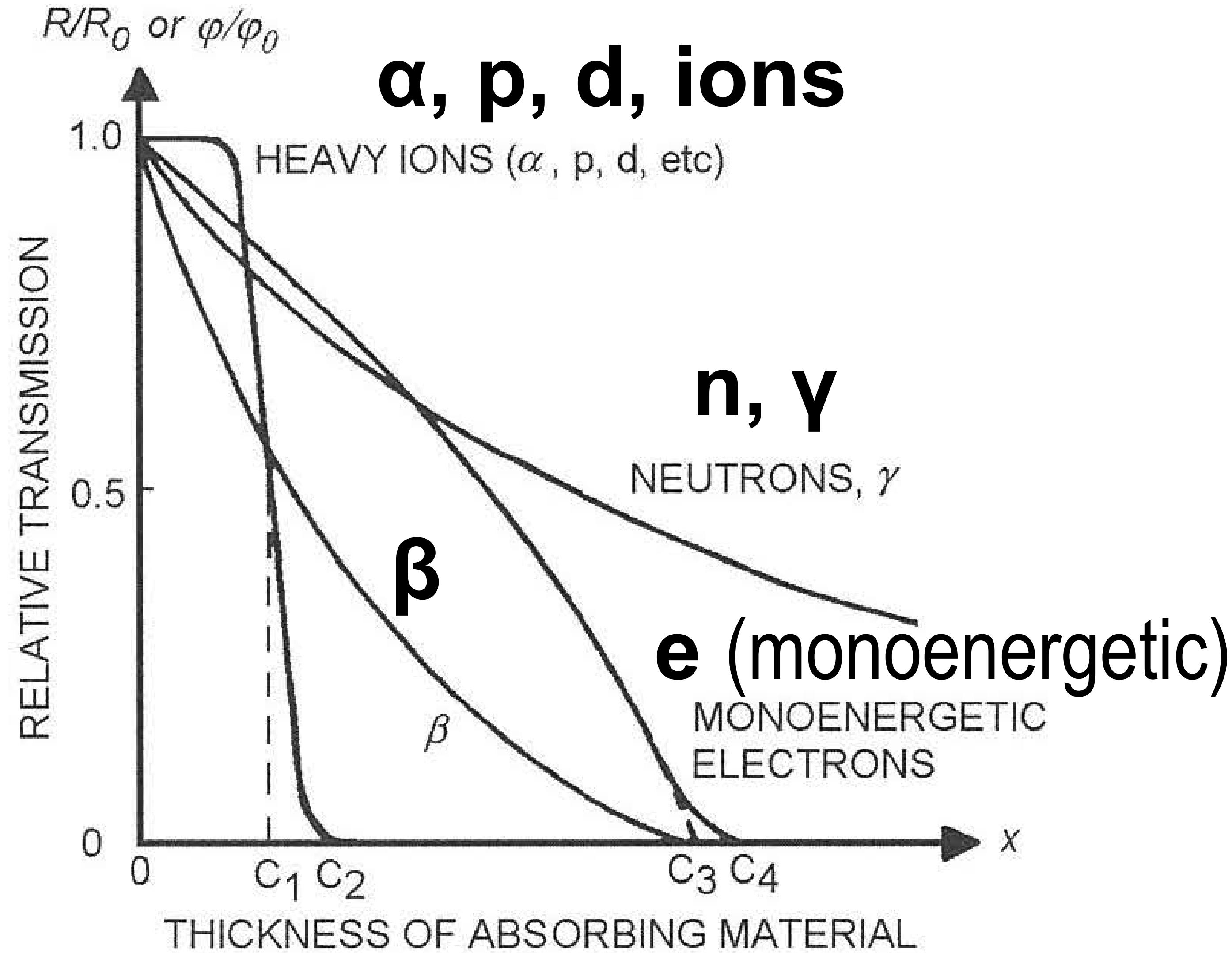
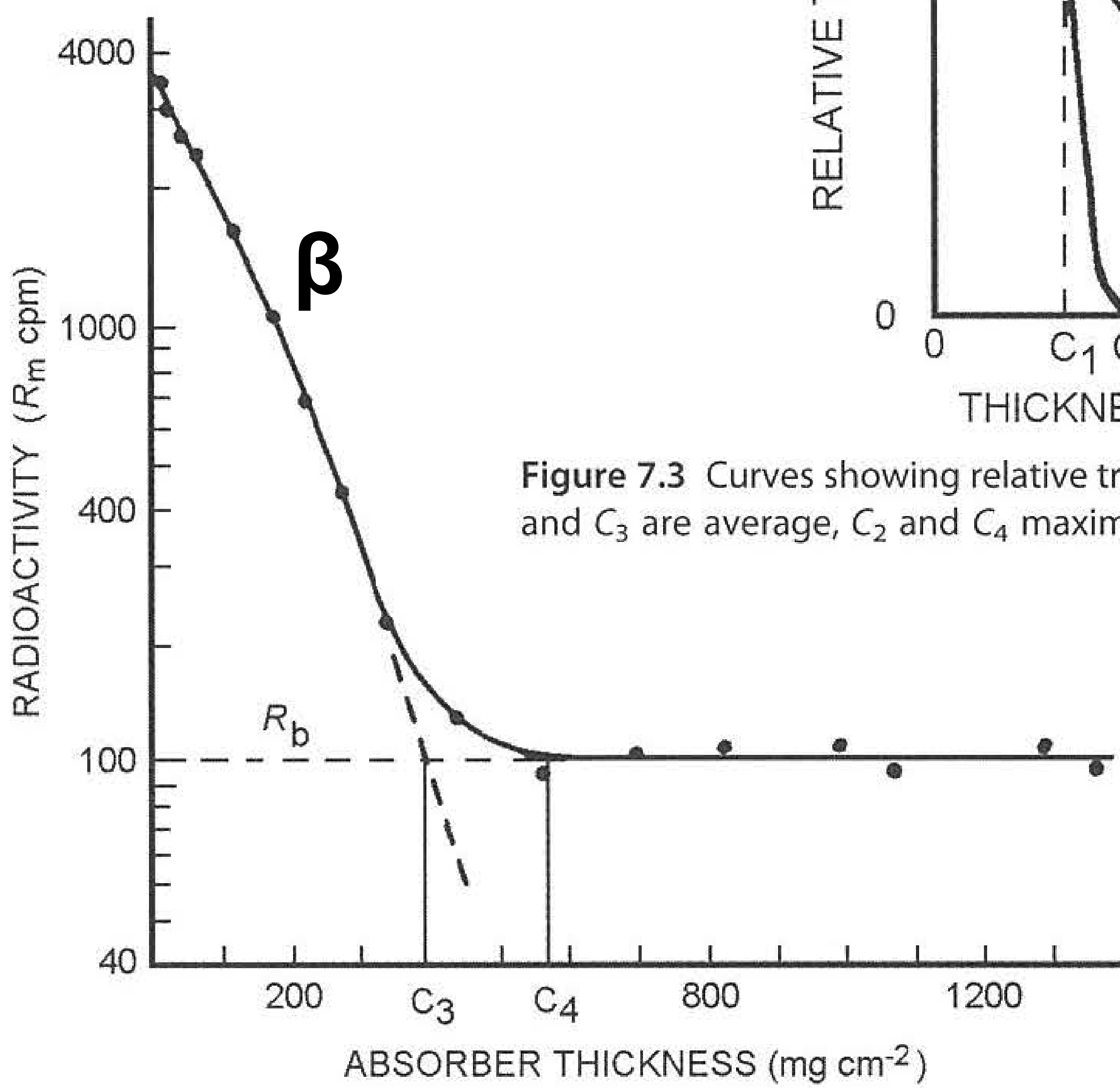


Figure 7.3 Curves showing relative transmission φ / φ_0 (or R/R_0) as function of absorber thickness x. C_1 and C_3 are average, C_2 and C_4 maximum range.

log.



$R_\beta = C_4$

$= 0.407\ (E\ /\ \mathrm{MeV})^{1.38}\quad \mathrm{g/cm^2}$
$(0.15\ \mathrm{MeV} < E_{max} < 0.8\ \mathrm{MeV})$

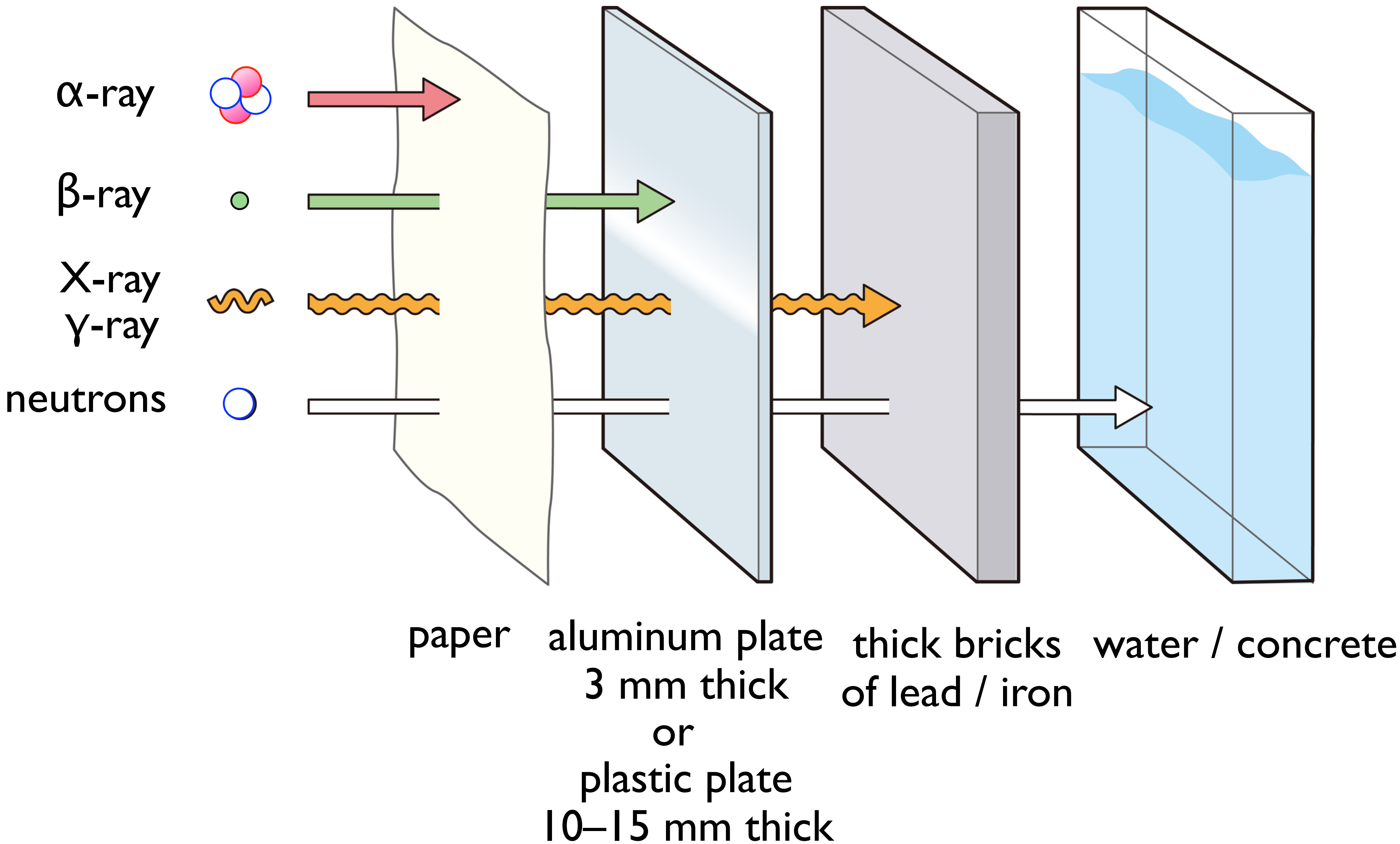
$= 0.542\ (E\ /\ \mathrm{MeV}) - 0.133\quad \mathrm{g/cm^2}$
$(0.8\ \mathrm{MeV} < E_{max} < 3\ \mathrm{MeV})$

$\lesssim 0.5\ (E\ /\ \mathrm{MeV})\quad \mathrm{g/cm^2}$

Figure 7.4 Absorption curve for ^{32}P β-radiation showing extrapolated (C_4) and average (C_3) ranges. The dashed curve is obtained after subtraction of background.

Range Integral of the reciprocal of the stopping power.

Shielding is easier for radiation with smaller interaction.



mass stopping power

MeV / (g / cm²)

$$-\frac{1}{\rho}\left\langle\frac{dE}{dx}\right\rangle \propto \frac{z^2}{v^2} = \frac{z^2\, M/2}{Mv^2/2} \propto \frac{z^2 M}{T}$$

Exposure to different radiations

- **α-ray :** a few cm of range in the air.
  Stops at surface cells of organism.
  Internal exposure needs attention :
  all the energies are given to cells within a short range.
- **β-ray : external exposure** to the **skin** & **internal exposure** need attention.
- **γ-ray : penetrates through the body**, some without any interaction while the others with some interaction (photoelectric effect / Compton scattering) and get **absorbed inside the body**.
  <u>The interior of the body are equally exposed to radiation even in the case of external exposure.</u>
- **X-ray : analogous to γ-ray.**
  Part of the energies are absorbed.

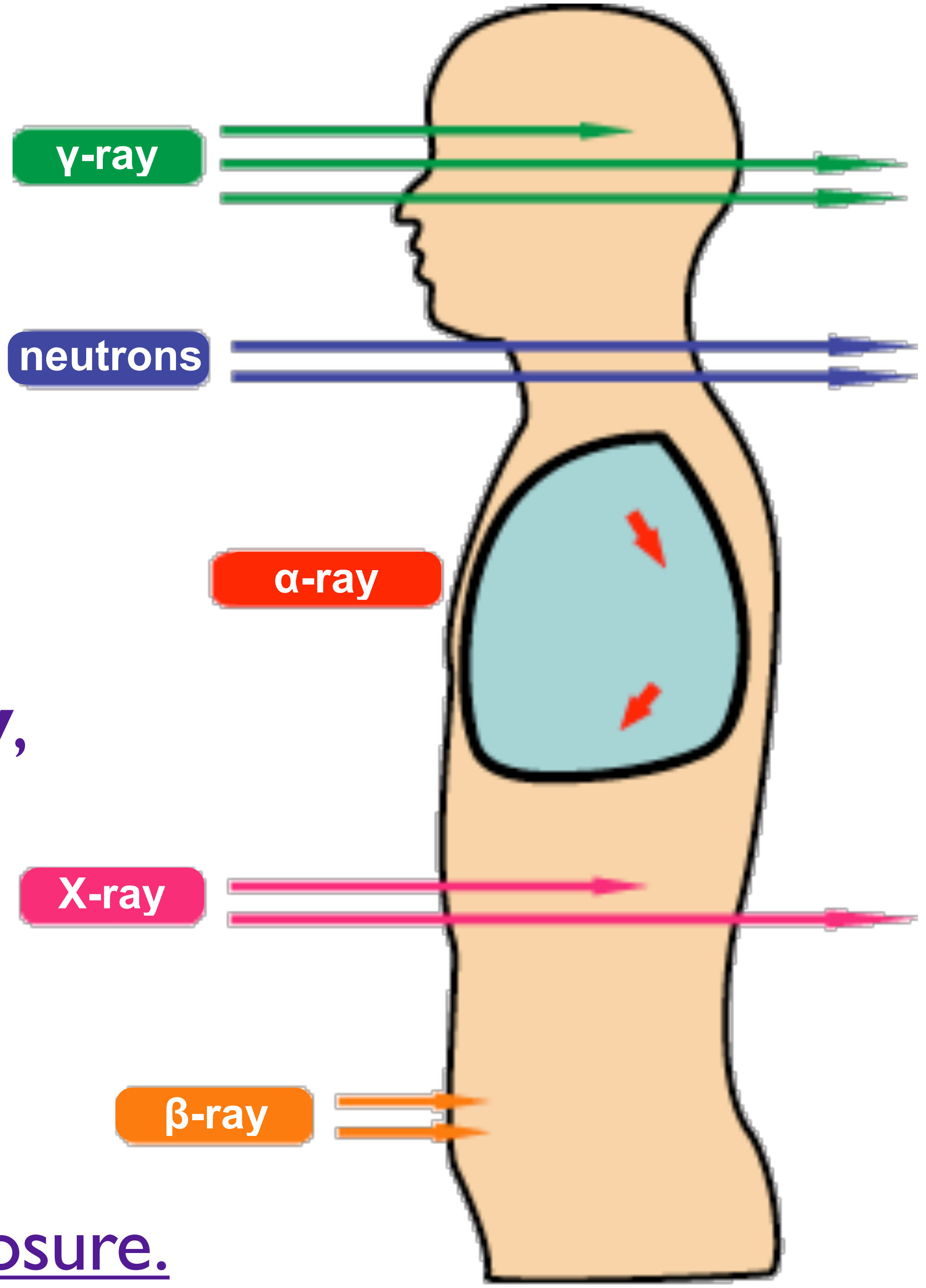


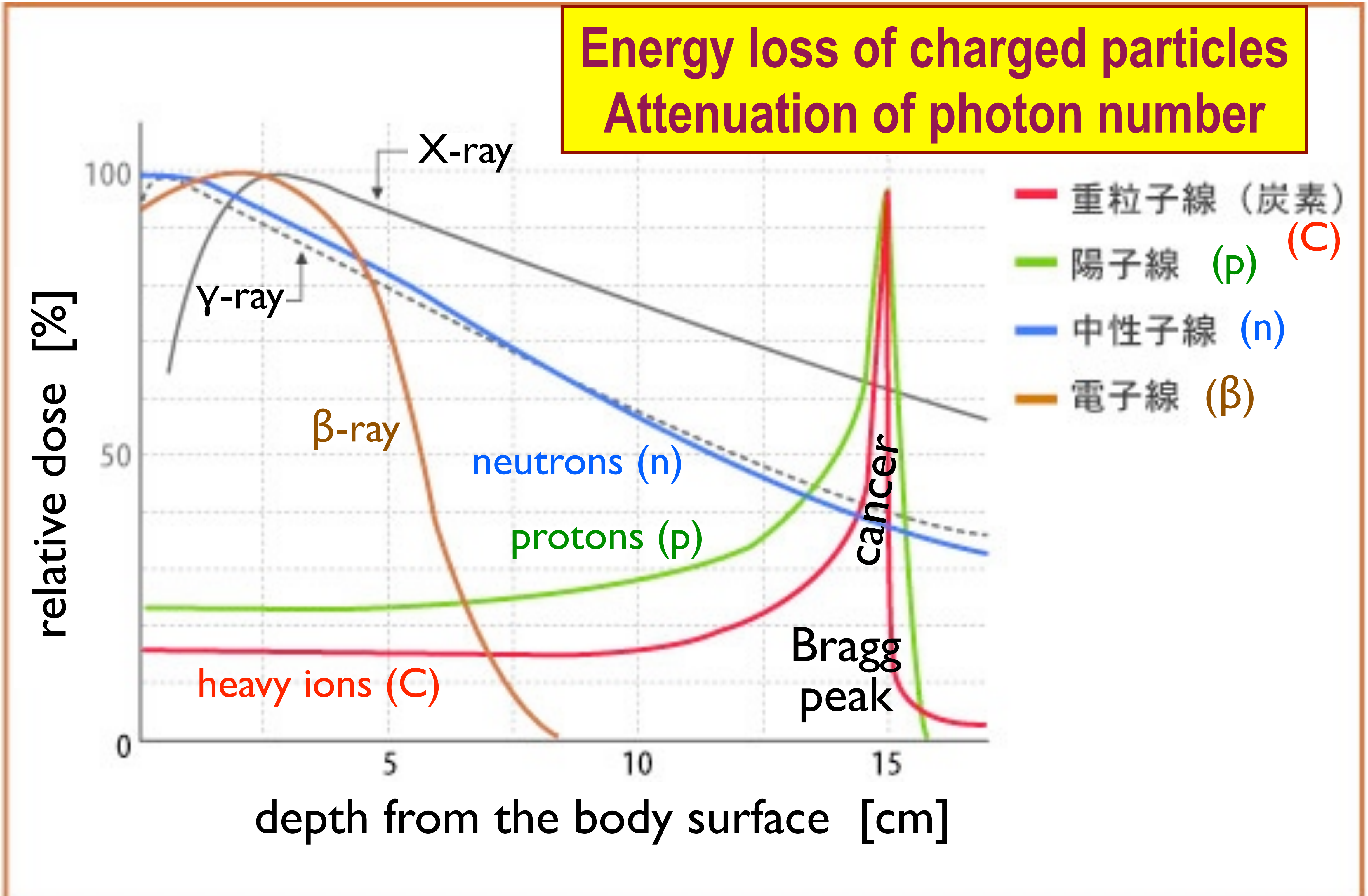
図3　人体を透過する放射線

Radioactive contamination map

早川由紀夫教授(群馬大学)作成、7月26日版

What does protective clothing
放射線防護服
protect ?

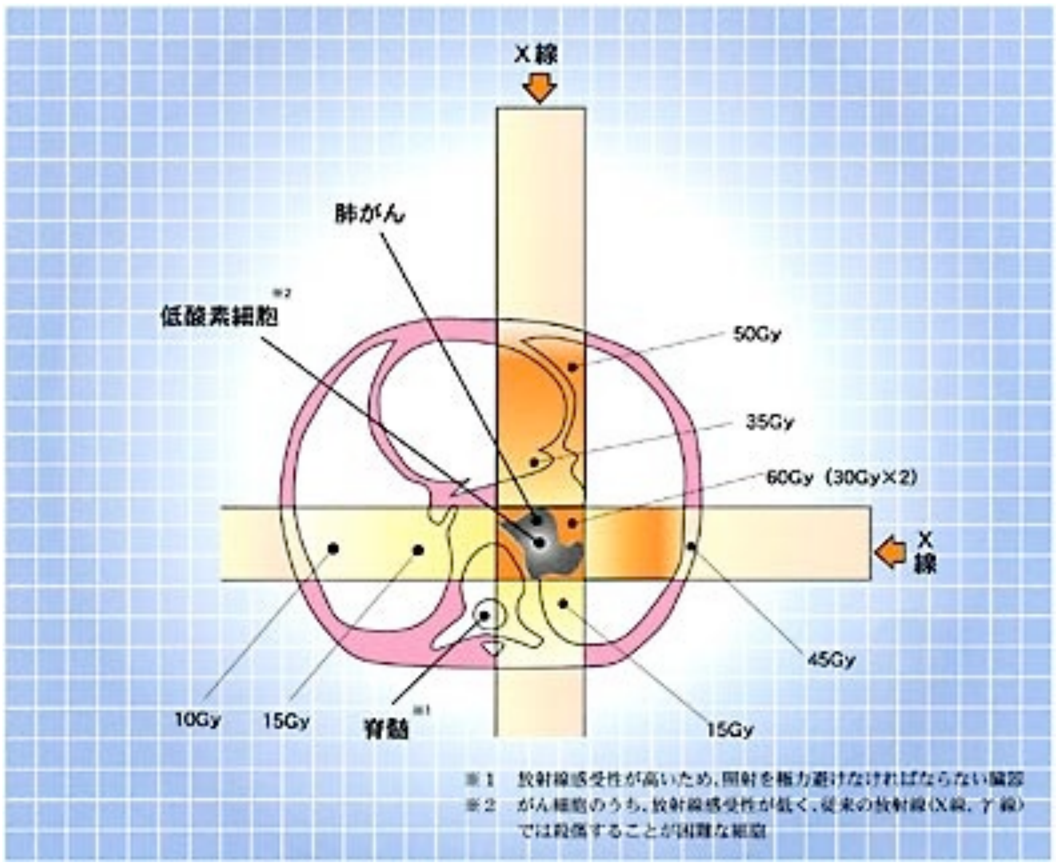
Protons, alpha-particles and ions have their uniform ranges as a function of their energy.
Electrons (beta-particles) are subject to scattering. The range measured as the rectilinear distance (or the material thichkness) has a large dispersion.
Neutrons and photons attenuate exponentially with depth, as the reaction occurs stochastically.



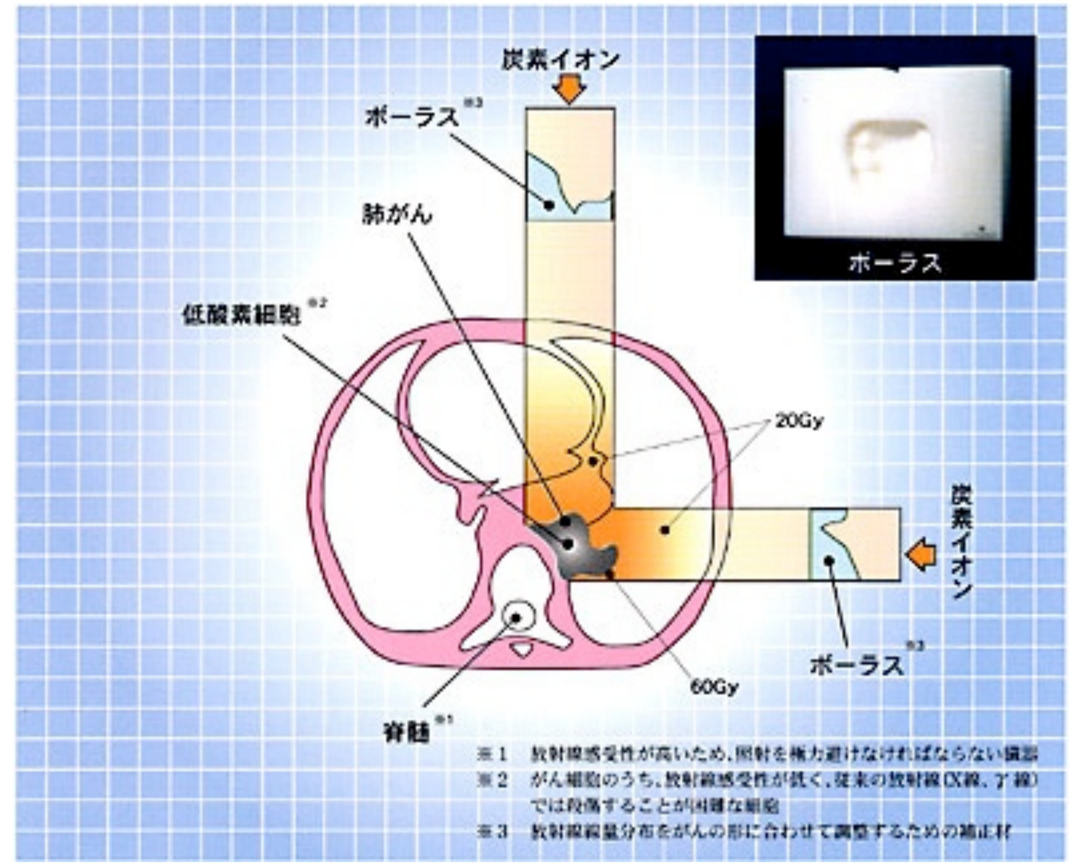
Radiation therapy for cancer

Multiple irradiation of a few Gy each.

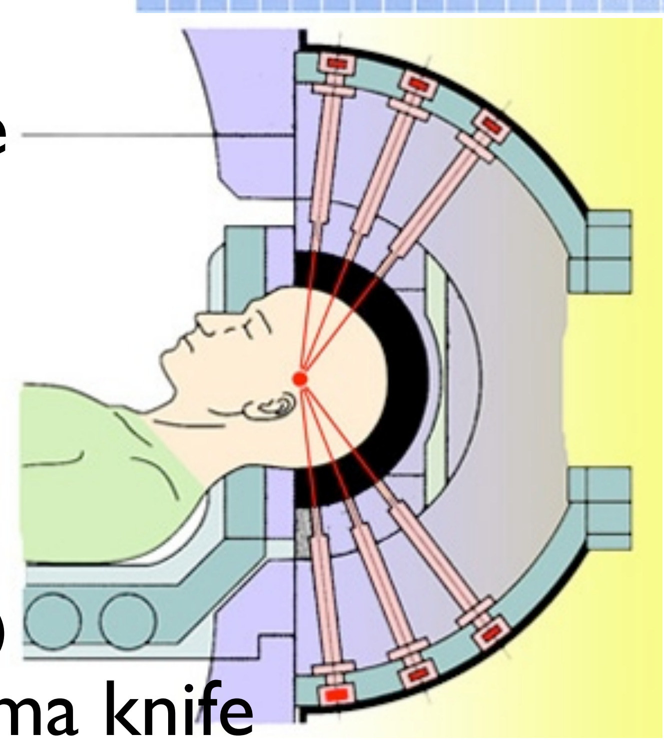
X-ray



heavy ion beam (Carbon ions)



cyberknife
(X-ray)

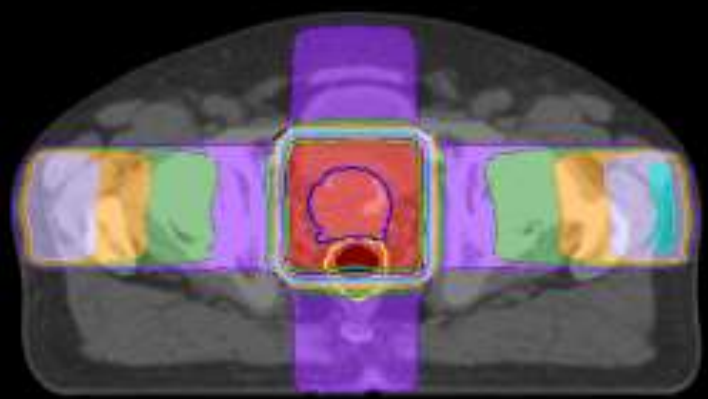


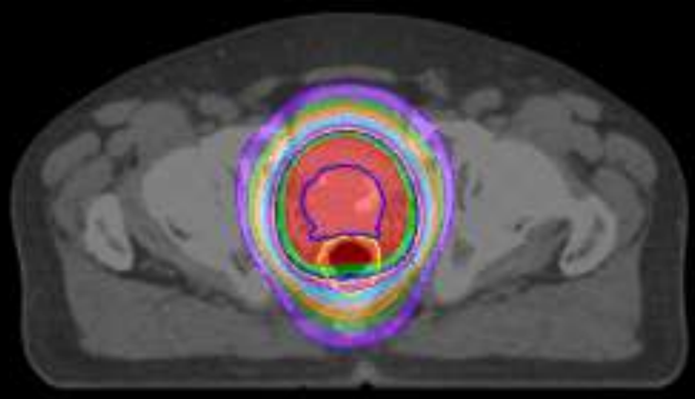
(γ-ray)
gamma knife

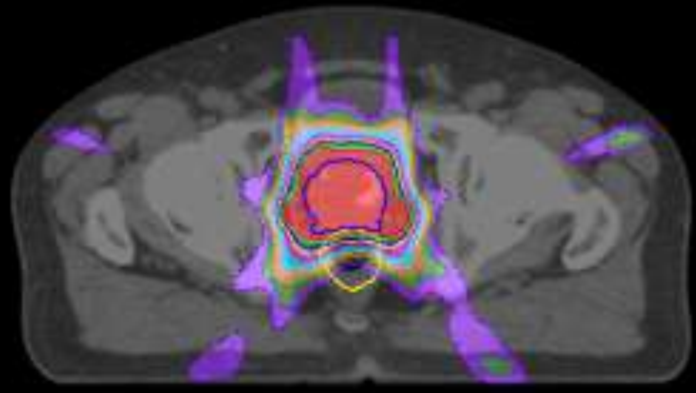
proton beam
pion beam
(antiproton beam)

e.g. prostate cancer（前立腺がんの例）

4-port irradiation	3D-CRT (three-dimensional conformal radiotherapy)	IMRT：Intensity-Modulated Radiation Therapy
前後左右4門照射	3次元原体照射	強度変調放射線治療







4-port irradiation（前後左右4門照射）

- 前立腺の他に、膀胱や直腸が高線量域に含まれる
- 70Gyが限界（難治性の晩期粘膜障害の発現を許容範囲に抑えるためには、実際には60～66Gy程度が限界となる）

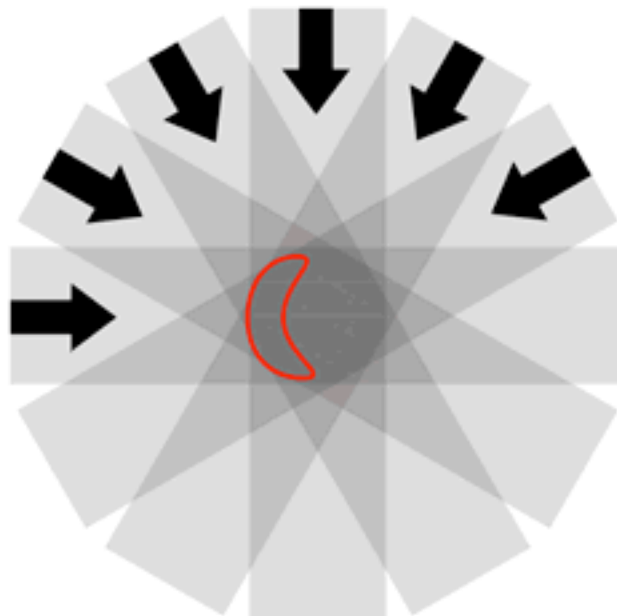
3D-CRT（3次元原体照射）

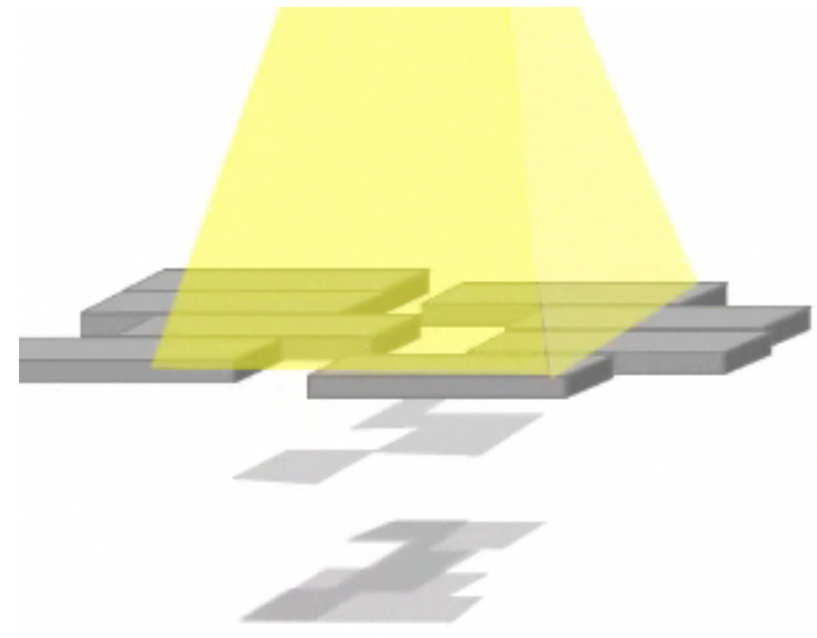
- 前立腺に線量が集中し、膀胱や直腸への線量が低く抑えられる
- 70Gy以上の投与が可能であるが、線量の集中に限界があり、線量増加に伴う副作用の増加が懸念される

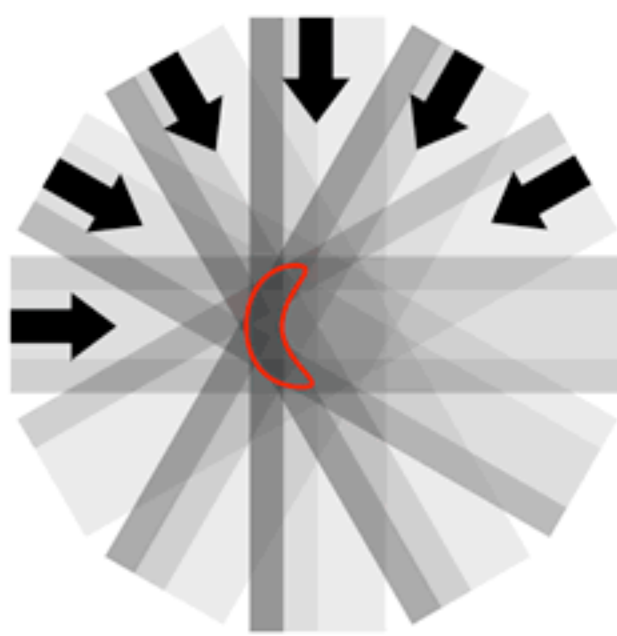
IMRT（強度変調放射線治療）

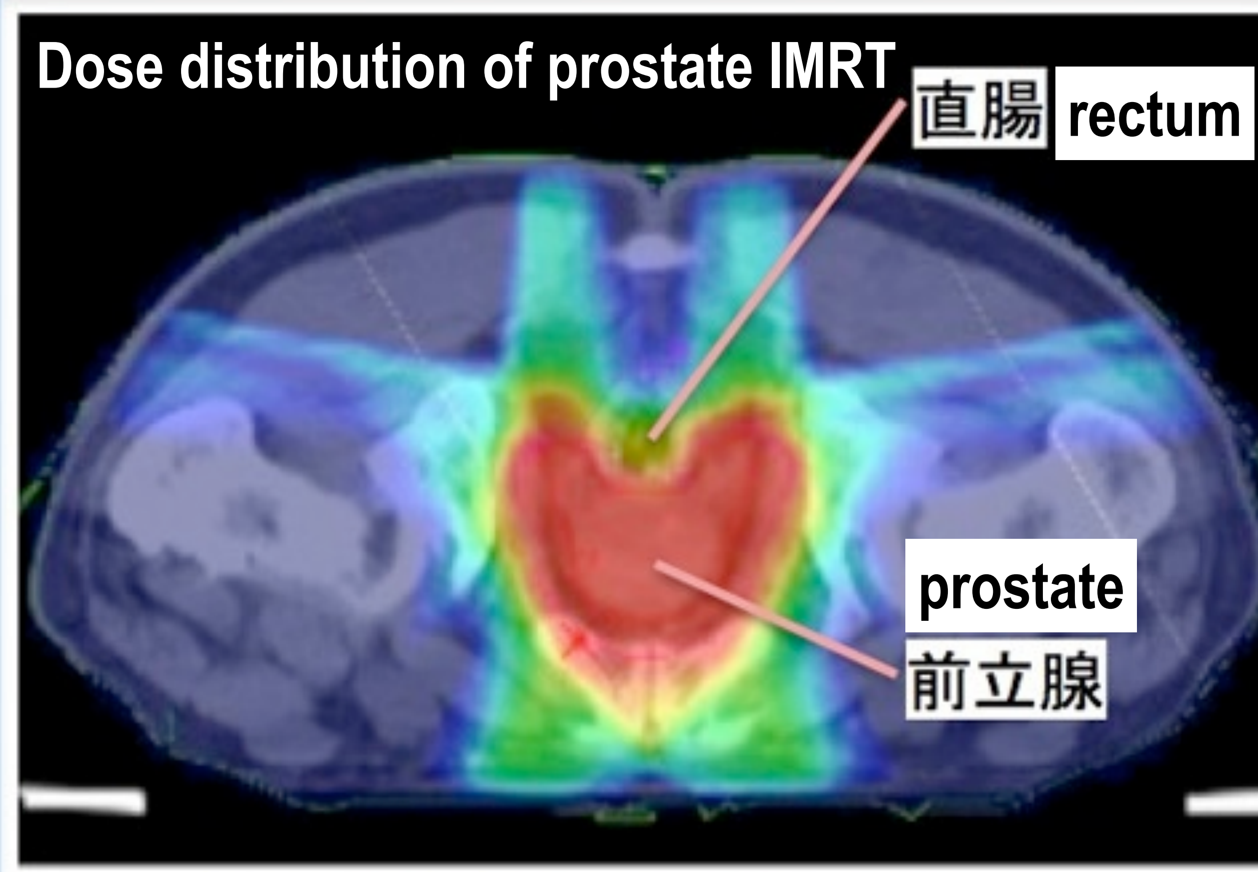
- 前立腺への集中性がさらに強化
- IGRTを併用することで、3次元原体照射を超える高線量を安全に投与することが可能

外照射法の進歩を背景に、前立腺癌に対する線量増加効果が積極的に検討されている。









前立腺IMRTの線量分布

Interaction between radiation and matter

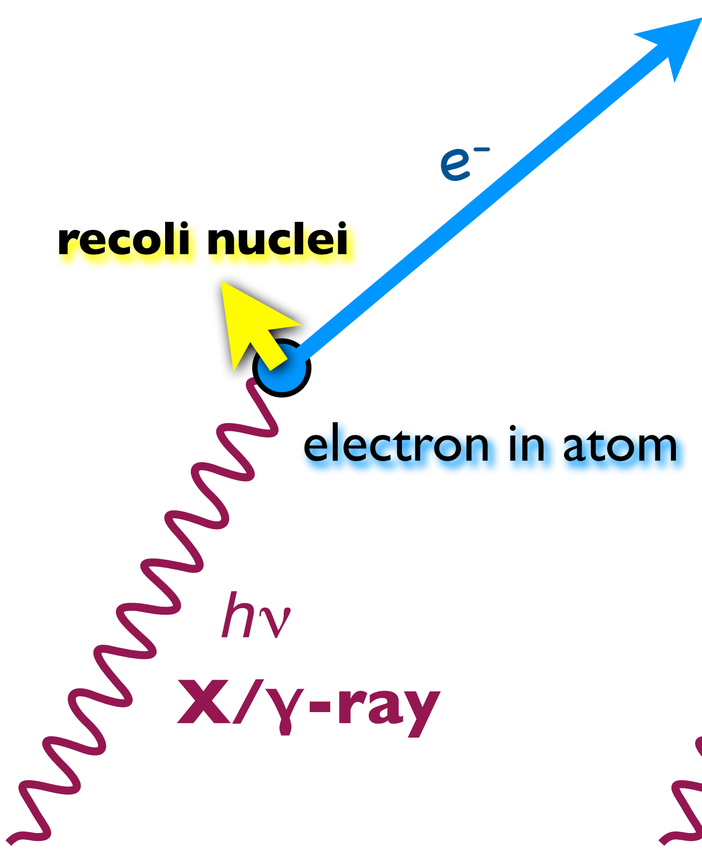
Attenuation of photons

放射線と物質との相互作用

光子の減衰

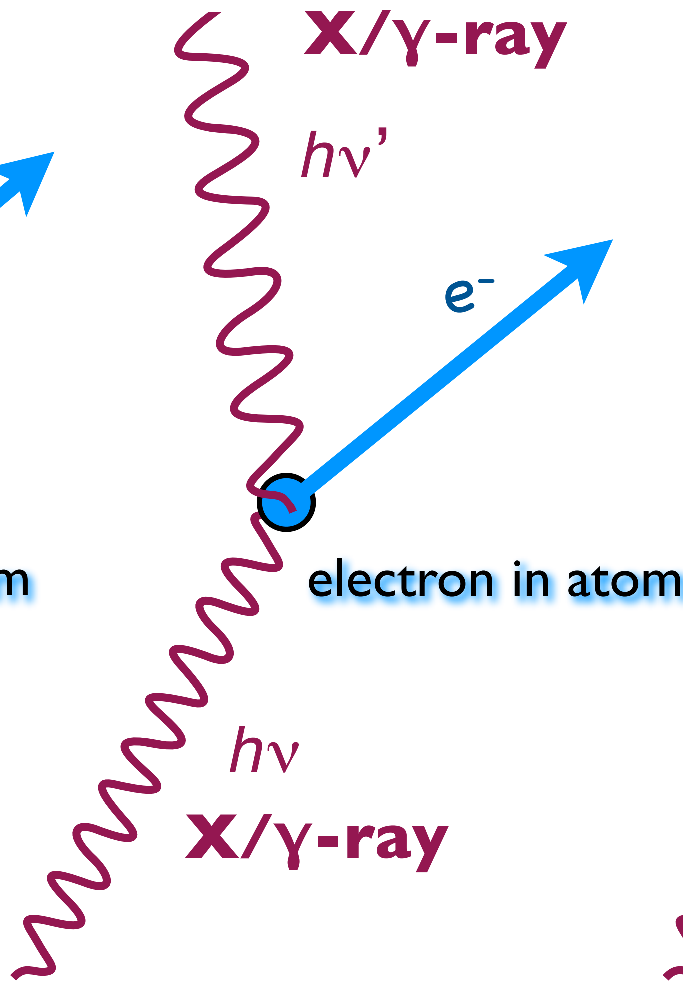
Interaction relating to photons (X-ray, γ-ray)

photoelectric effect 光電効果



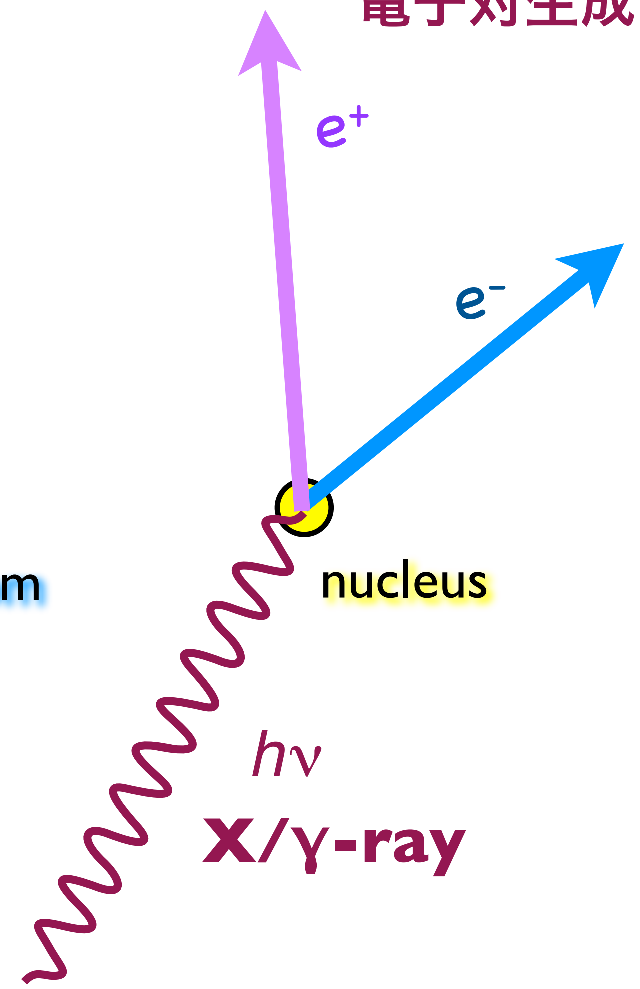
A photon kicks **one electron** out of an atom. The photon is absorbed.

Compton scattering コンプトン散乱



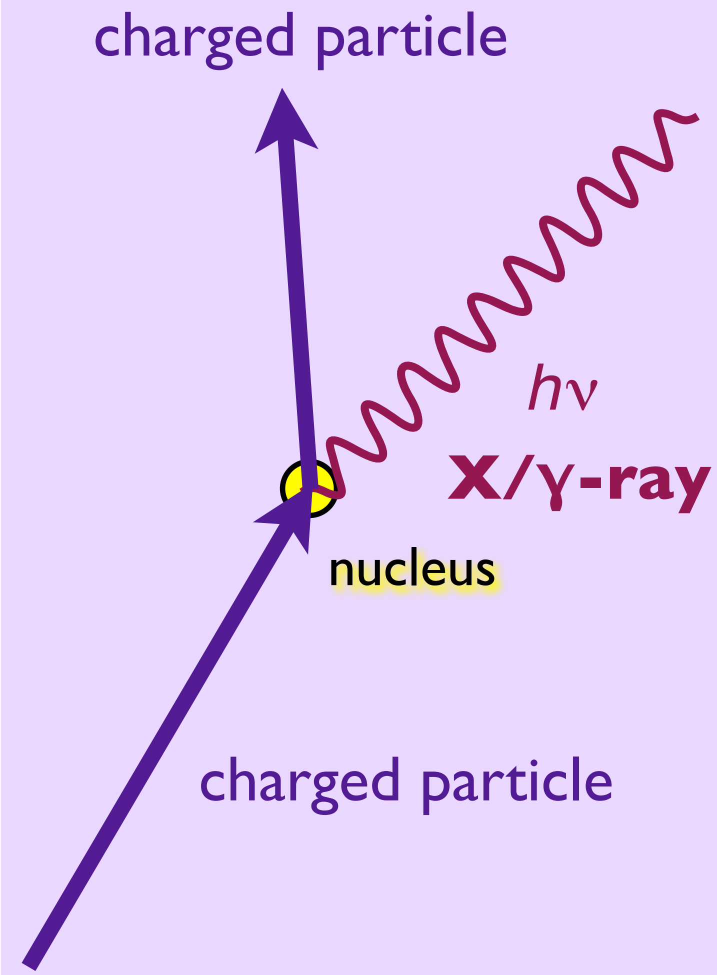
A photon is **scattered by one electron**. The photon loses a large fraction of its energy.

pair production 電子対生成



A photon with more than a MeV energy produces electron-positron pair.

bremsstrahlung 制動放射



A charged particle emitts a photon when they are abruptly decelerated or when their trajectory is curved.

Generation of high-energy electrons

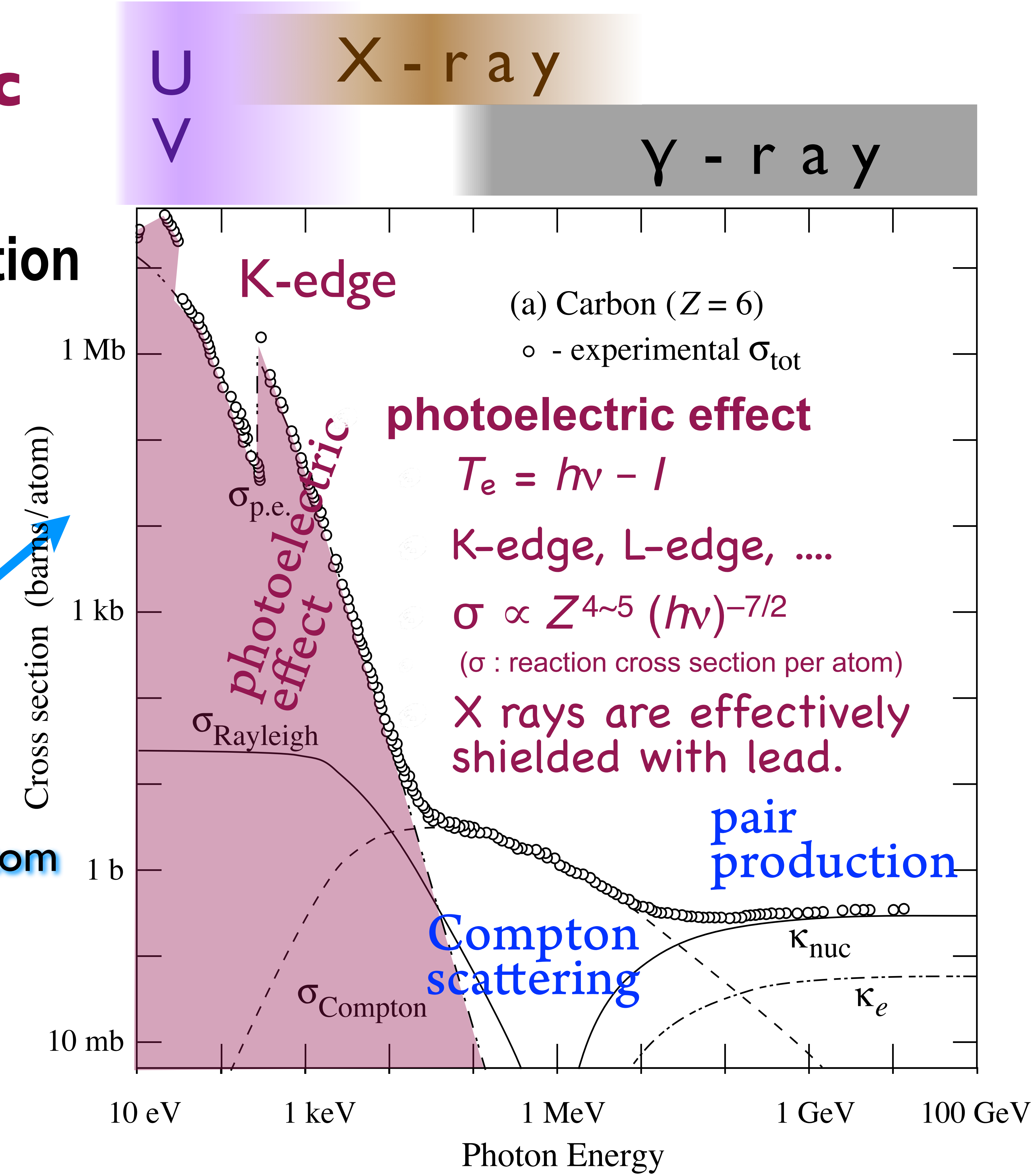
(same particles as β-ray)

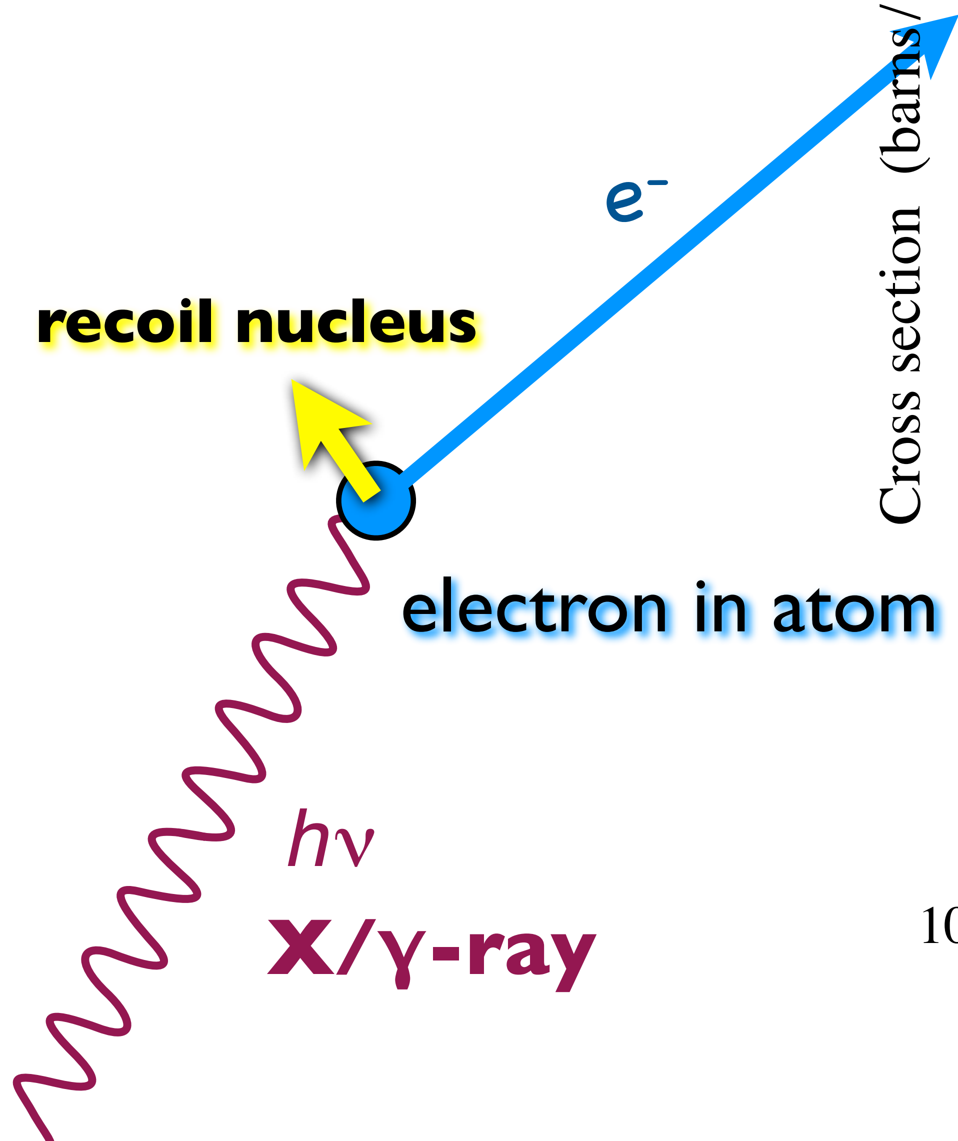
photoelectric effect

reaction **cross section**

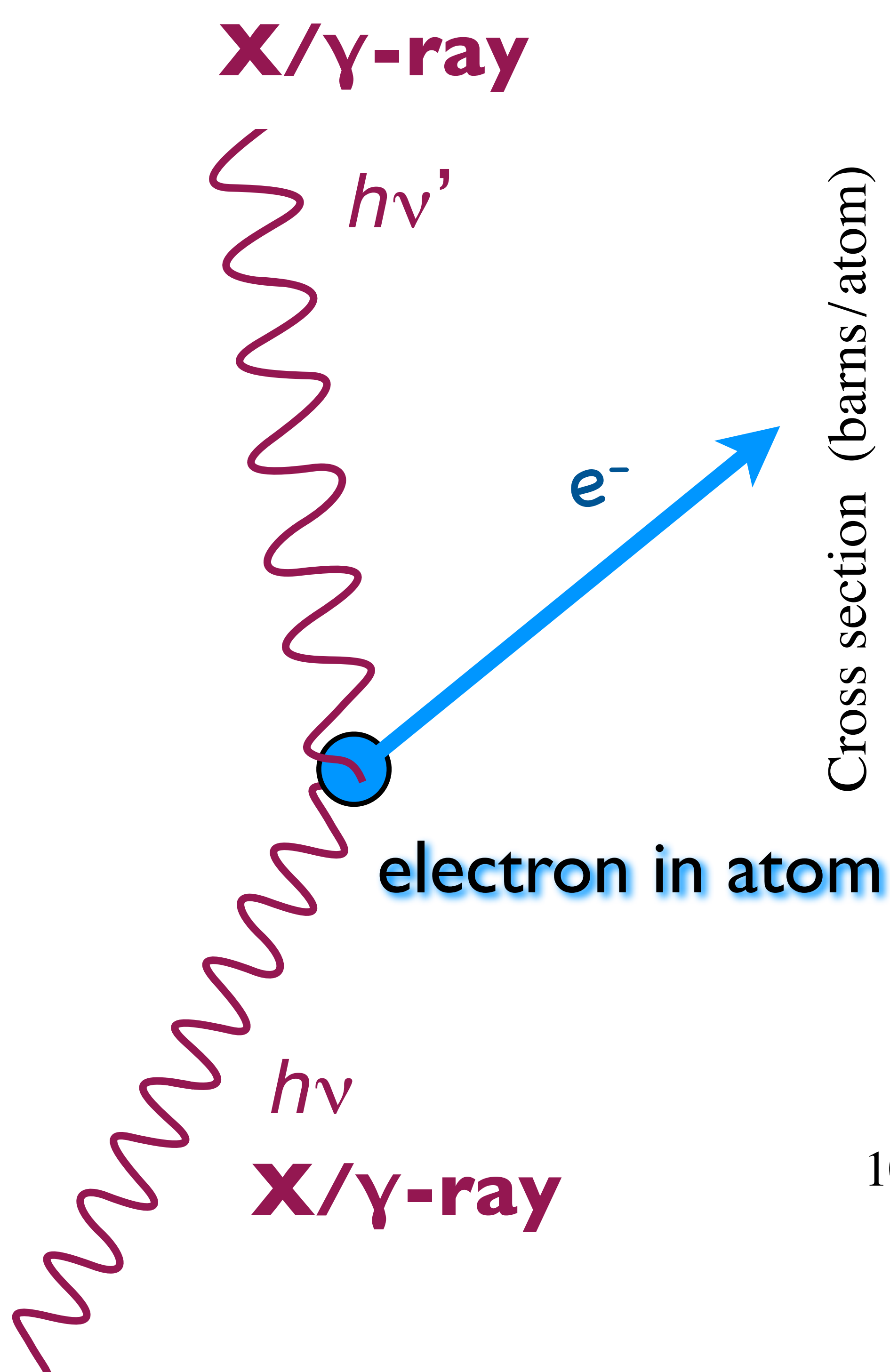
1 Mb = $(0.1\ \text{Å})^2$

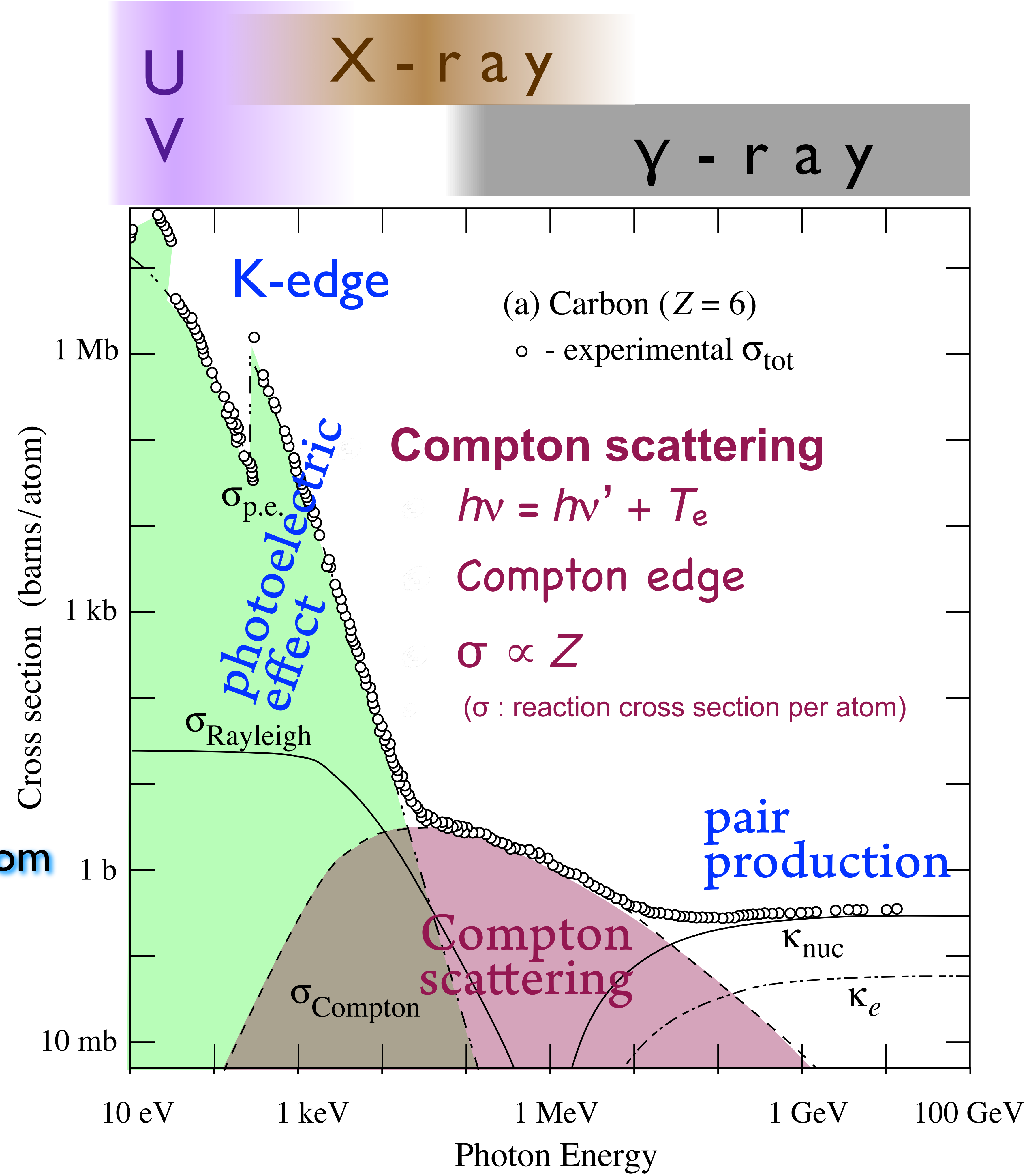
1 barn = $10^{-28}\ \text{m}^2$ = $(10\ \text{fm})^2$



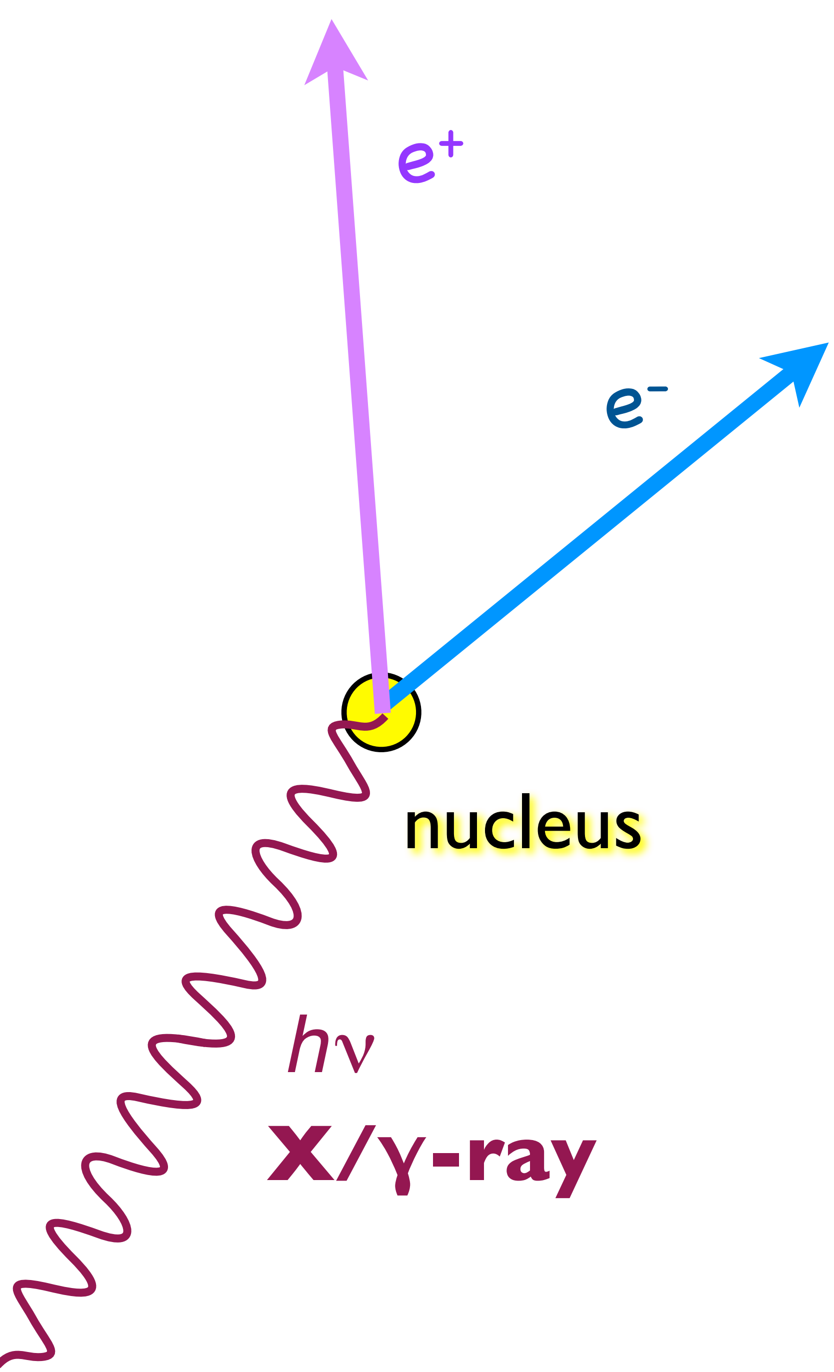


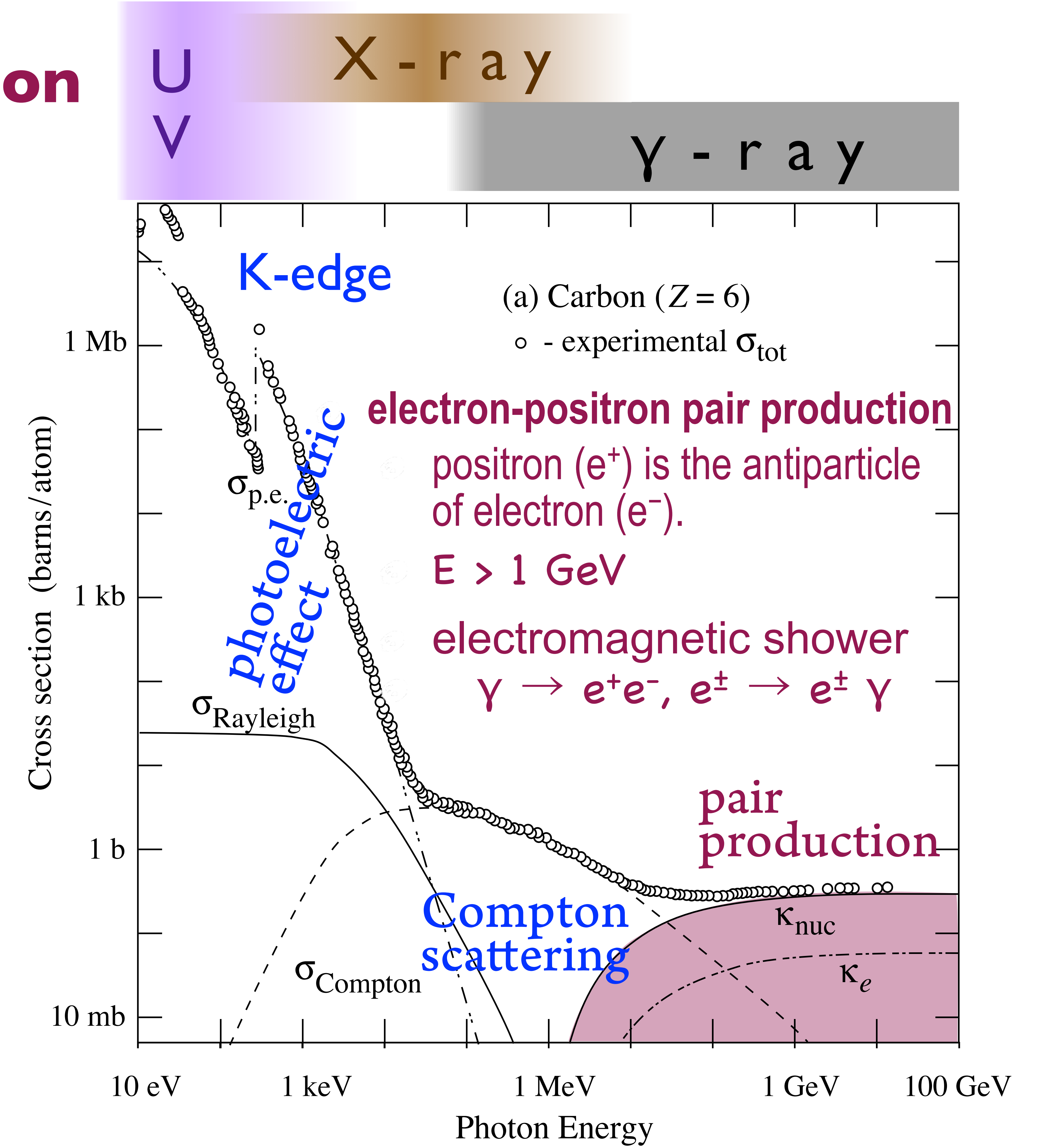
Compton scattering





pair production



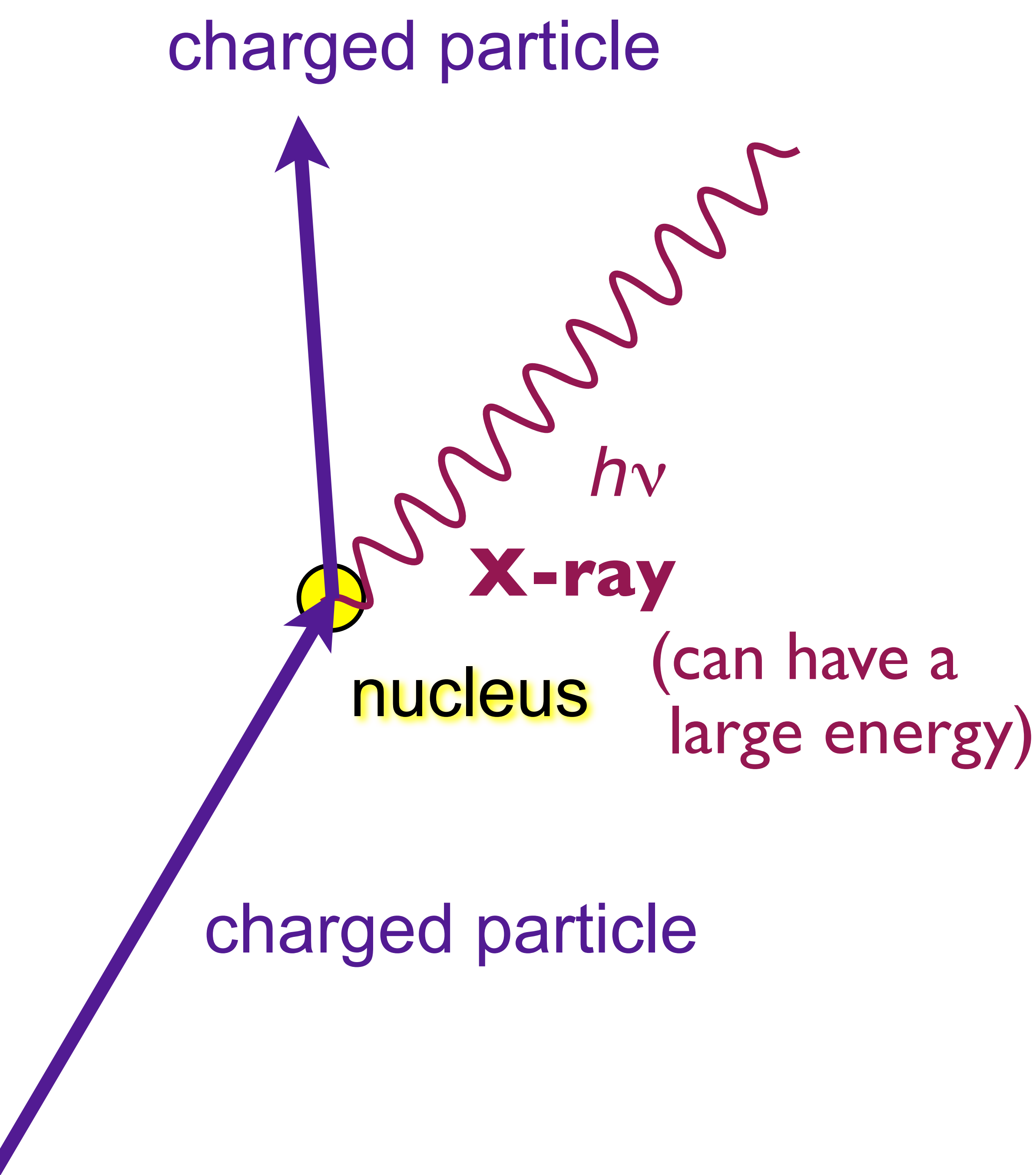


Bremsstrahlung
制動放射

Charged particles emit photons (X-ray) when their velocity is abruptly changed (i.e. decelerated or their orbits are curved).

$\Delta E \propto Z^2$

β-rays should not be stopped with lead.



bremsstrahlung : energy loss S_{rad}

$$\frac{S_{rad}}{S_{col}} = \frac{(E+mc^2)\,Z}{1600\; mc^2}$$

electrons (β-ray)

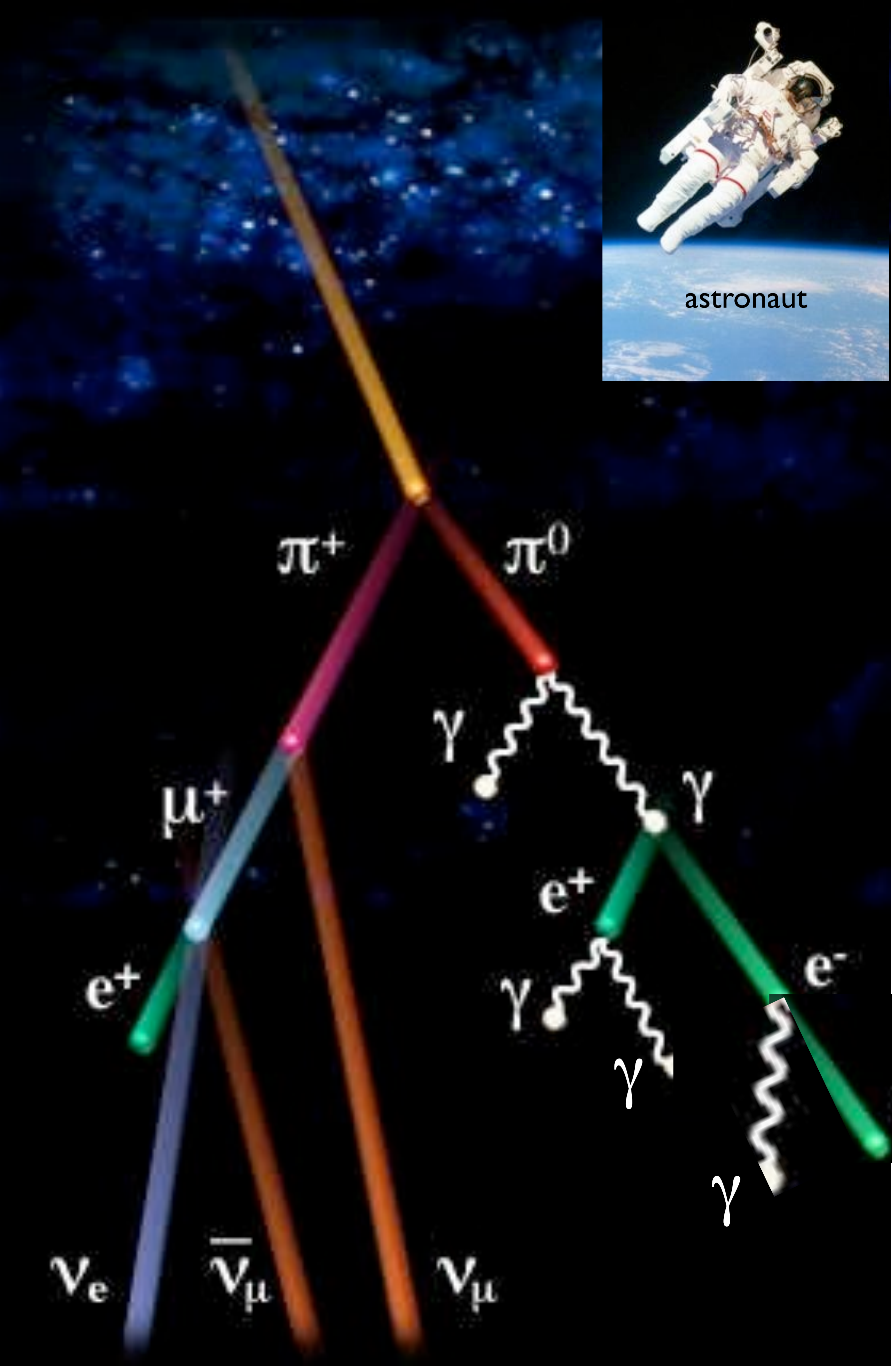
Pb (lead; Z = 82)

$$\frac{S_{rad}}{S_{col}} \approx \frac{E\,Z}{800\ \mathrm{MeV}} \approx \frac{E\,/\,\mathrm{MeV}}{10}$$

β-rays should not be stopped with lead.

protons or α-ray

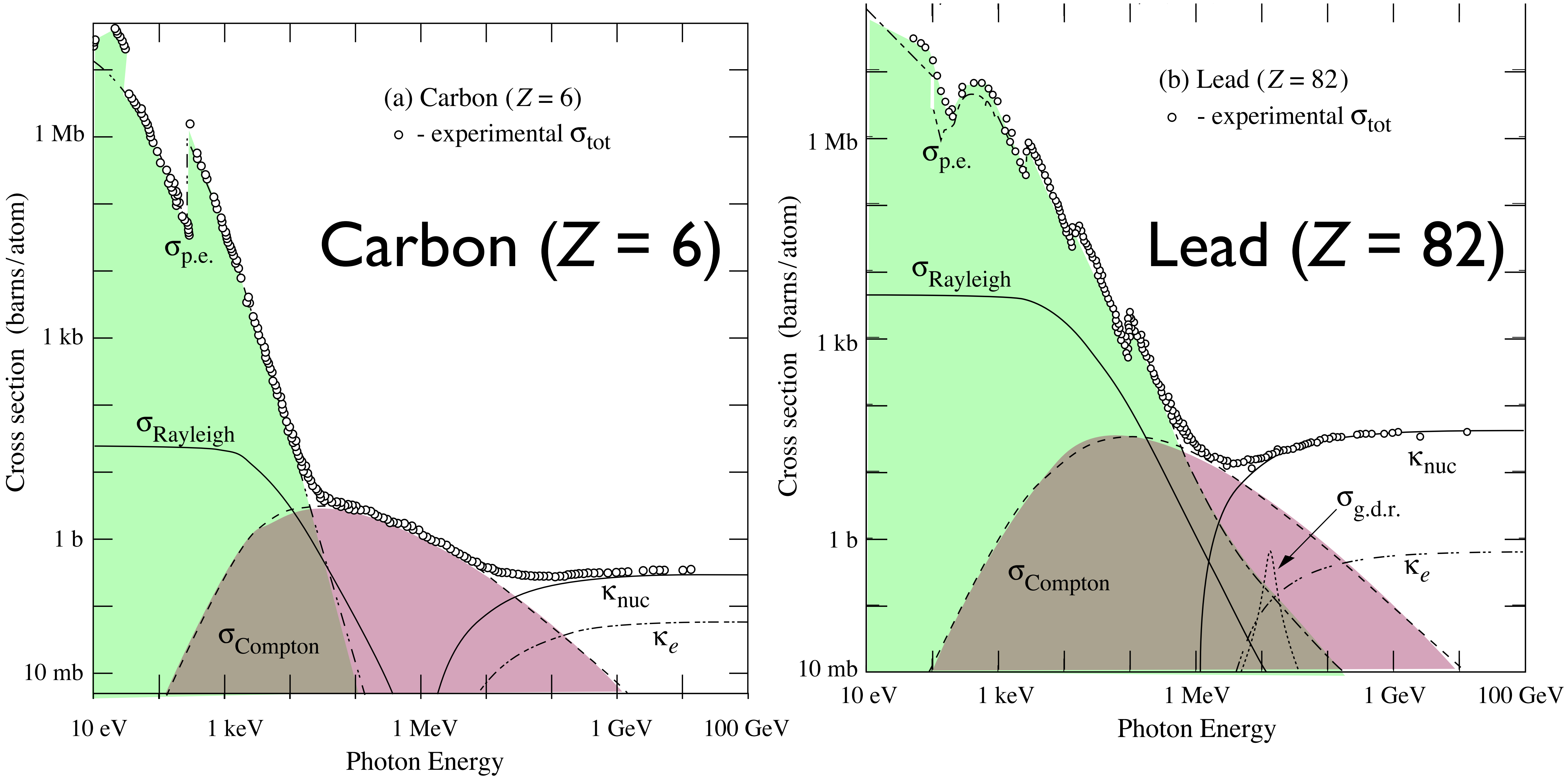
Bremsstrahlung is negligible compared with stopping power by electron collision, unless the energy is more than the order of a GeV.



cosmic ray

electromagnetic shower

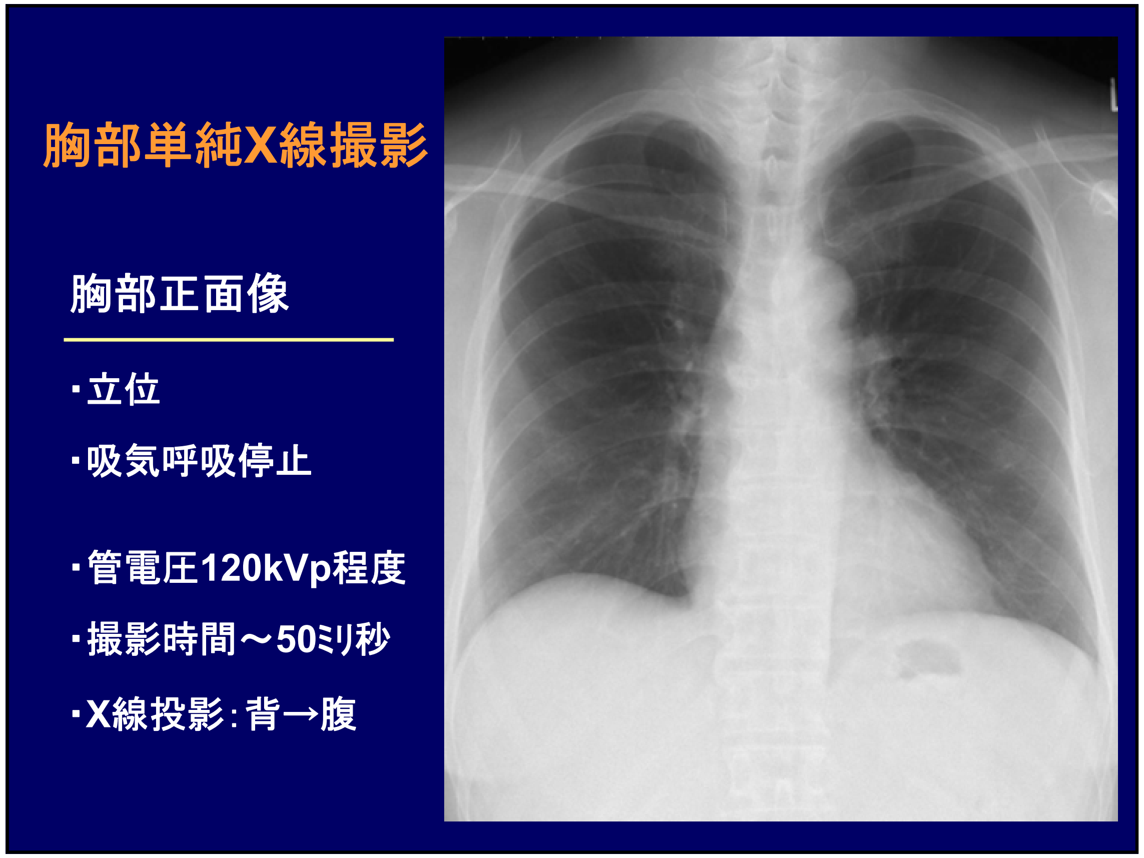
Material dependence of photon cross sections



photoelectric effect $\propto Z^{4\sim5}$

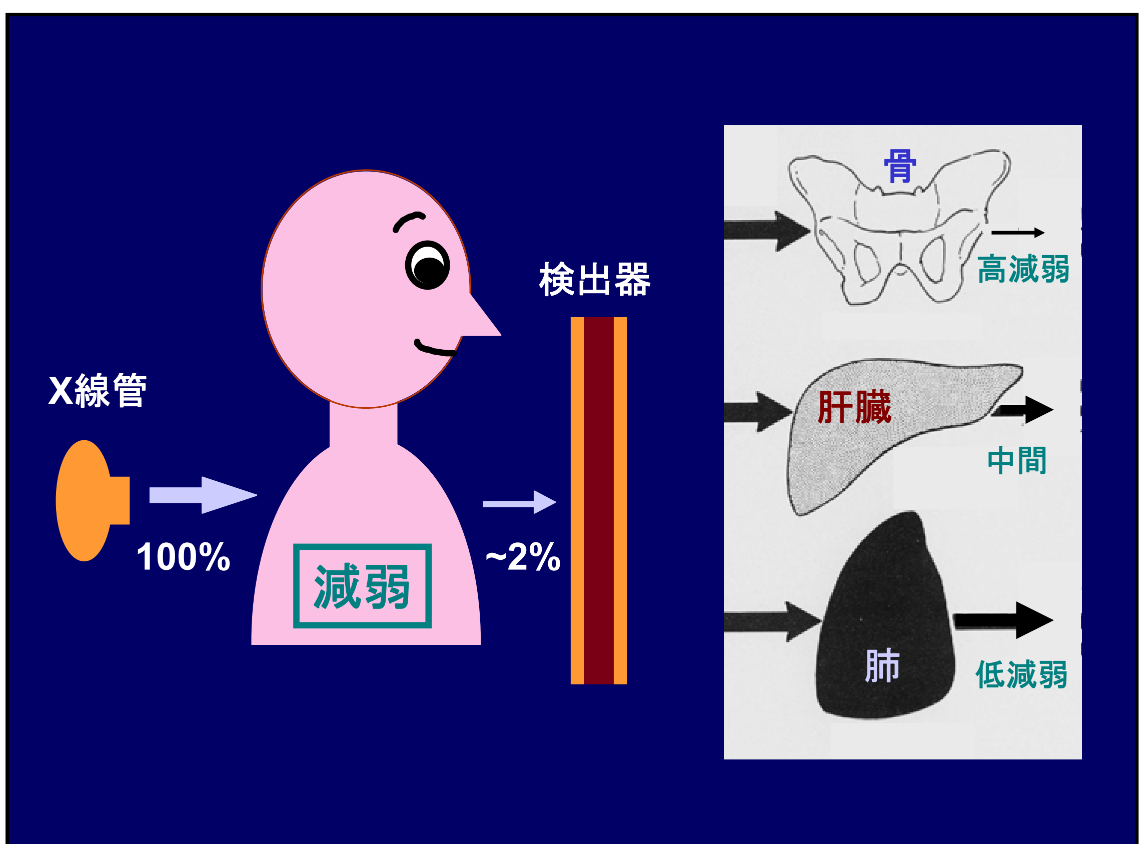
Compton scattering $\propto Z$

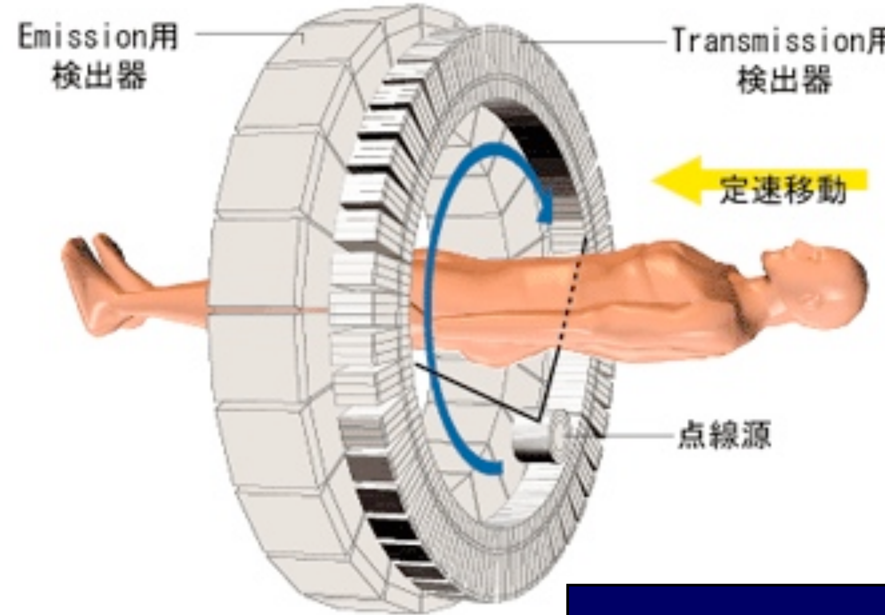
bremsstrahlung $\propto Z^2$



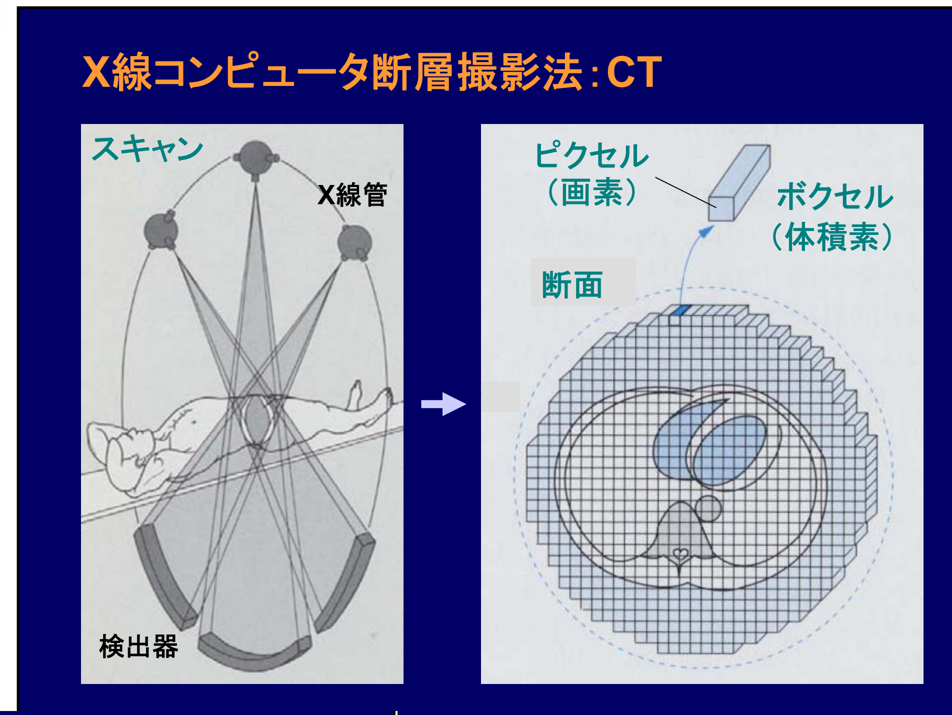
Röntgen radiography

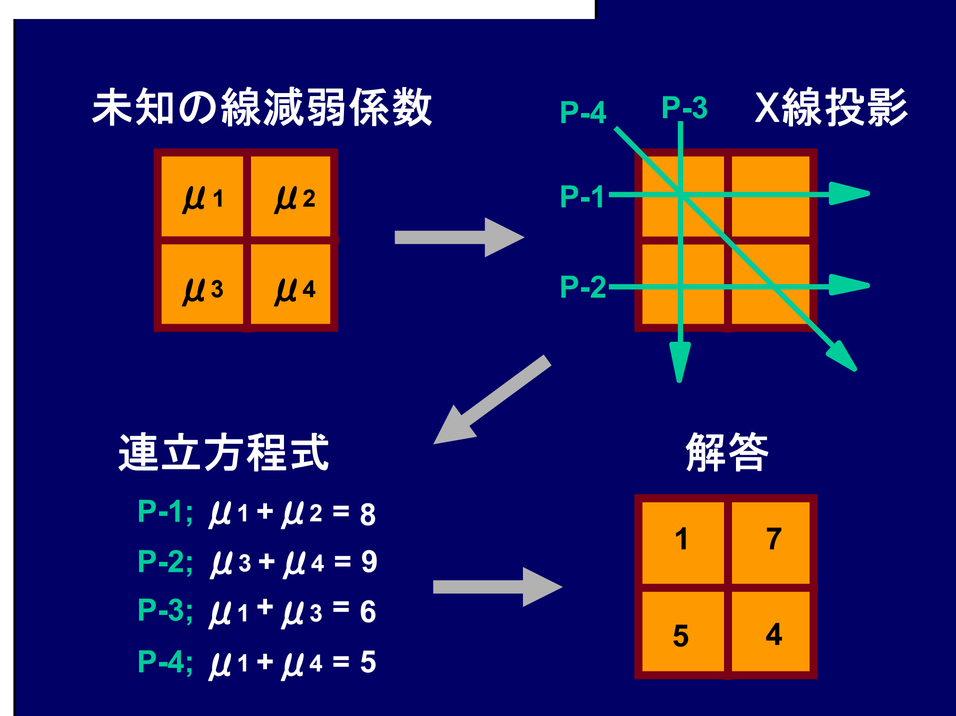
国立循環器病センター 内藤博昭先生のスライドより借用





X-ray CT





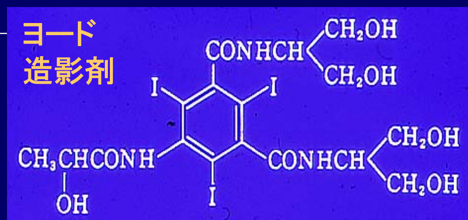
X線検査用造影剤

＊陽性造影剤	元素	原子番号	K吸収端
・ヨード造影剤：血管造影用	I	53	33.16 keV
・硫酸バリウム：消化管造影用	Ba	56	37.41 keV
・キセノン ガス（脳血流CT）	Xe	54	34.56 keV

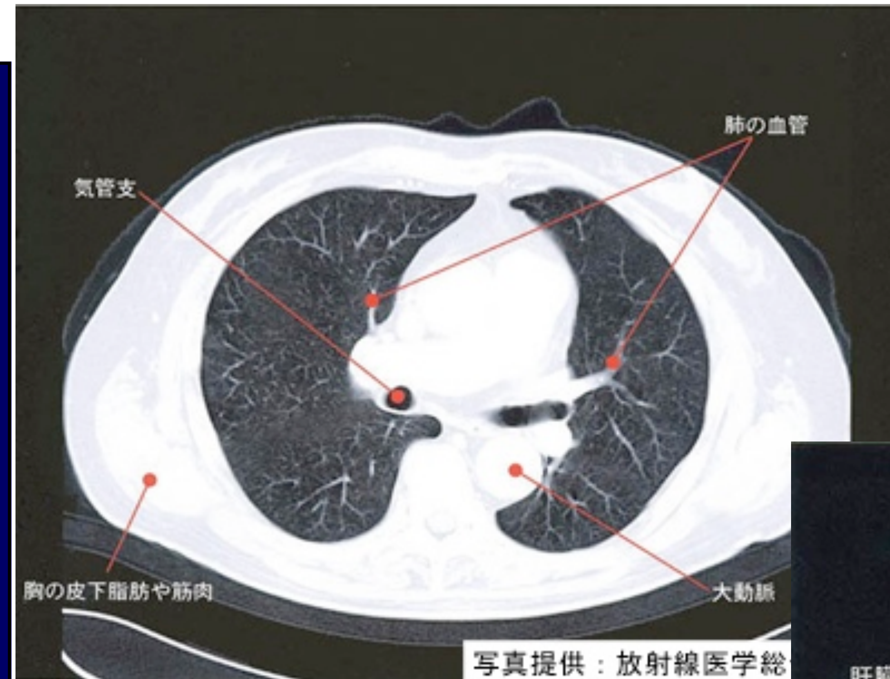
＊陰性造影剤

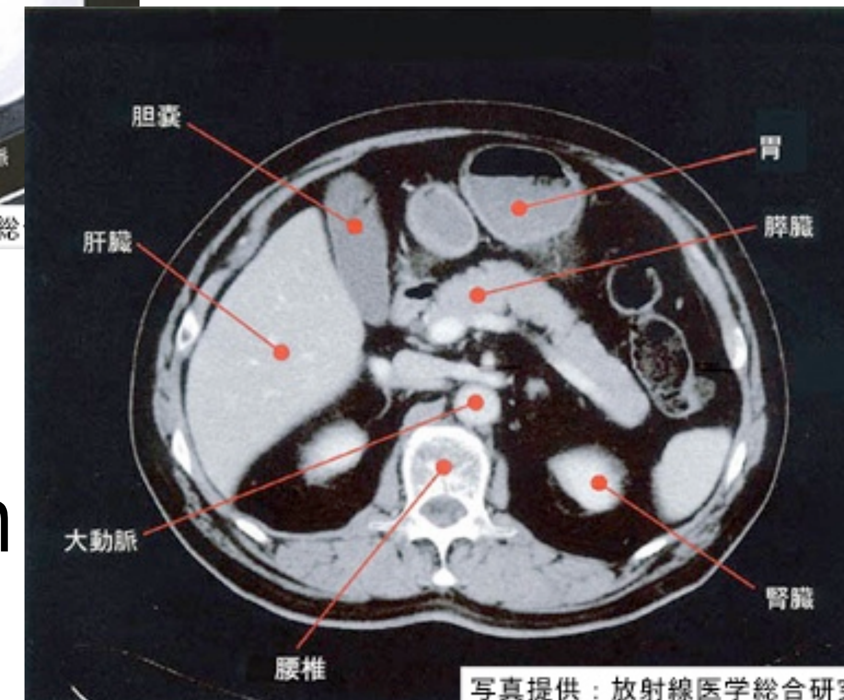
- 気体：空気，酸素，炭酸ガス...
- オリーブ油（膀胱CT）

ヨード造影剤



イオパミドール　分子量: 777.09



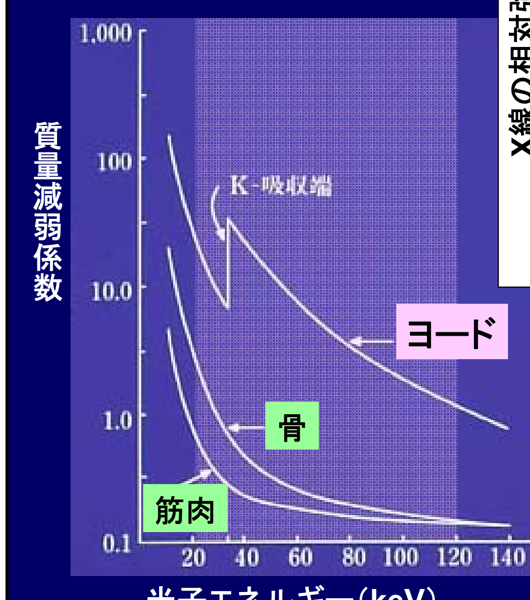


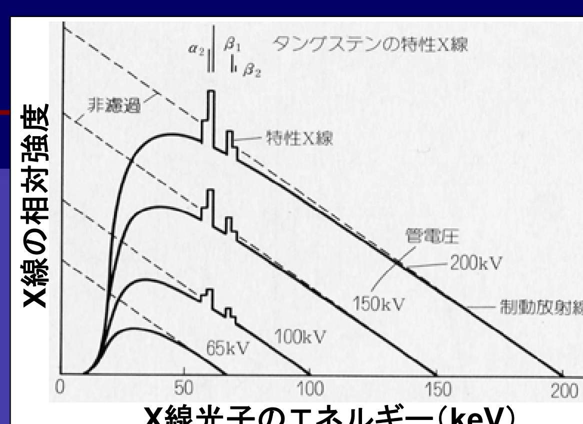
contrast media (**I, Ba, Xe**) : large **Z** = large attenuation

造影剤 (radiopaque substances)　　　**減衰（減弱）係数 大**

国立循環器病センター 内藤博昭先生のスライドより借用

X線の発生と減弱





＊光電効果：光電吸収

・元素のK吸収端（keV）：
H 0.0136, C 0.283, O 0.531

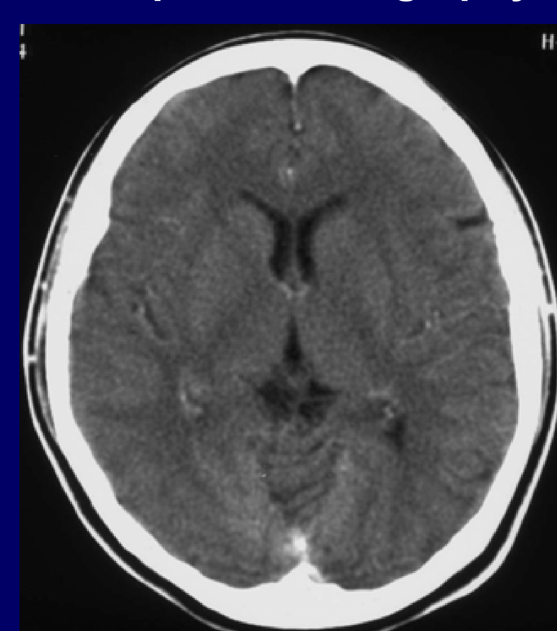
＊コンプトン散乱：非弾性散乱

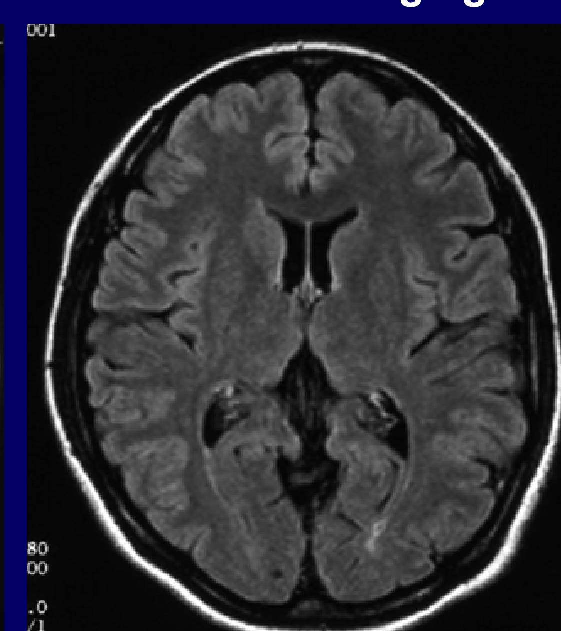
X線コンピュータ断層撮影法

X-Ray CT: Computed Tomography

磁気共鳴画像診断法

MRI: Magnetic Resonance Imaging





Attenuation and absorption of photons (γ-ray) in material.

Exponential decrease of photon number

Photoelectric effect, Compton scattering &c. are stochastical processes.

$$\frac{\mathrm{d}\dot{\Phi}(x)}{\mathrm{d}x} = -\mu\,\dot{\Phi}(x) \qquad \dot{\Phi}(x) = \dot{\Phi}(0)\,\mathrm{e}^{-\mu x}$$

$$\dot{\Phi}(L) = \dot{\Phi}(0)\,/\,2 \qquad L = \ln 2\,/\,\mu$$

$\ln x$: natural logarithm.
$\equiv \log_e x$

$\dot{\Phi}$: particle fluence rate

for γ ($h\nu$ = 0.66 MeV) from ^{137}Cs

x : distance, L : half-value thickness

$L^{\mathrm{air}} = 69.2$ m

μ : linear attenuation coefficient

$\mu^{\mathrm{air}} = 0.0100$ m^{-1}

μ/ρ : mass attenuation coefficient

$(\mu/\rho)^{\mathrm{air}} = 0.077$ (g/cm^2)$^{-1}$

$\mu_{\mathrm{en}}/\rho < \mu/\rho$

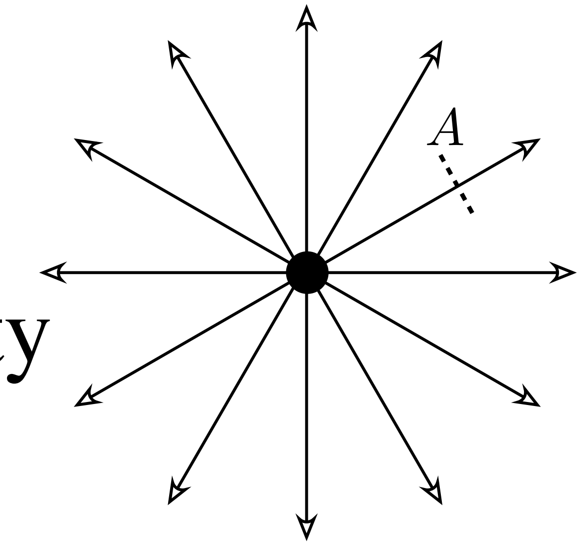
μ_{en}/ρ : mass energy-absorption coefficient

$(\mu_{\mathrm{en}}/\rho)^{\mathrm{water}} = 0.033$ (g/cm^2)$^{-1}$

$\dot{H}$: equivalent dose rate (= absorption dose rate for γ-ray)

$$\dot{H} = h\nu\,(\mu_{\mathrm{en}}/\rho)\,\dot{\Phi}\,, \quad h\nu\,(\mu_{\mathrm{en}}/\rho)^{\mathrm{water}} = 3.5\times 10^{-16}\ \mathrm{Sv\ m^2}$$

P : radioactivity [Bq]



$\dot{H}$: equivalent dose rate [Sv/s]

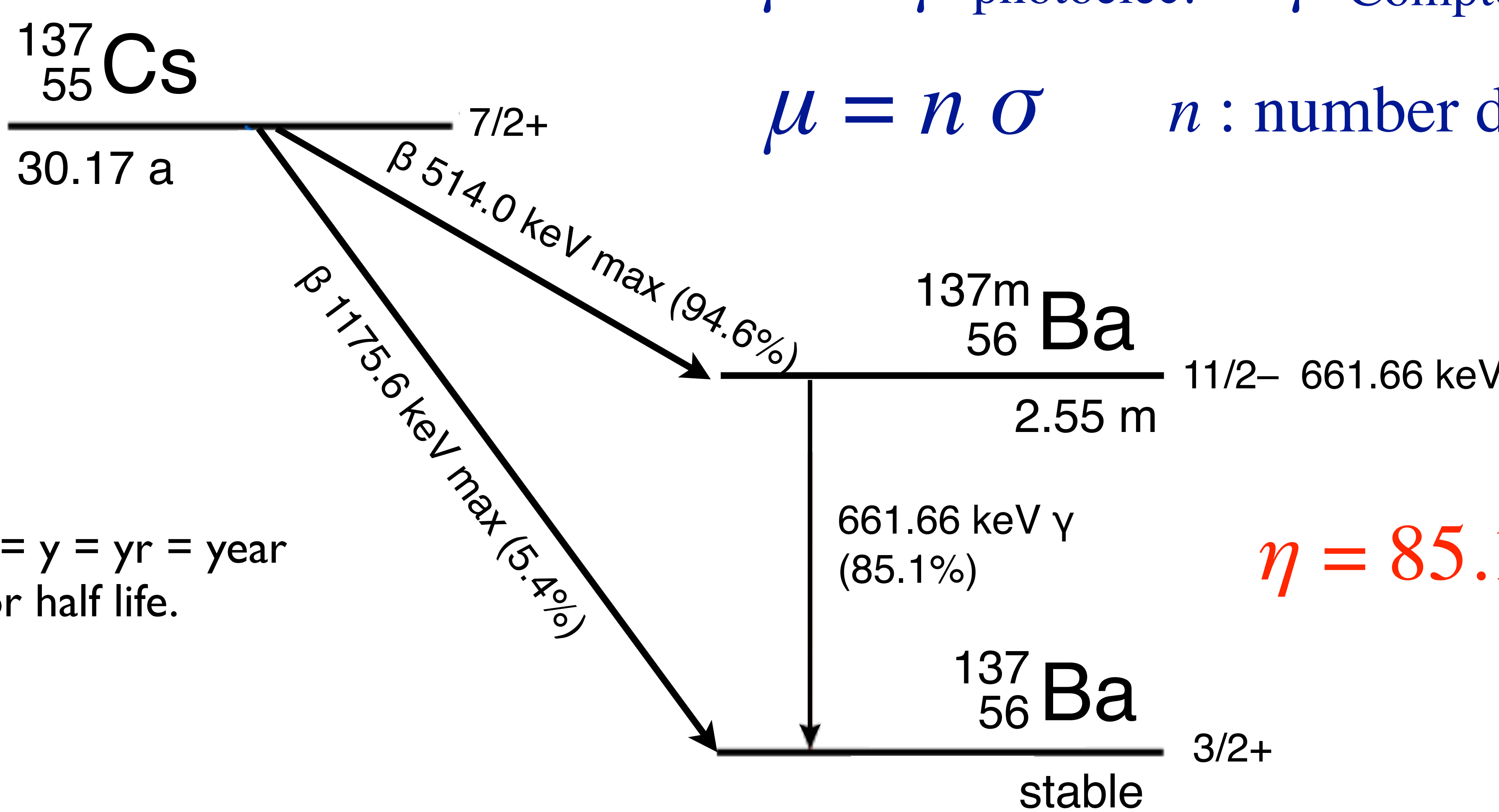
$$\dot{H} = h\nu\,(\mu_{\mathrm{en}}/\rho)\,\dot{\Phi}$$

$$\dot{\Phi} = \frac{e^{-\mu^{\mathrm{air}} r}\,\eta P}{4\pi r^2}$$

μ : linear attenuation coefficient

$$\mu = \mu_{\mathrm{photoelec.}} + \mu_{\mathrm{Compton}} + \mu_{\mathrm{pair\ prod.}} + \ldots$$

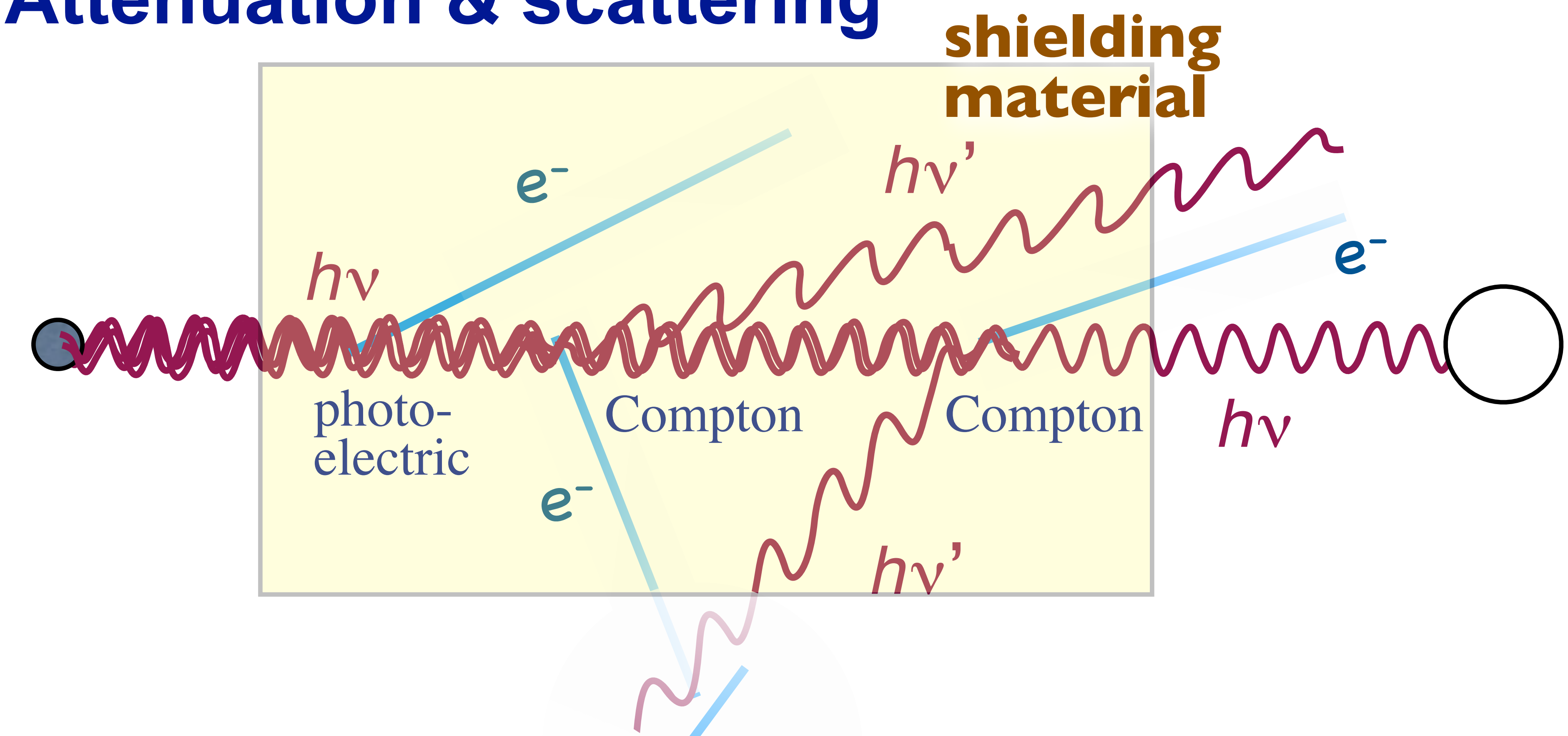
$\mu = n\,\sigma$ n : number density σ : cross section



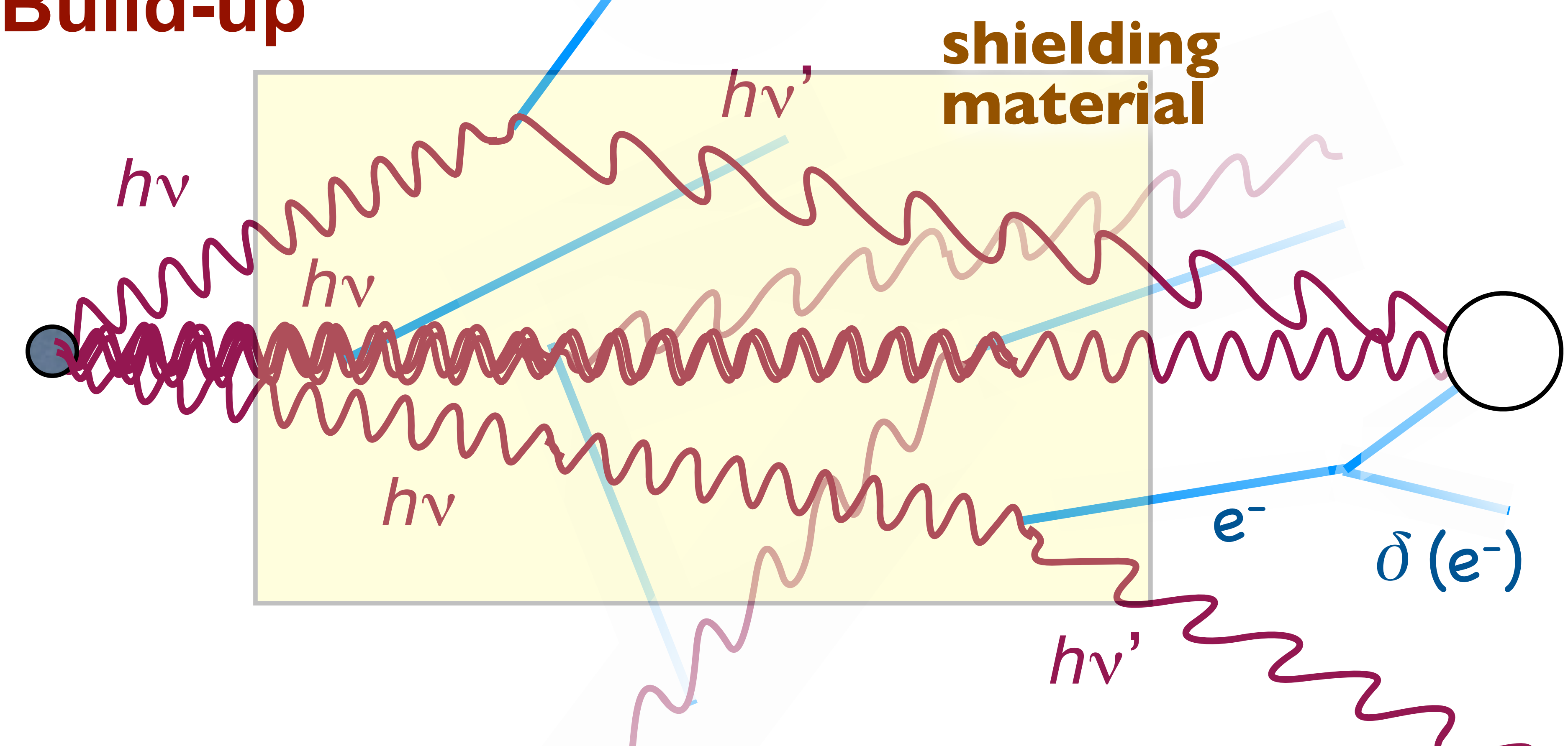
a = y = yr = year
for half life.

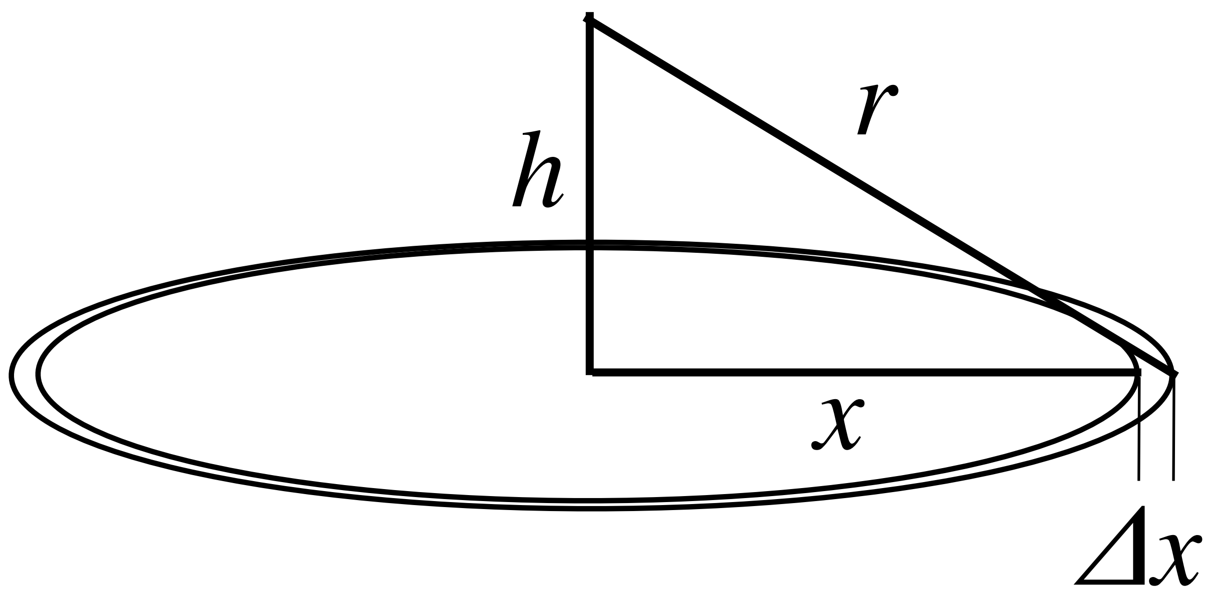
$\eta = 85.1\%$

Attenuation & scattering



Build-up





$$\dot{\Phi} = \int_0^{\infty} \frac{e^{-\mu^{air} r}\,\eta p}{4\pi r^2}\, 2\pi x\, dx$$

$\eta = 0.851$

$$= \frac{\eta p}{2} \int_h^{\infty} \frac{e^{-\mu^{air} r}}{r}\, dr$$

p : surface density of radioactivity [Bq/m²]

$$\dot{\Phi} \approx \frac{\eta p}{2} \int_0^{L^{air}} \frac{x}{x^2 + h^2}\, dx$$

$\dot{H}$: equivalent dose rate [Sv/s] $\dot{H}/\dot{\Phi} = h\nu\,(\mu_{en}/\rho)$ $= 3.5 \times 10^{-16}$ Sv m²

$$\int_0^{L^{air}} \frac{x}{x^2 + h^2}\, dx = \frac{1}{2} \ln\,(x^2 + h^2)\Big|_{x=0}^{L^{air}} = \frac{1}{2} \ln\,[\,(L^{air}/h)^2 + 1\,]$$

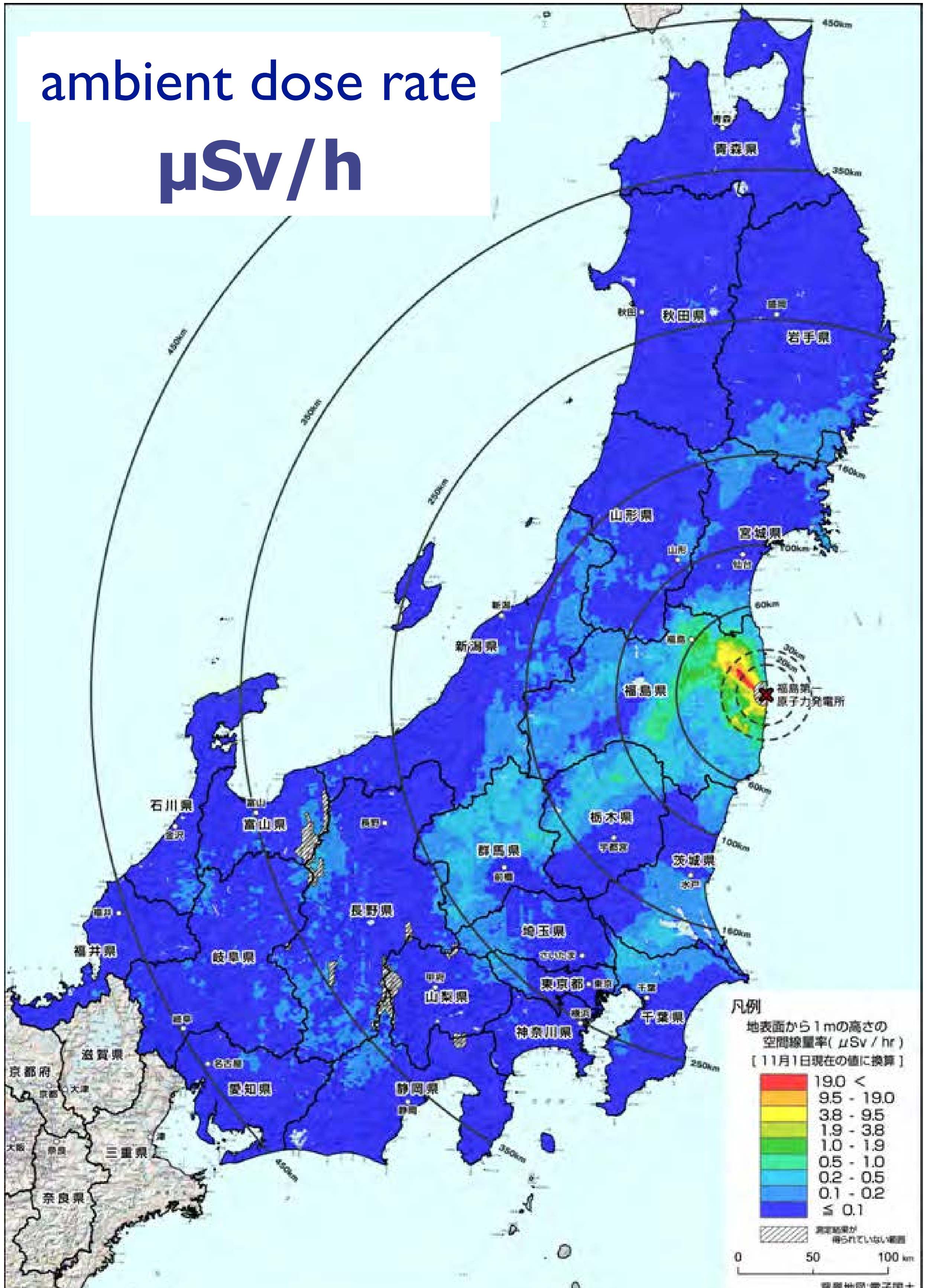
$L^{air} = 69.2$ m $\quad h = 1$ m

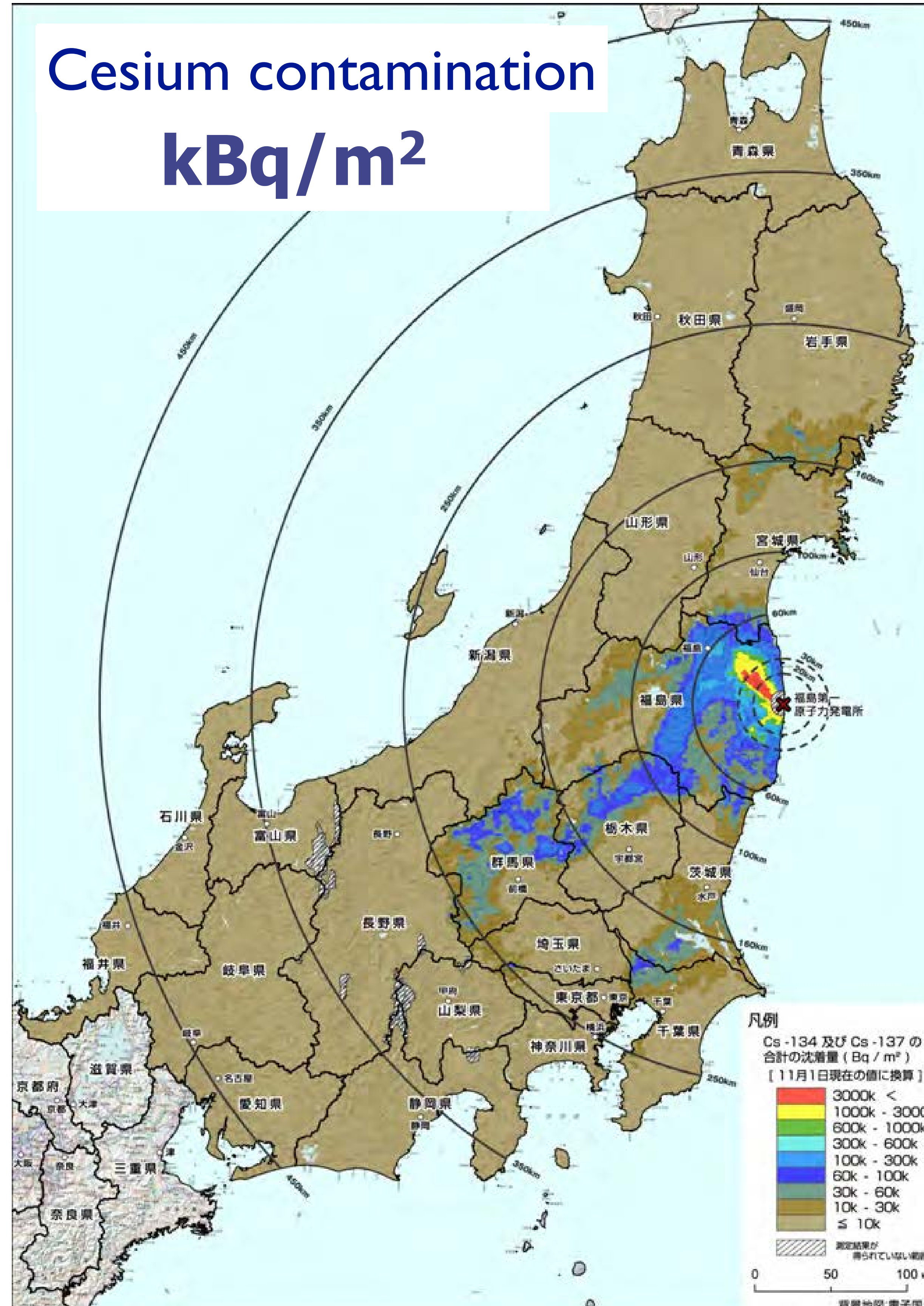
+ Build-up effect due to Compton scattering (ca. + 50%)

^{137}Cs : 2.1 (μSv/h) / (MBq/m²) .... calculation by IAEA

Problem with decontamination : half of the dose due to soil contamination of distance 10–100 m.

Radioactive contamination map : aerial monitoring by MEXT



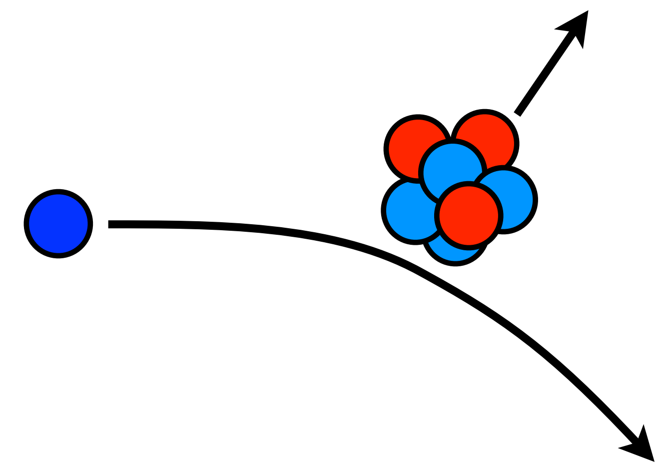


http://radioactivity.mext.go.jp/ja/1910/2011/11/1910_1125_2.pdf

^{137}Cs : 2.1 (μSv/h) / (MBq/m^2) …. calculation by IAEA

neutron reaction and activation

Elastic scattering of neutrons



Fast neutrons slow down by repeated **collision with nuclei.**
Each collision decreases the energy exponentially.

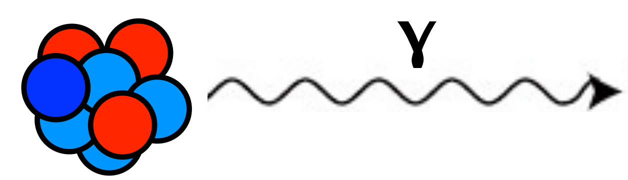
Neutrons are most **effectively decelerated** by collision **with protons** having the same mass.

Neutrons are effectively **shielded by water or concrete** containing hydrogen atoms.

Scattered nuclei such as protons (**charged** high-LET particles) **ionize** atoms & molecules.

Absorption of neutron and nuclear reaction

After having formed a nucleus with a mass number larger by unity, the formed unstable nucleus often emits e.g. a γ-ray, leaving radioactive nuclide, thus resulting in **activation.**



Activation 放射化

For non-radioactive materials to **obtain radioactivity by irradiation of radiation**.

Radioactive nuclides can be created via nuclear reactions by **neutrons,** or by **γ-rays with energies over 10 MeV**.

β-rays or γ-rays from radioisotopes nor X-rays from atoms can cause activation.

Be careful with activation in radiation control areas such as accelerator facilities and nuclear reactors.

Radiation chemistry
放射線化学

Number of ionizations (electron-ion pairs) per unit length = **Specific ionization**

Stopping power / Specific ionization = *W*-value

***W*-value** : Average energy required to produce 1 ion pair.

Does not depend on species or energy of charged particles.

Value larger than the ionization energy (due to loss by excitation).

***W* ~ 30 eV** not depending on the material.

***G*-value** : radiation chemical yield :

The G value refers to the number of molecules of reactant consumed or product formed per 100 eV of energy absorbed.
Normally the number is up to 10, but it can sometimes be huge in the case of a chain reaction.

Elementary reactions induced by radiation (selected)

$AB \rightsquigarrow AB^{+} + e^{-}$	ionization
$AB \rightsquigarrow AB^{*}$	excitaion
$AB^{+} + e^{-} \rightarrow AB^{*}$	recombination
$AB^{*} \rightarrow A\cdot + B\cdot$	formation of radicals

Reactions in water

$H_2O \rightsquigarrow H_2O^{+}\cdot + e^{-}$

$H_2O \rightsquigarrow H_2O^{*}$

$H_2O^{+}\cdot + H_2O \rightarrow H_3O^{+} + \cdot\mathbf{OH}$ **(hydroxyl radical)**

$e^{-} (+\, n\, H_2O) \rightarrow \mathbf{e^{-}_{aq}}$ **(hydrated electron)**

$H_2O^{*} \rightarrow H\cdot + \cdot OH$

$H_3O^{+} + e^{-}_{aq} \rightarrow \mathbf{H}\cdot + H_2O$ **(hydrogen radical)**

oxygen effect

$\mathbf{HO_2\cdot}$ **(hydroperoxyl radical)**

$\mathbf{O_2^{-}\cdot}$ **(superoxide anion)**

$\mathbf{H_2O_2}$ **(hydrogen peroxide)**

(active oxygen)

Reactions in water

radiation chemical yield
(G-value) by γ-ray.

$H_2O \rightsquigarrow H_2O^{+}\cdot + e^{-}$ ionization

$H_2O \rightsquigarrow H_2O^{*}$ excitation

$G(\cdot OH) = 2.7$
(hydroxyl radical)

$H_2O^{+}\cdot + H_2O \rightarrow H_3O^{+} + \mathbf{\cdot OH}$ ion-molecule reaction

$e^{-} (+ n\,H_2O) \rightarrow \mathbf{e^{-}_{aq}}$ **(hydrated electron)** production of hydrated electron

$G(e^{-}_{aq}) = 2.65$

$H_2O^{*} \rightarrow H\cdot + \cdot OH$ dissociation (production of radicals)

$H_3O^{+} + e^{-}_{aq} \rightarrow \mathbf{H\cdot} + H_2O$ electron capture

(hydrogen radical) $G(H\cdot) = 0.55$

$H_2O^{+} + e^{-} \rightarrow H_2O^{*}$ recombination

$\cdot OH + e^{-}_{aq} \rightarrow OH^{-}$ electron capture

$H_2O^{*} \rightarrow H_2O$ deexcitation

$H\cdot + H\cdot \rightarrow H_2$ $G(H_2) = 0.45$ production of molecule

$\cdot OH + \cdot OH \rightarrow H_2O_2$ $G(H_2O_2) = 0.7$ production of molecule

$H\cdot + \cdot OH \rightarrow H_2O$ production of molecule

oxygen effect

(active oxygen)

$H\cdot + O_2 \rightarrow$ **$HO_2\cdot$** (hydroperoxyl radical)

$O_2 + e^-_{aq} \rightarrow$ **$O_2^-\cdot$** (superoxide anion)

$\cdot OH$ (hydroxyl radical)

$O_2^-\cdot + H_2O \rightleftarrows HO_2\cdot + OH^-$

$HO_2\cdot + H\cdot \rightarrow$ **H_2O_2** (hydrogen peroxide)

radiation chemical reactions of organic compounds

$RH \rightsquigarrow RH^+ + e^-$

$RH \rightsquigarrow RH^*$

$RH^+ + e^- \rightarrow RH$

$RH^* \rightarrow R\cdot + H\cdot$

$RH + H\cdot \rightarrow RH_2\cdot \ / \ R\cdot + H_2$

$RH + \cdot OH \rightarrow RHOH\cdot \ / \ R\cdot + H_2O$

$RH + HO_2\cdot \rightarrow R\cdot + H_2O_2$

radioprotector (radical scavenger)

SH group, S-S bond

e.g. cysteine, cysteamine

(glutathione)

$G\text{-}S{:}H + H\cdot \rightarrow G\text{-}S\cdot + H_2$

$G\text{-}S{:}H + R\cdot \rightarrow G\text{-}S\cdot + RH$

$G\text{-}S\cdot + G\text{-}S\cdot \rightarrow G\text{-}S{:}S\text{-}G$

Graft polymerization by irradiation of e⁻ beam or γ-ray.

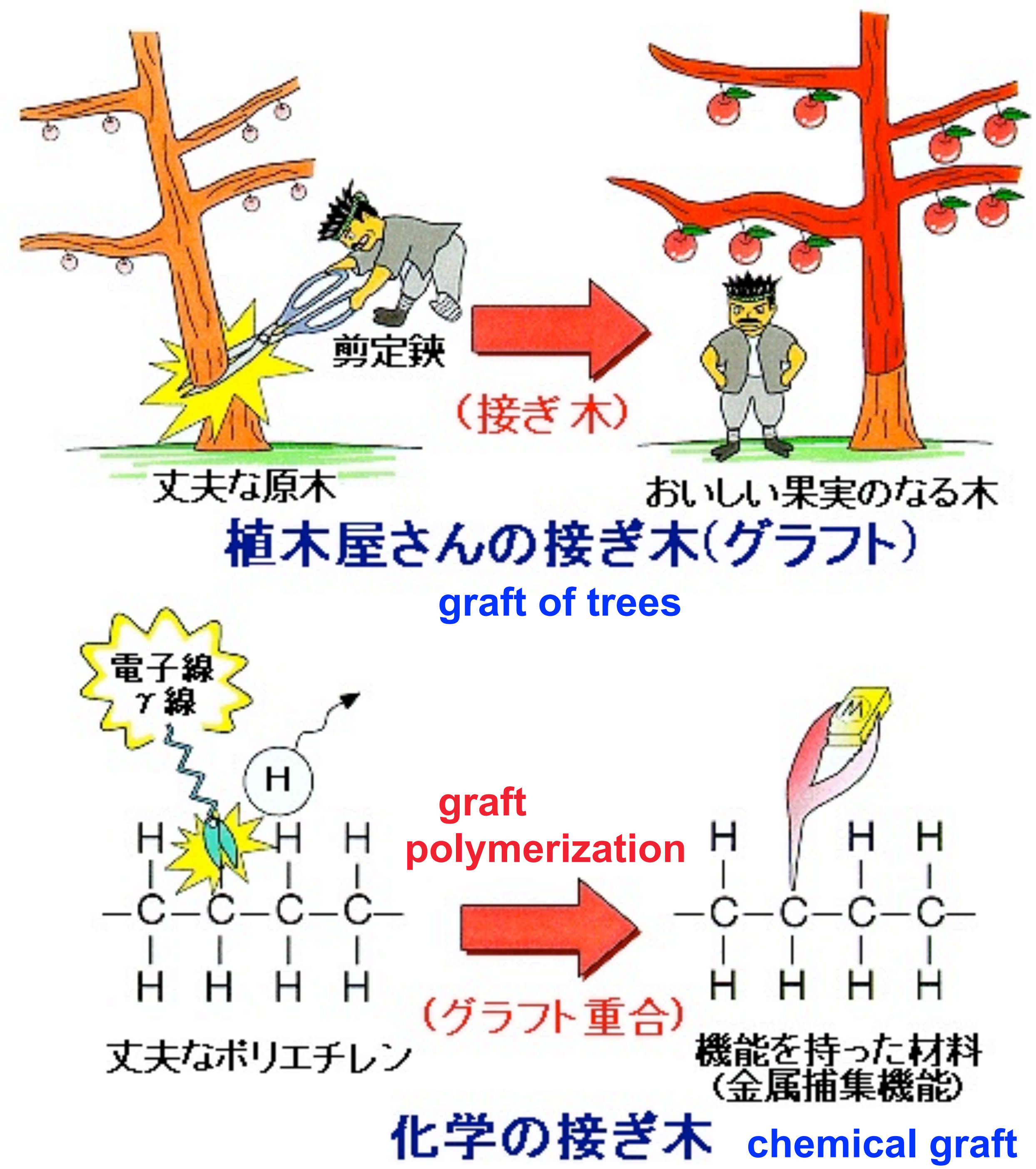


図1　接ぎ木の技術とグラフト重合

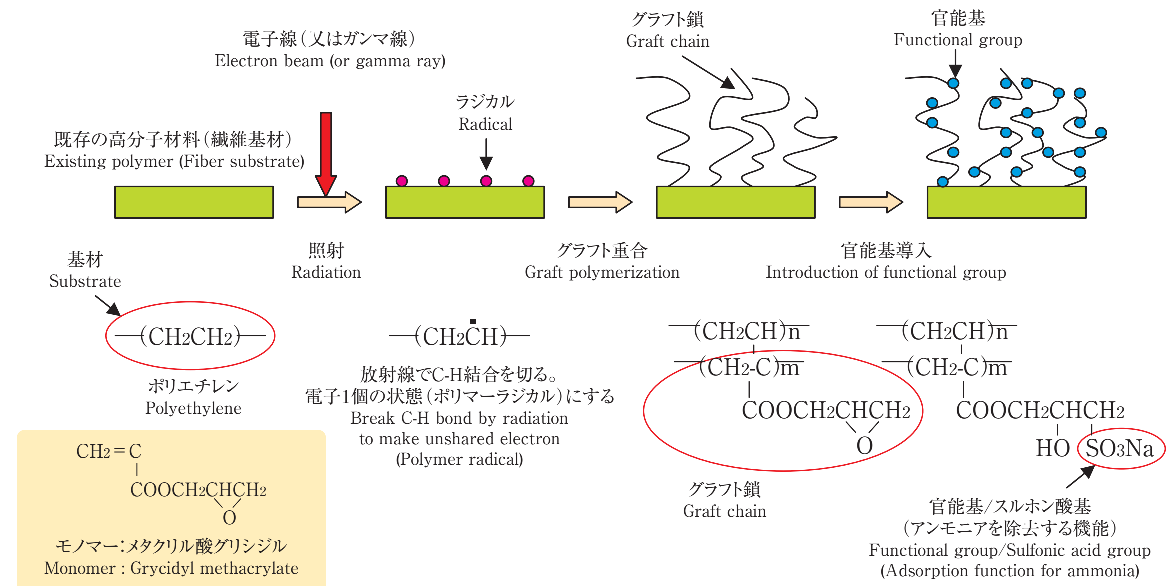


図1　放射線グラフト重合法によるイオン交換体の合成方法

Fig. 1　Reaction scheme of ion exchange material by radiation induced graft polymerization

エバラ時報 No. 216 (2007-7) 藤原邦夫氏論文より引用

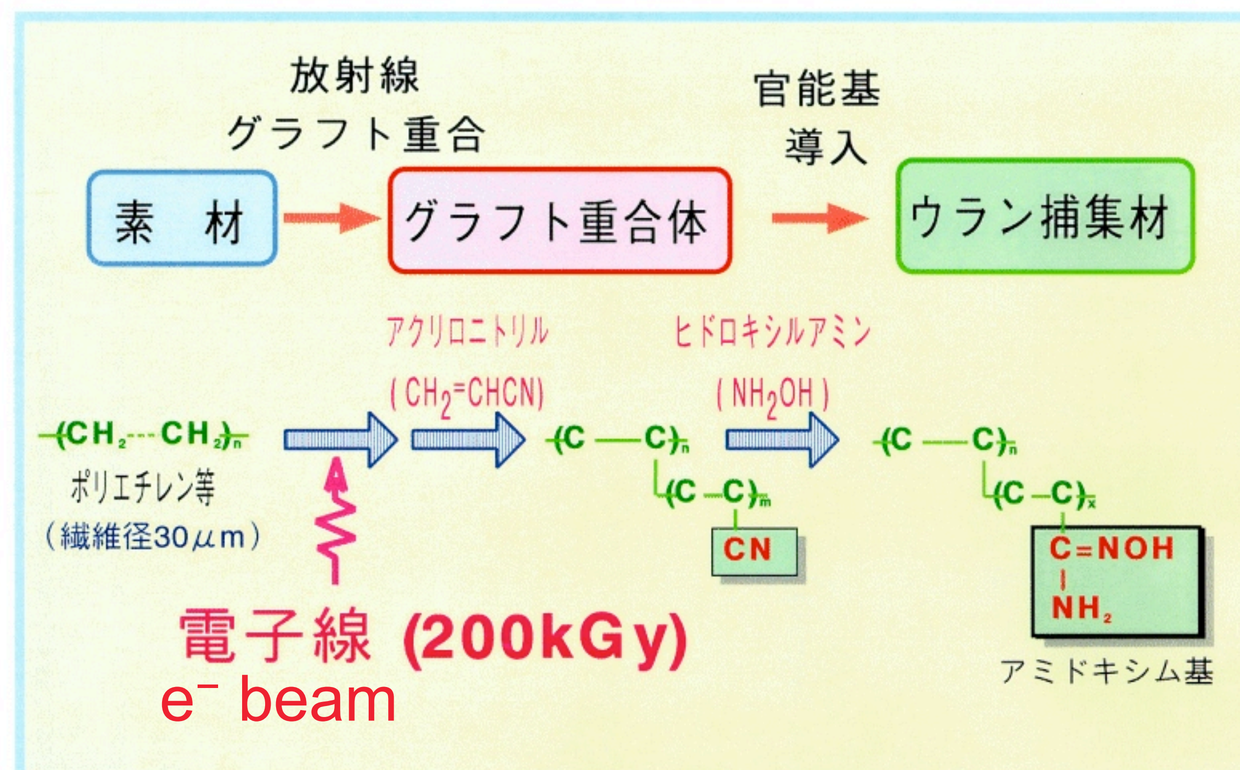


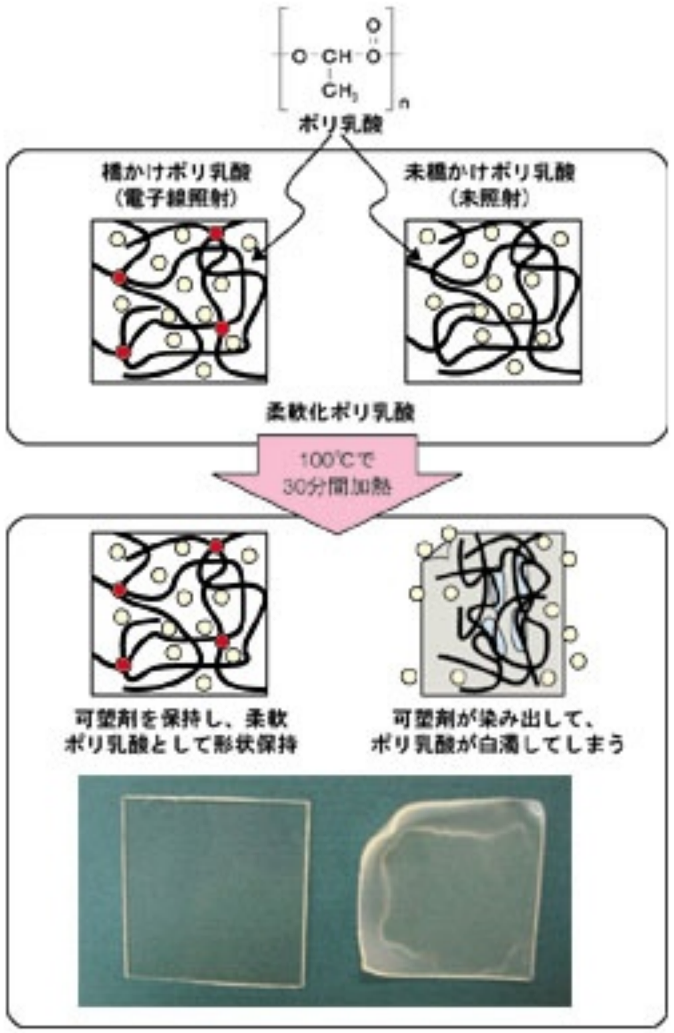
図2　放射線グラフト重合によるウラン捕集材の合成法

A braid adsorbent having the functional group of amidoxime is a promising material for the recovery of uranium.

[出典]片貝 秋雄、瀬古 典明、川上 尚志、斉藤 恭一、須郷 高信、原子力学会誌 40(11)、879(1998)

Synthesis of uranium-adsorbent by means of graft polymerization by irradiation of radiation.

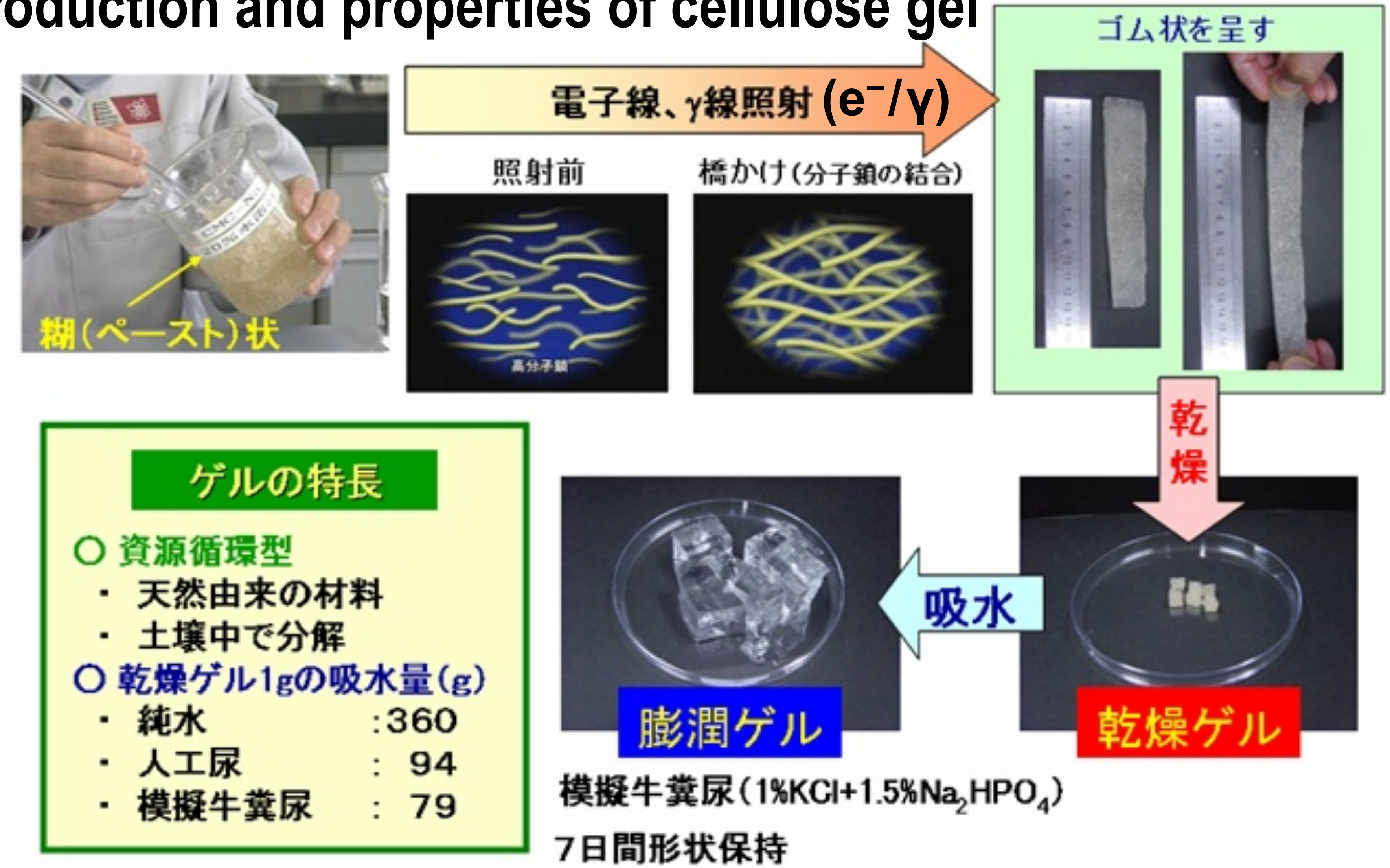
Radiation-induced cross-linking reaction



▲放射線橋かけ軟質ポリ乳酸の耐熱性

セルロースゲルの製法と性質

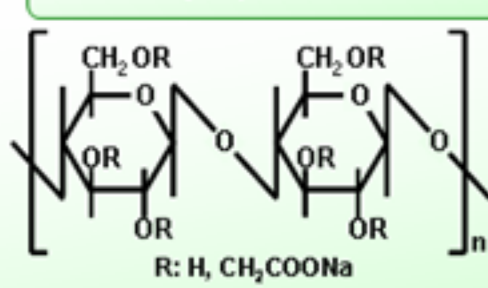
production and properties of cellulose gel



模擬牛糞尿(1%KCl+1.5%Na_2HPO_4)

7日間形状保持

カルボキシメチルセルロース(CMC)の特徴



- CMCは天然セルロースを原料として得られる水溶性高分子です。
- CMSは人体に無害で、緩やかな生分解性を有す、環境にやさしい素材です。
- CMCは食品、医薬品、化粧品から、繊維産業、窯業、建設業などの分野まで幅広く利用されています。

Application in industry

○ラジアルタイヤ、耐熱電線　radial tires

ラジアルタイヤは、有機繊維で補強されたゴムで高圧に耐えられる構造になっています。成形器で熱と圧力を加えてタイヤの形にしますが、この時、繊維補強ゴムは大きな変形を受け、補強繊維のずれやはみ出しがおきやすくなります。これを防ぐため、繊維補強ゴムに電子線を照射して強度を上げます。（市場規模：平成15年度１兆円）

また、電線の被覆に使われているゴムやプラスチックはそのまま熱を加えると溶けて流れ落ちます。電子線を照射すると熱を加えても溶けにくくなります。

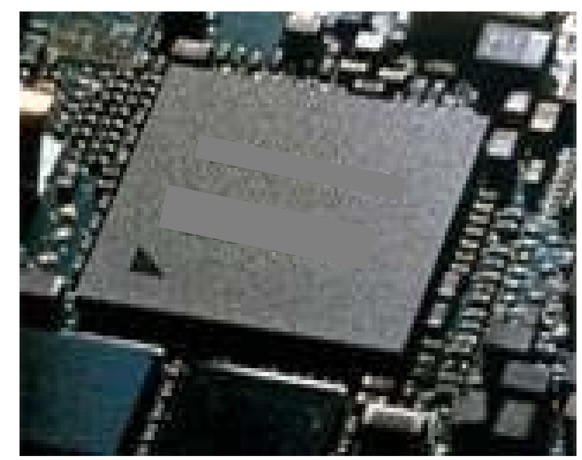
ラジアルタイヤ、耐熱電線

heat-resistant electric wires

○半導体　semiconductors

IC（集積回路）の回路のパターンの線は髪の毛の太さの50～100分の1であり、その細工をするためにリソグラフィといった技術が使われる。リソグラフィは版画の技術のようなもので、半導体表面に光や放射線を当てると化学変化する感光剤を塗り、加工したい形状に切り抜いた板（マスク）をのせて放射線を当てて、マスクの型どおりに加工するもの。イオンビームや中性子ビームを利用した不純物導入等も行っています。

（市場規模：平成15年度6.3兆円）

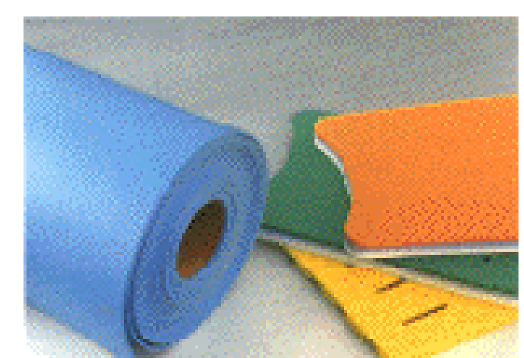


半導体

○発泡材料（緩衝材料、断熱材料）

お風呂場で使うバスマット、あるいはプールで使うビート板に使用されている発泡ポリエチレンをご存じですか。あの防水性、浮力が高く、ほどよく硬い素材 は、ポリエチレンに放射線を照射し、加熱することで内部に細かい気泡をつくりだしたもので、これもいまから20年以上も前に開発された素材です。

foamed materials



発泡ポリエチレン

原子力委員会 市民参加懇談会スライドより借用

Lecture slides

http://radphys4.c.u-tokyo.ac.jp/~torii/lecture/

東大　鳥居　放射線　講義

検索

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Fine. Per oggi è tutto.

Fini pour aujourd'hui

That’s all for today.

Всё за сегодня.

오늘은 이만 마치겠습니다.

今天就学到这儿了。

Ci vediamo la prossima settimana.

On se voit la semaine prochaine.

See you next week.

Увидимся на следующей неделе.

다음 주에 또 만납시다.

下周见。