東京大学理学部

Radiation Safety Course, School of Science, University of Tokyo

放射線取扱者講習会
(一般講習会)

光子の遮蔽と線量計算
加速器・放射光施設の安全利用
密封線源・エックス線装置の安全取扱

Shielding of Photons & Dose Calculation
Safety at Accelerator & Synchrotron Radiation Facilities
Safe Handling of Sealed Sources & X-ray devices

2021年度 前期

Spring 2021

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)

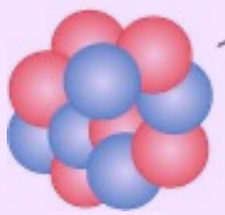
Speed of radiation

☞ **few～100% of light speed**

Nucleus N

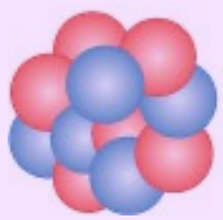
MeV order

high energy



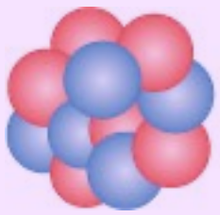
α ray : He nucleus

several MeV



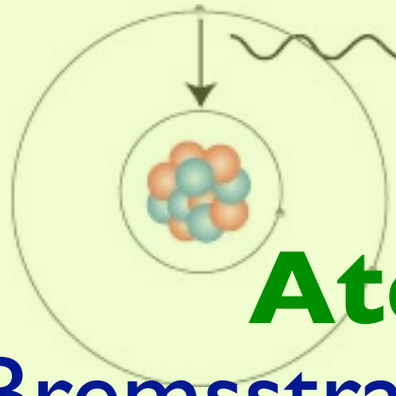
10 keV ～ MeV

β ray : electron at high speed



10 keV ～ MeV

γ ray : photon (EM wave)

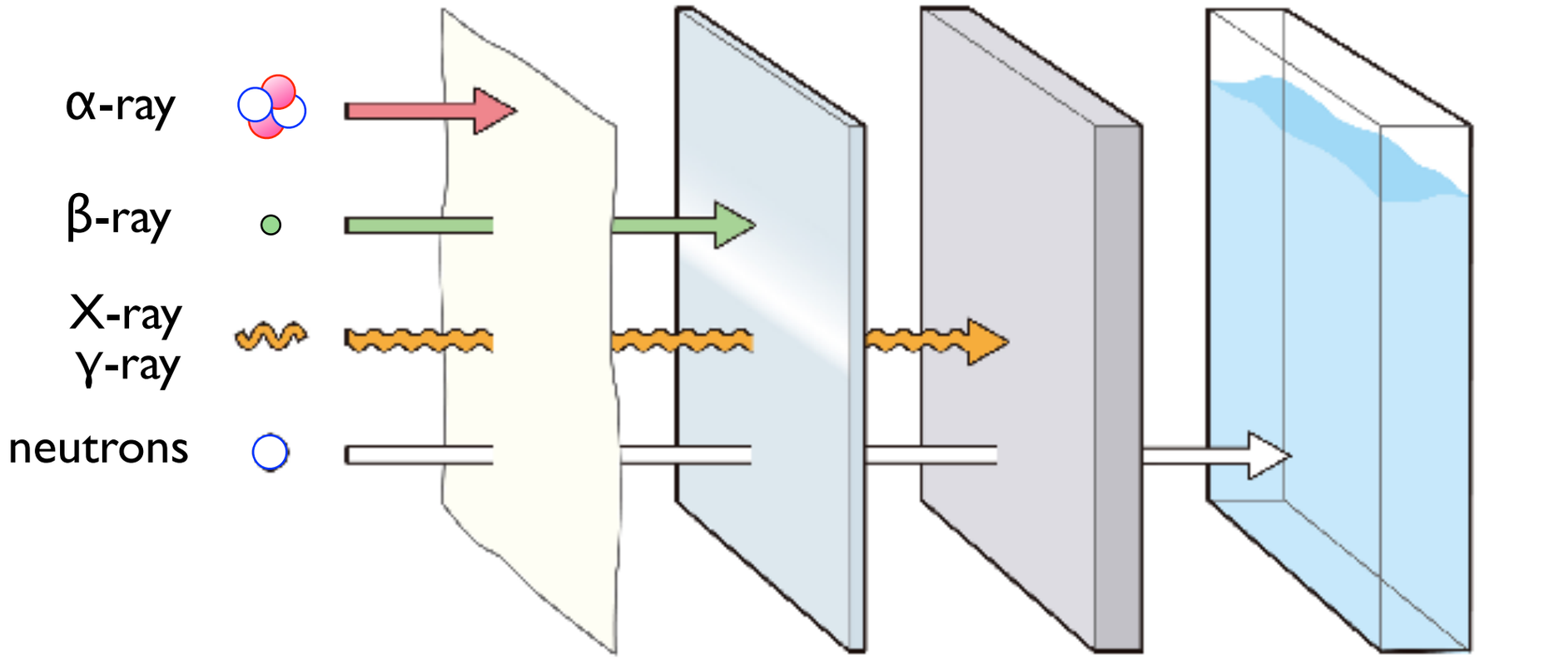


X ray : photon (EM wave)

Atom A **1 ～ 100 keV**

Bremsstrahlung ～ several **MeV**

Penetration of radiation



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**.
  The interior of the body are equally exposed to radiation even in the case of external exposure.
- **X-ray** (> 500 keV)**: analogous to γ-ray.**
  X-ray (< 50 keV)**: damage mainly to skin.**

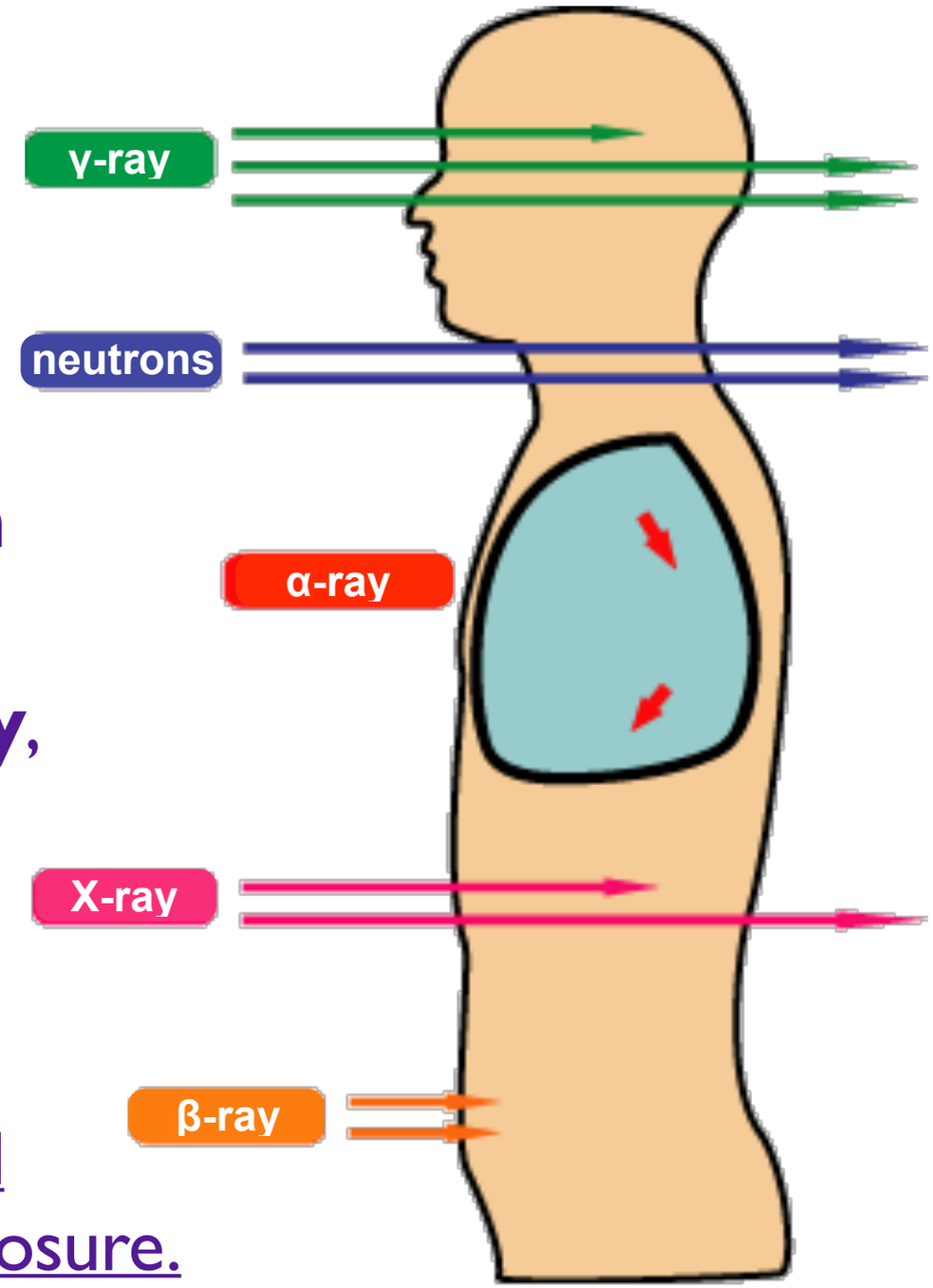


図３　人体を透過する放射線

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 = $-\left\langle \frac{\mathrm{d}E}{\mathrm{d}x} \right\rangle$

Attenuation of photons (X-ray, γ-ray)

光子の減衰（減弱）

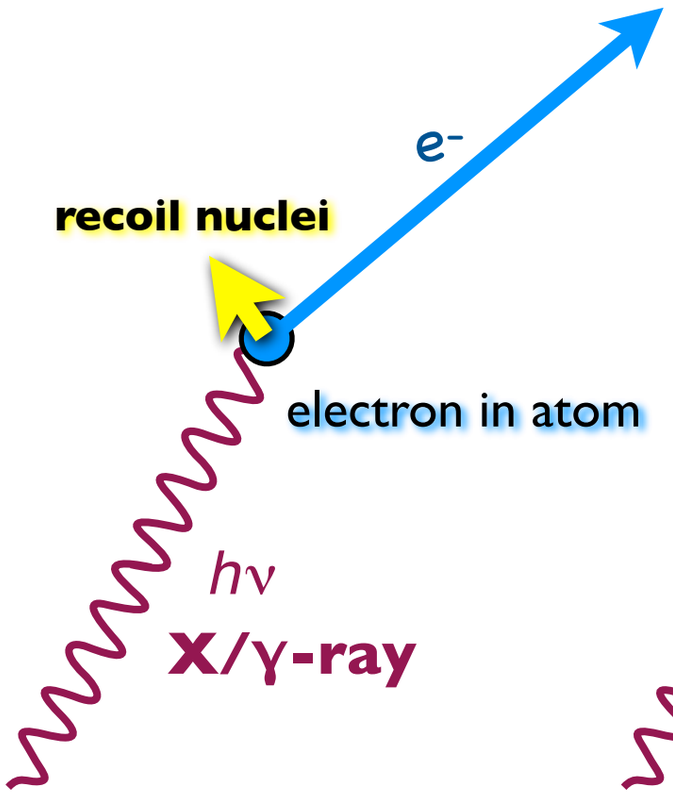
Photons are lost by stochastic processes of absorption or scattering, but the rest remain intact through.

☞ **Exponential decrease of photon number**

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

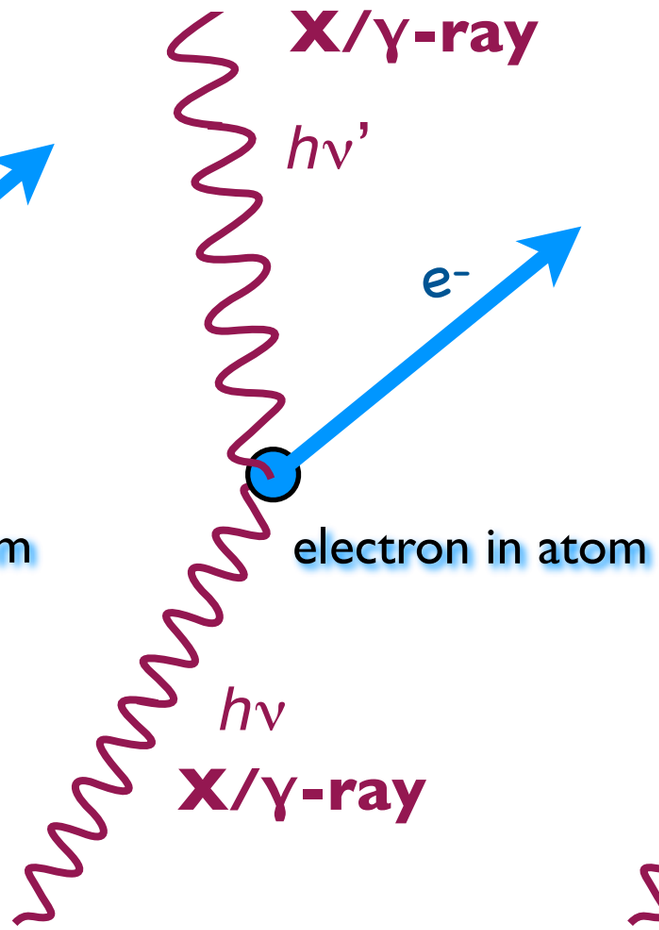
Interaction relating to photons (X-ray, γ-ray)

photoelectric effect 光電効果



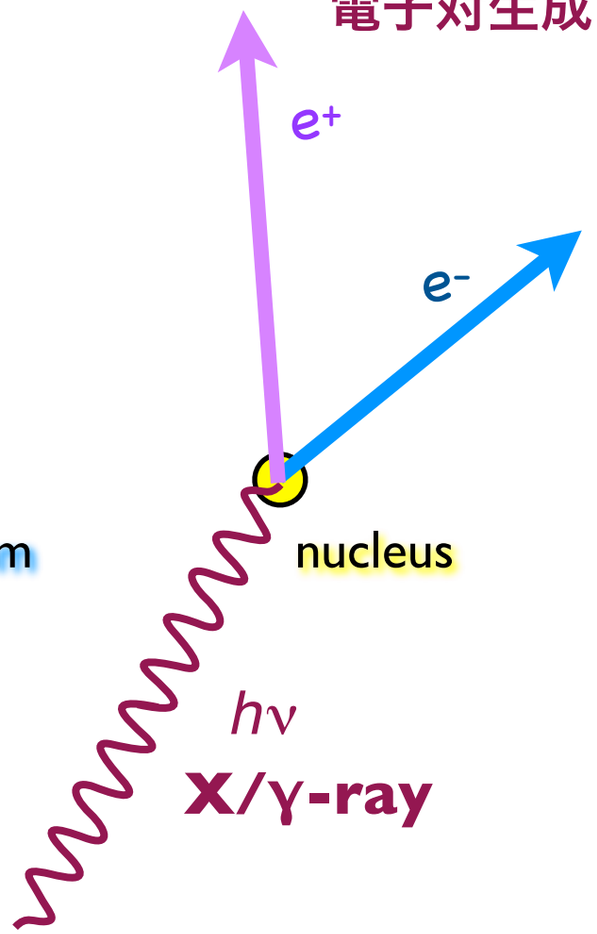
A photon kicks **one electron** out of an atom. The photon is absorbed.

Compton scattering コンプトン散乱



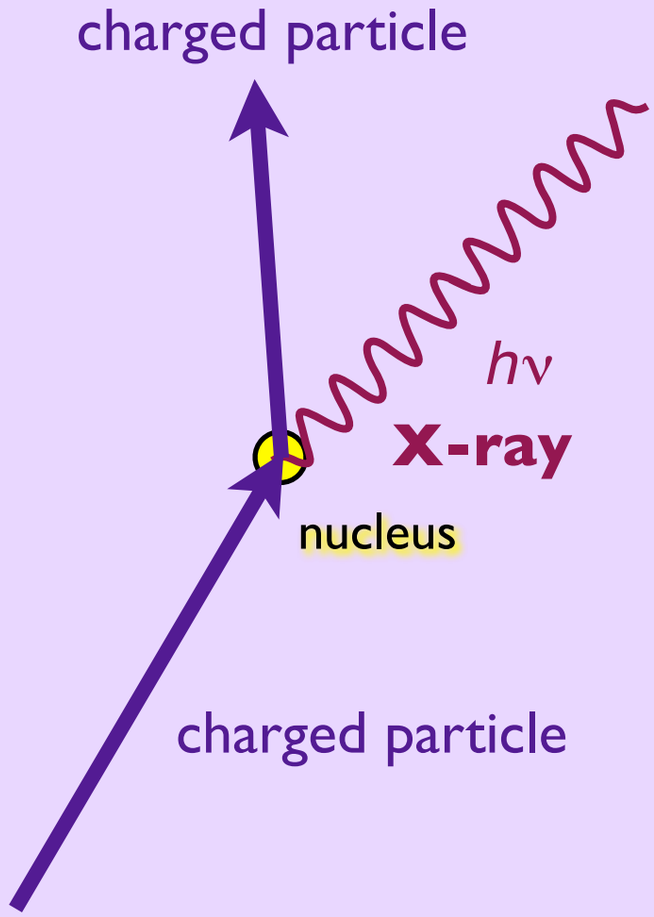
A photon is **scattered by one electron**. The photon loses a large fraction of its energy.

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 emits a photon when they are abruptly decelerated or when their trajectory is curved.

Generation of high-energy electrons (same particles as β-ray)

photon

reaction **cross section**

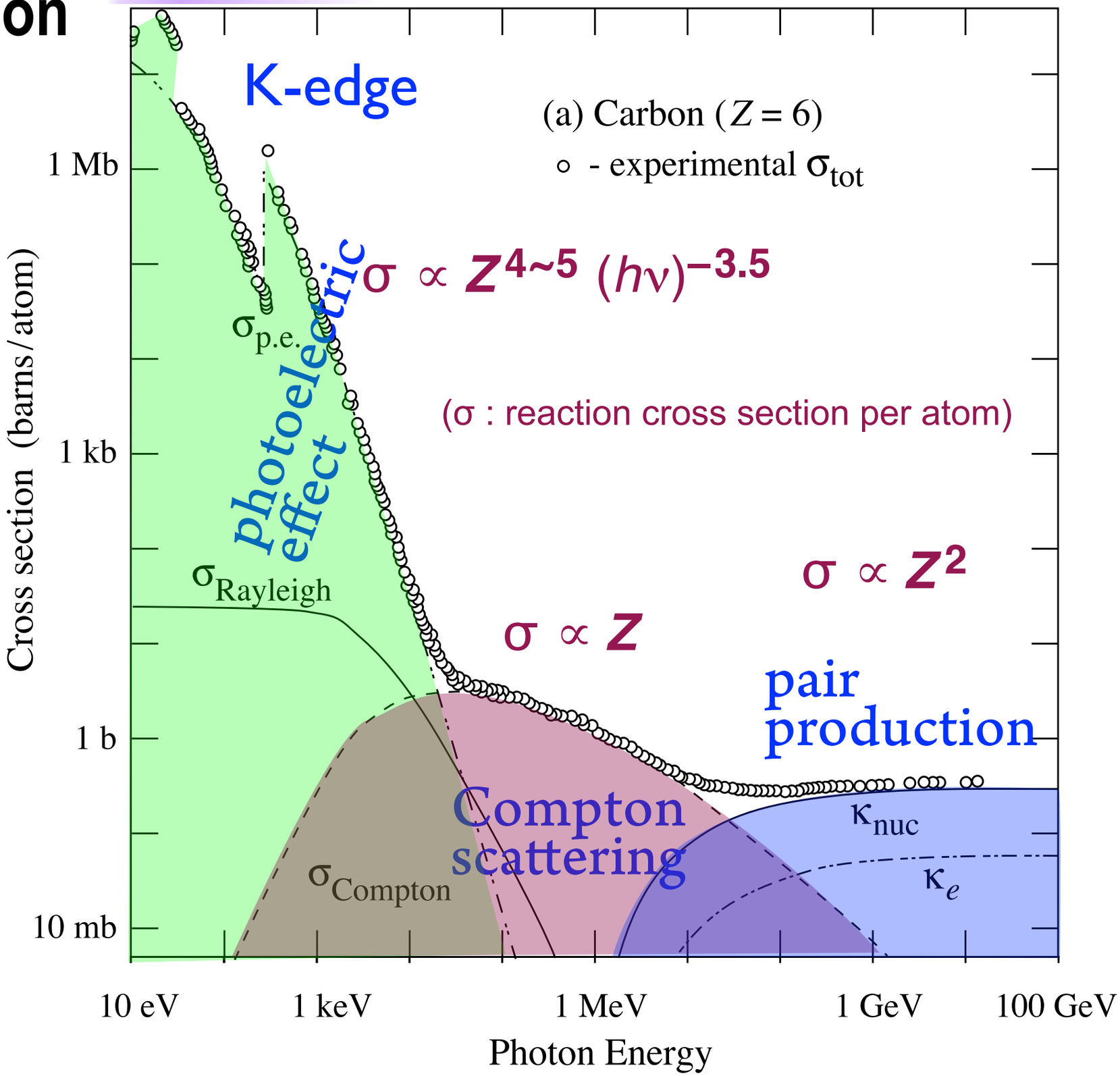
1 Mb
= (0.1 Å)²

1 Mb

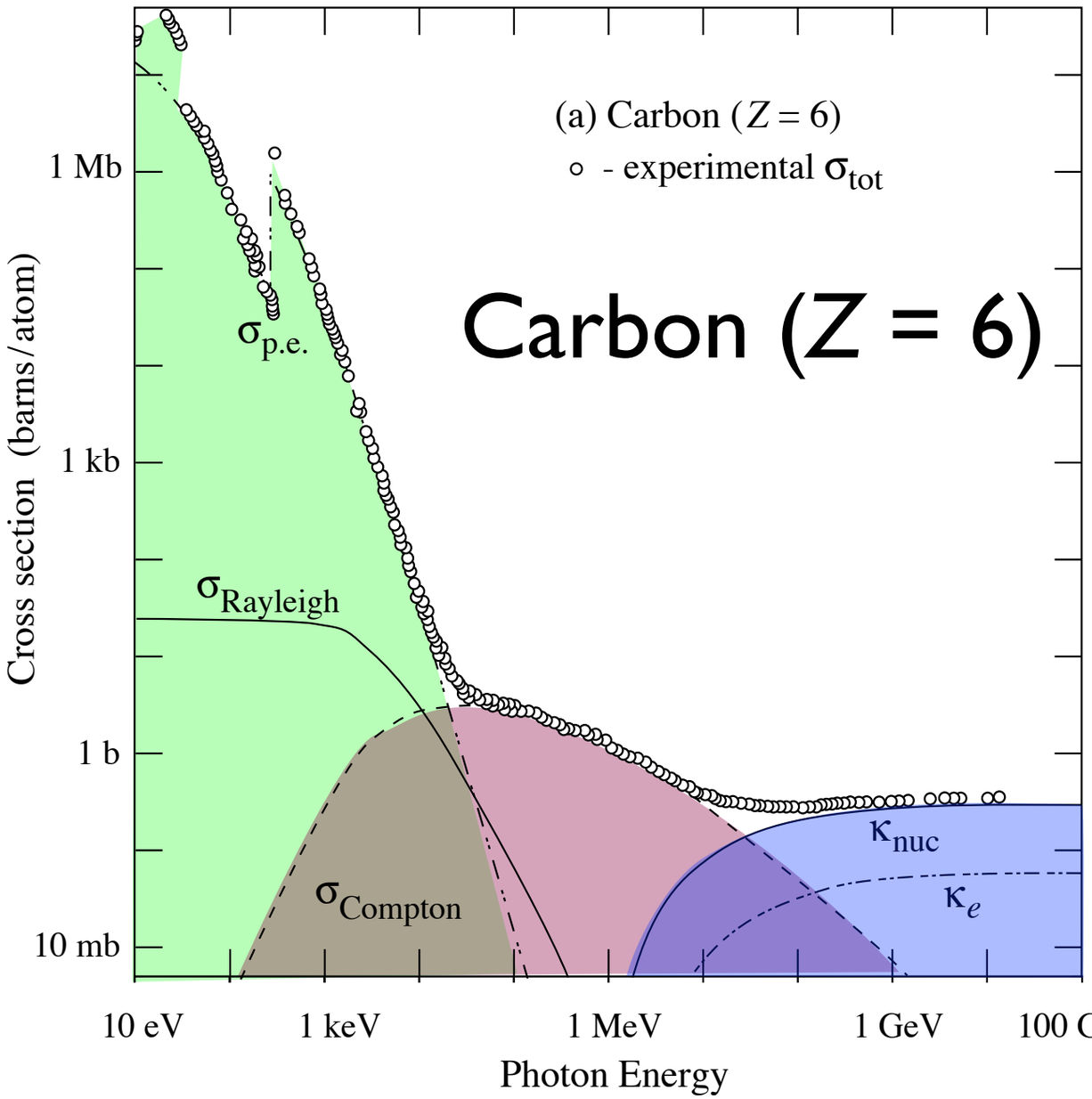
1 kb

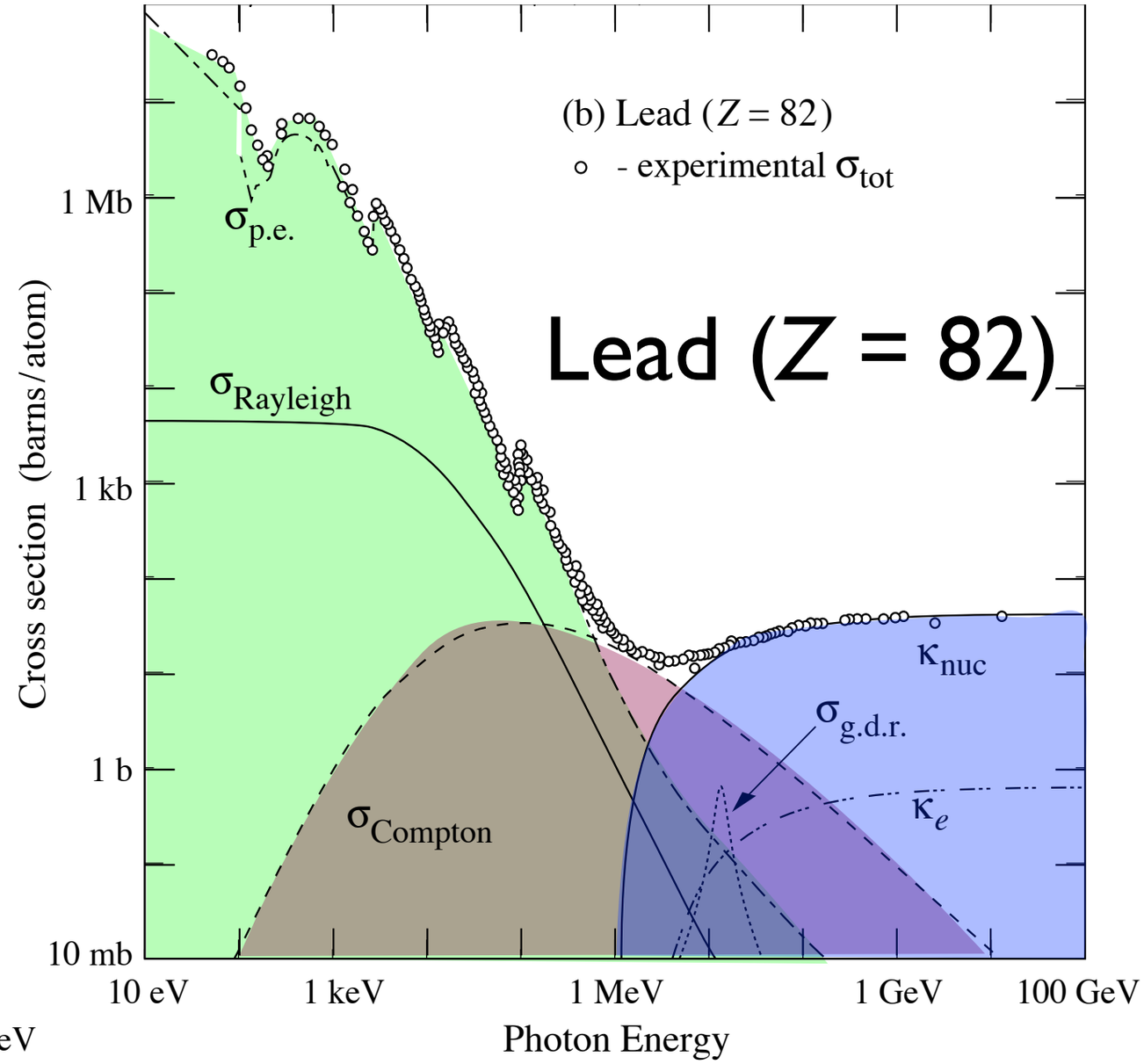
1 barn
= 10⁻²⁸ m²
= (10 fm)²

1 b



Material dependence of photon cross sections





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

Compton scattering $\propto Z$

pair production $\propto Z^2$

Röntgen radiography

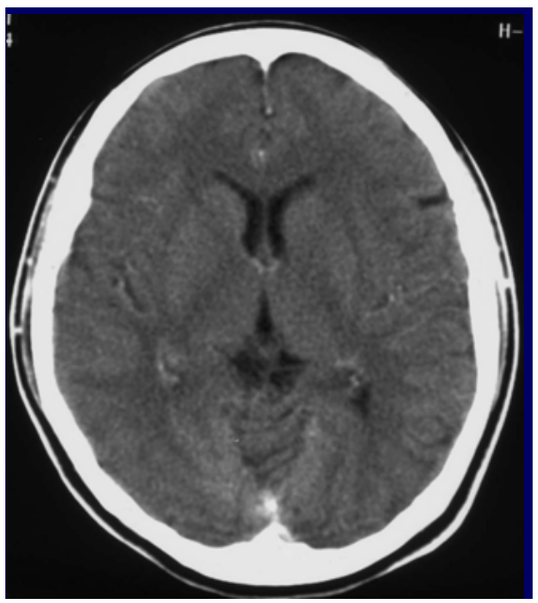
photographing using the difference in the absorption coefficient

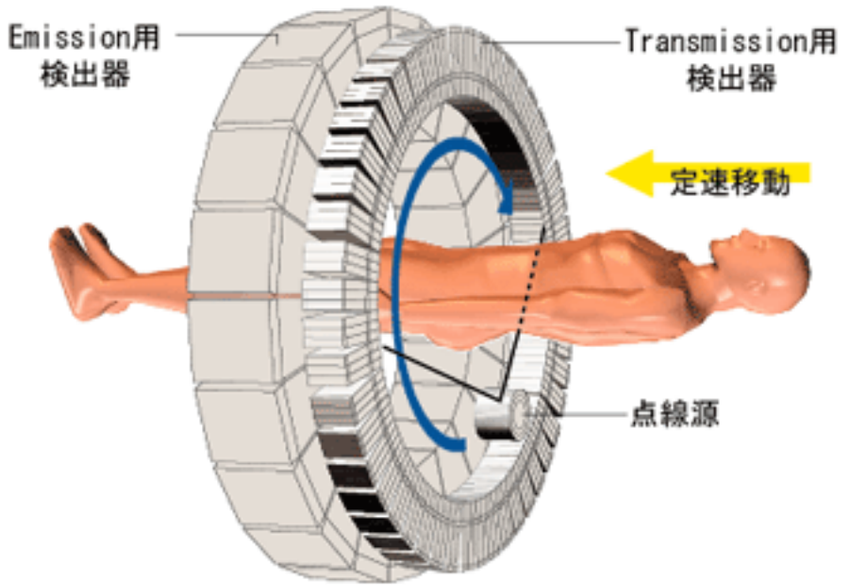
contrast media (**I, Ba, Xe**) : large ***Z*** **=** large attenuation

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

drastically larger cross sections for larger atomic number *Z* of the photoelectric effect and Compton scattering

X線 CT





X線検査用造影剤

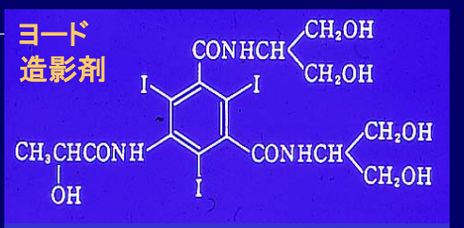
＊陽性造影剤	元素	原子番号	K吸収端
・ヨード造影剤：血管造影用	I	53	33.16 keV
・硫酸バリウム：消化管造影用	Ba	56	37.41 keV
・キセノン ガス（脳血流CT）	Xe	54	34.56 keV

＊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

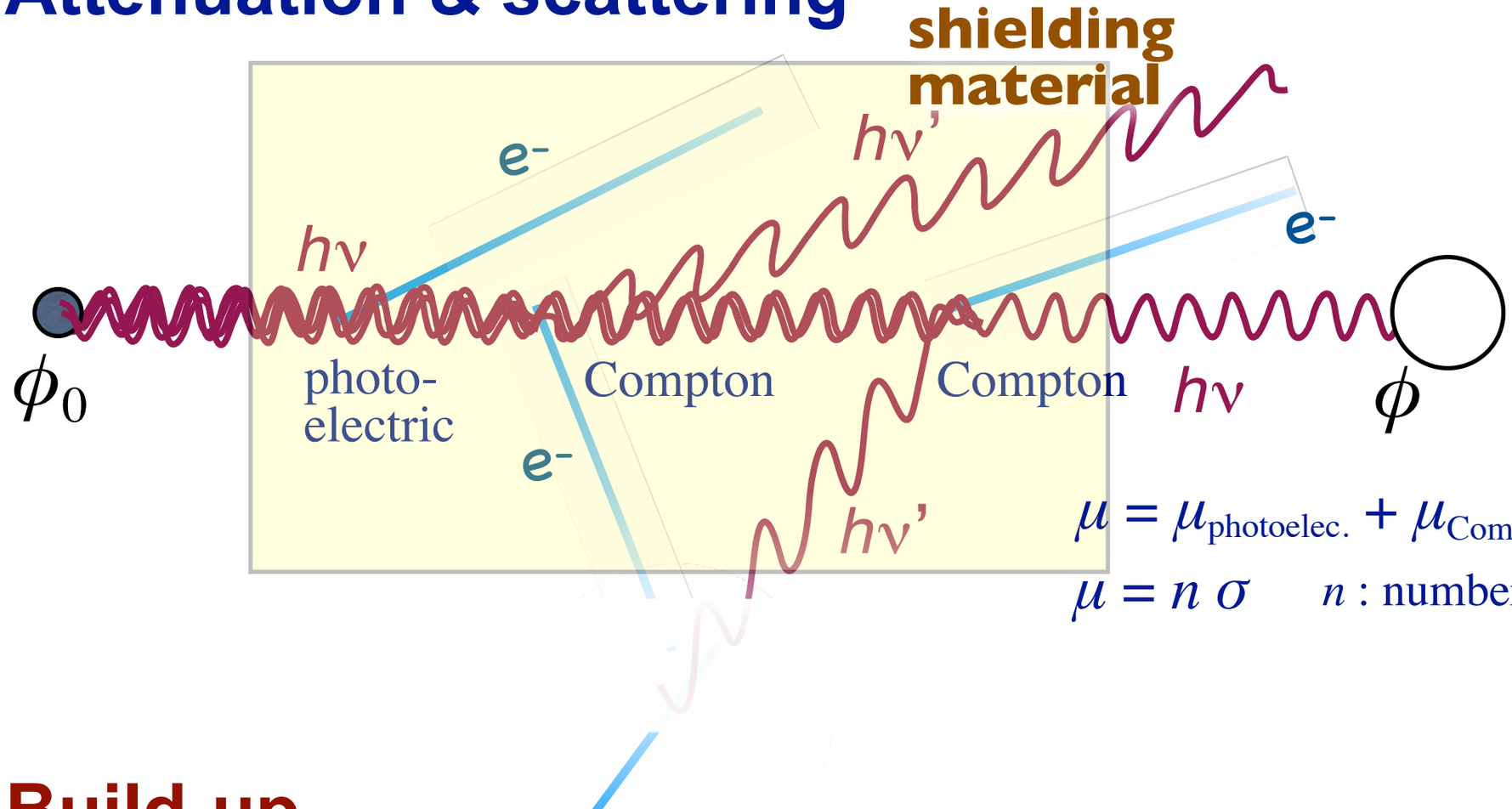
国立循環器病センター 内藤博昭先生のスライドより借用

Quiz #3

Choose the physical process which contributes most to the attenuation of **100 keV X-rays** in a shielding material of lead ?

- photoelectric effect
- Compton scattering
- pair production
- Rayleigh scattering

Attenuation & scattering



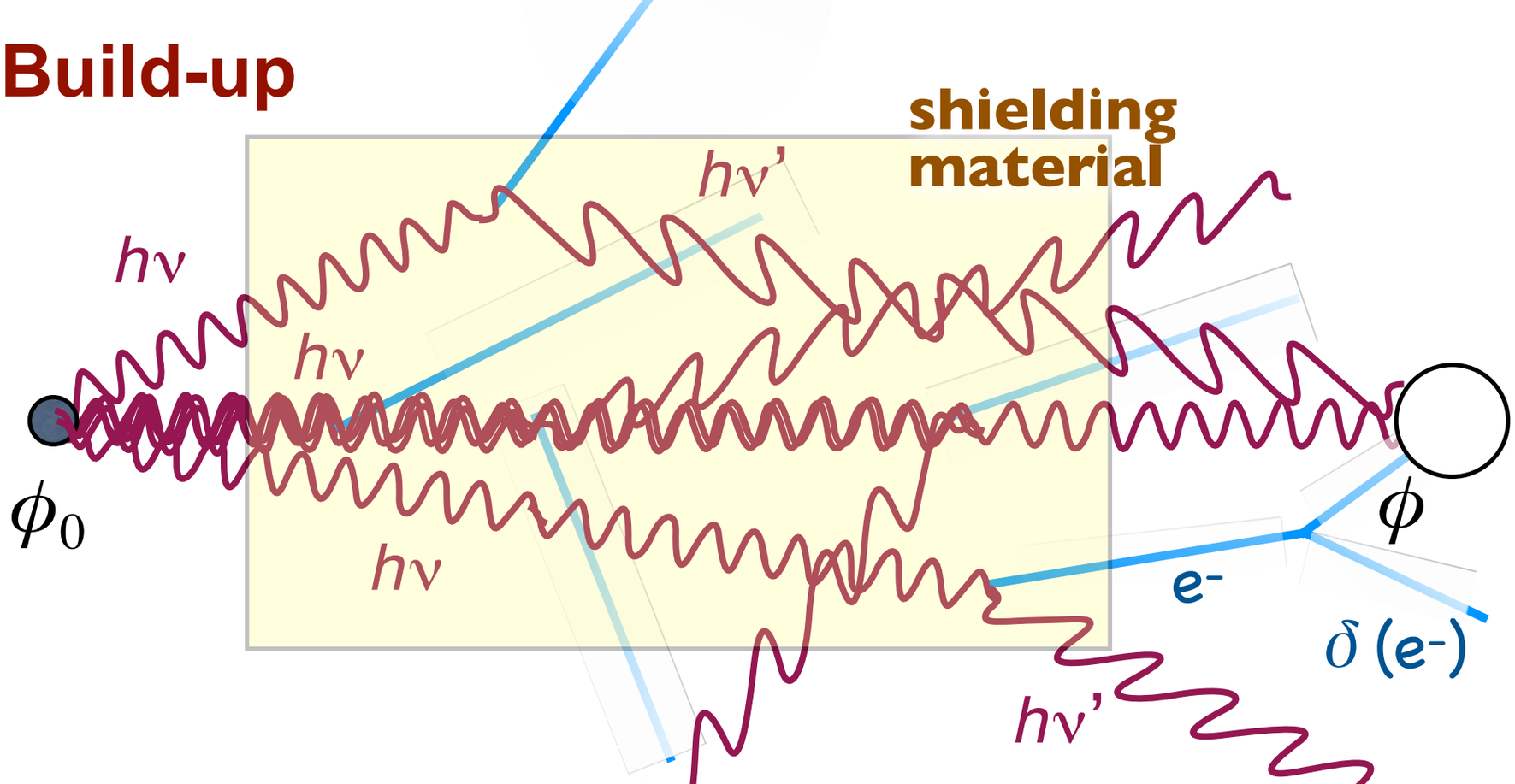
$$\phi = \phi_0 \, e^{-\mu x}$$

μ : linear attenuation coefficient

$$\mu = \mu_{\text{photoelec.}} + \mu_{\text{Compton}} + \mu_{\text{pair prod.}} + \cdots$$

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

Build-up

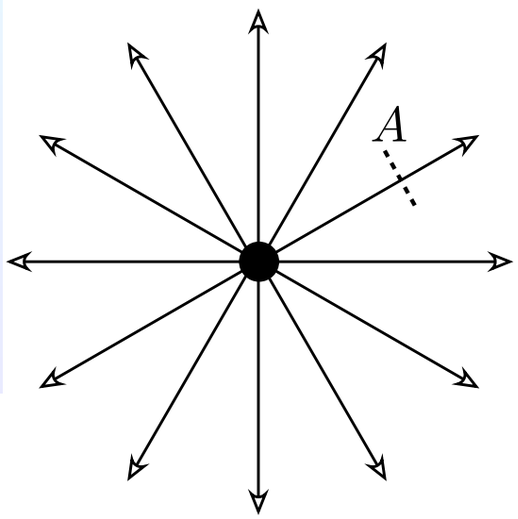


$$\phi = \phi_0 \, B \, e^{-\mu x}$$

B : Build-up coefficient

$B \sim 1.5$

Dose calc. for external exposure (γ-ray)



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

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

$\eta = 0.851$

γ-ray emission probability

P : radioactivity [Bq]

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

$\mu^{air} = 0.0100\ m^{-1}$ linear attenuation coefficient for air

^{137}Cs γ-ray attenuates to half in 70 m in air.

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

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

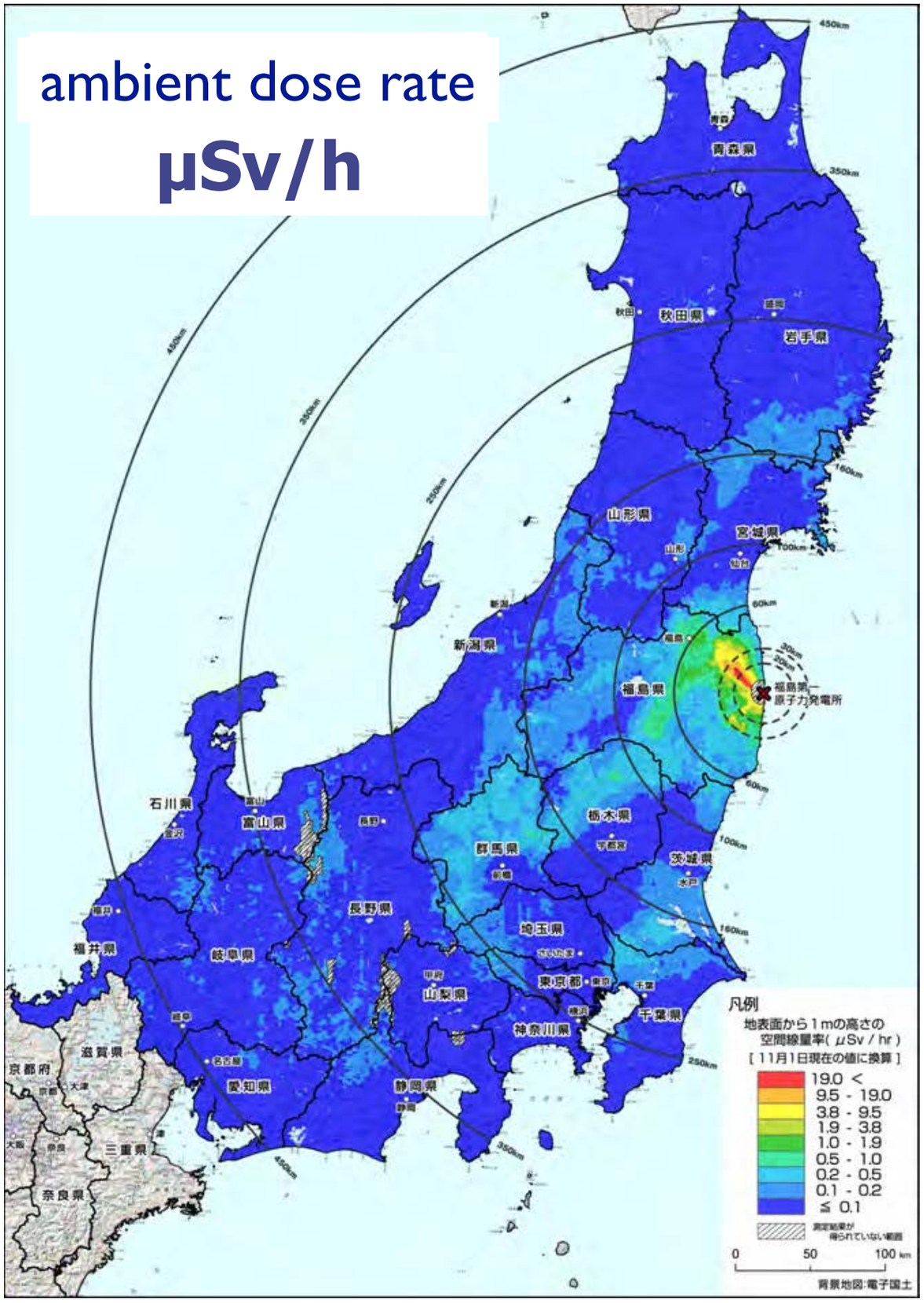
mass energy-absorption coefficient for water

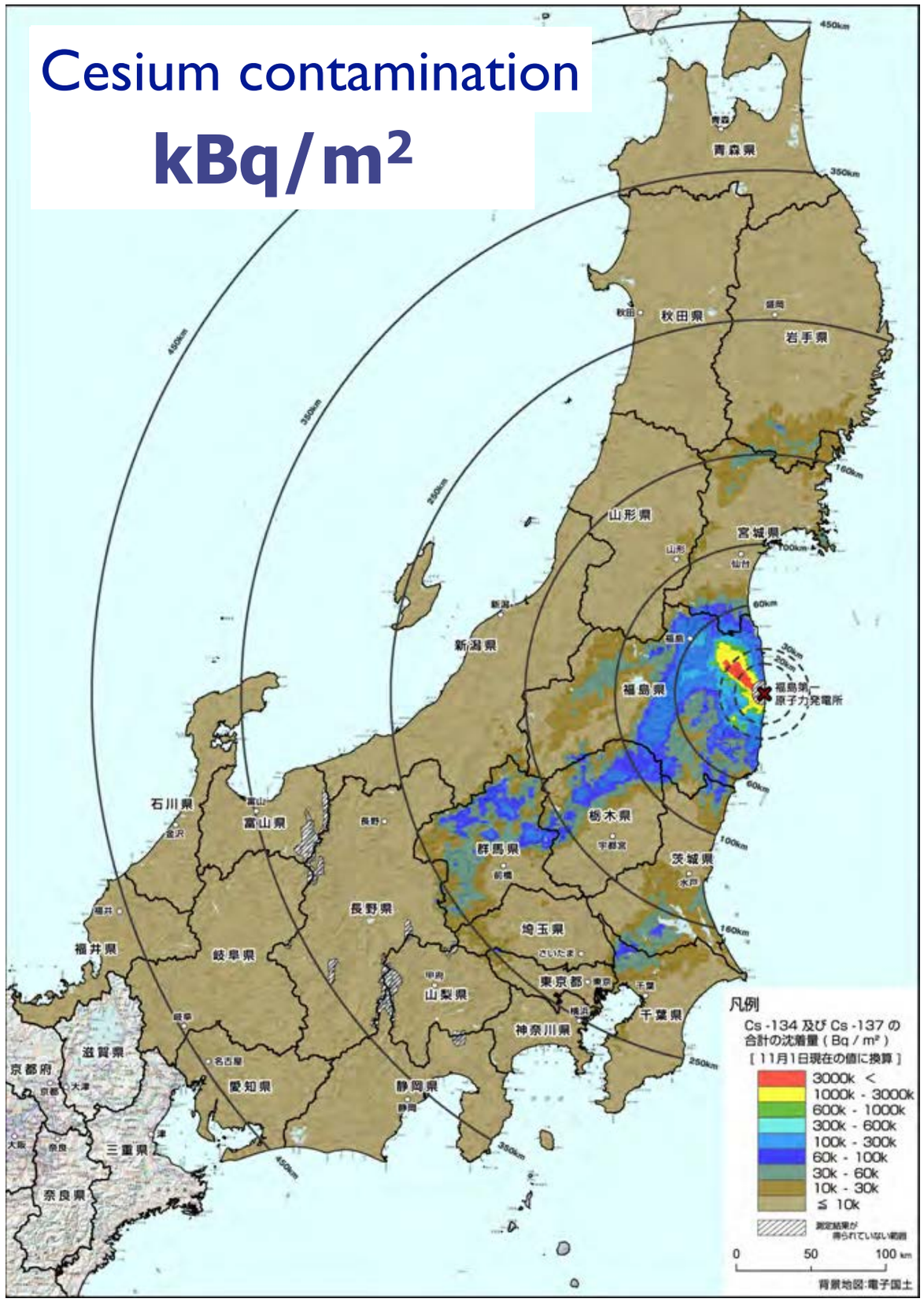
Case of soil contamination of uniform surface density :

^{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

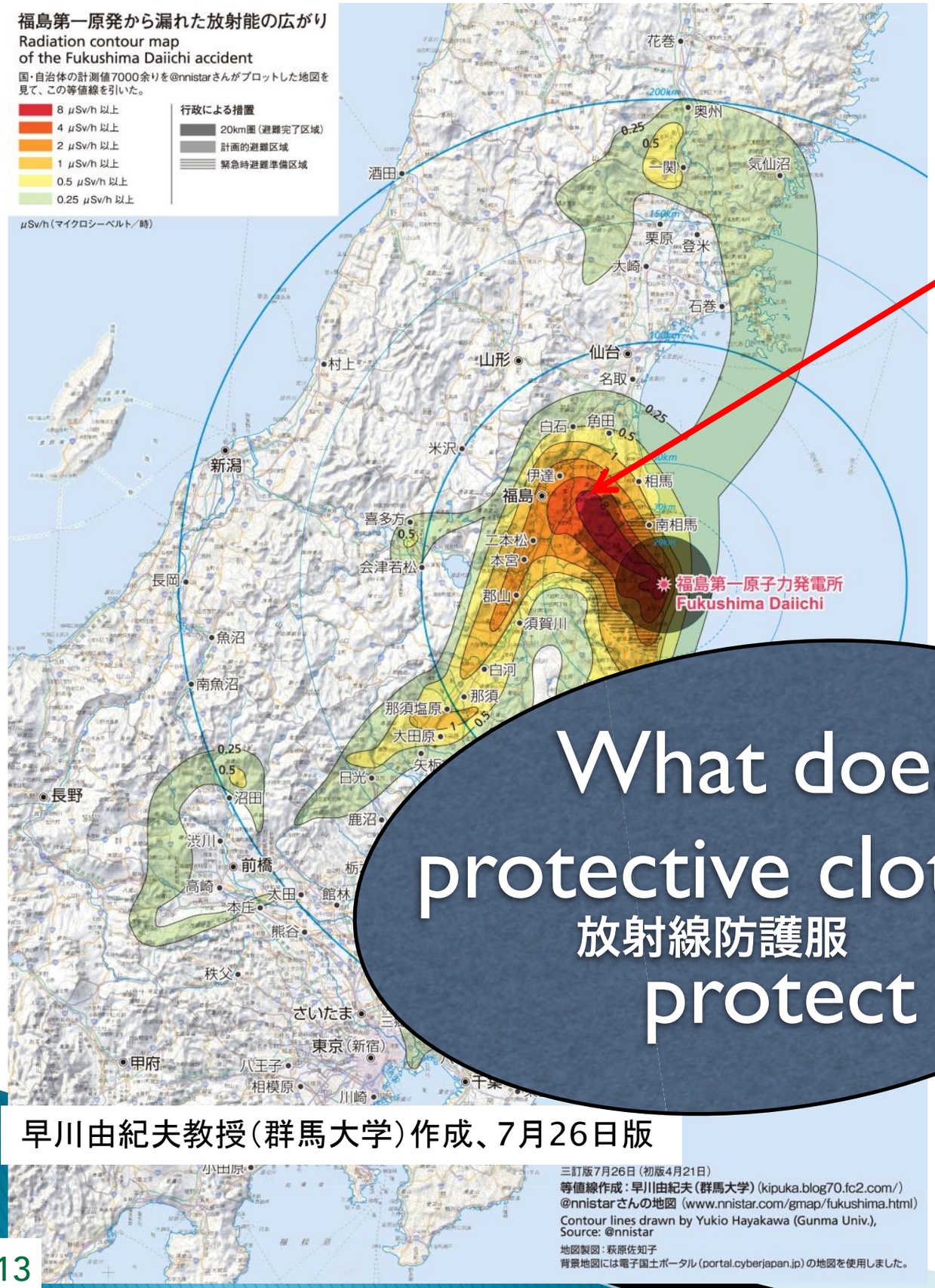




http://radioactivity.mext.go.jp/ja/1910/2011/11/1910_1125_2.pdf

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

Radioactive contamination map



What does protective clothing 放射線防護服 protect ?

早川由紀夫教授（群馬大学）作成、7月26日版

Calc. of internal exposure　e.g. Exposure to thyroid by I-133

放射線防護のための線量 protection quantity

預託線量 committed dose (internal exposure) [Sv]

内部被曝

預託等価線量
committed equivalent dose

預託実効線量
committed effective dose

Sum of calculated dose over the coming 50 years (or dose until the age 70 for children and infants).

Effective dose coefficient

(for adults)

isotope	half life	ingestion (Sv/Bq)	inhalation (Sv/Bq)
C-14	5730 yr	5.8×10^{-10}	5.8×10^{-9}
P-32	14.3 d	2.4×10^{-9}	3.4×10^{-9}
K-40	1.28×10^{9} yr	6.2×10^{-9}	2.1×10^{-9}
I-131	8.04 d	2.2×10^{-8}	7.4×10^{-9}
Sr-90	29.1 yr	2.8×10^{-8}	1.6×10^{-7}
Cs-137	30.0 yr	1.3×10^{-8}	3.9×10^{-8}

ingestion	baby (3 mo)	infant (1 yr)	child (2-7 yr)	adult
I-131	1.8×10^{-7}	1.8×10^{-7}	1.0×10^{-7}	2.2×10^{-8}

Dosimeters (personal / environment monitoring)

Fricke dosimeter フリッケ線量計

Fe^{2+} + radiation → Fe^{3+}, absorbance measurement

thermoluminescence dosimeter (TLD) 熱ルミネッセンス線量計

Fluorite or other crystal + radiation → (heating) → fluorescence

蛍石

Electrons / holes are captured in lattice defects.

glass badge (RPL: radio-photoluminescence) 蛍光ガラス線量計

Ag^{+}-activated Phosphate Glass + radiation → (UV) → fluorescence

$Ag^{+} \rightarrow Ag^{0}, Ag^{++}$ production of color centers

ガラス線量計

glass dosimeter : cobalt glass → color center (colored)

OSL Luxel badge ®

optically stimulated luminescence (OSL) badge

光刺激ルミネッセンス線量計

ポケット線量計

pocket dosimeter : ioniz. chamber / semiconductor detector

film badge フィルムバッジ : Silver halide film AgBr

他機関施設でのバッジの使用（加速器・放射光など）

Using Your Radiation Badge (at accelerators, SR facilities)

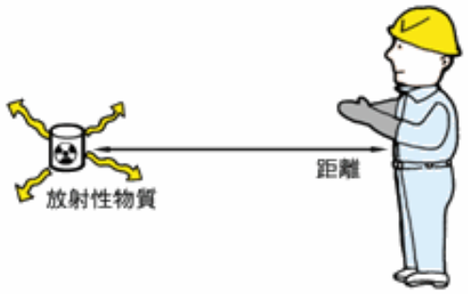
- 国内の放射線施設を利用する場合 **at domestic facilities**
  - 東大理学部のバッジも持参することを原則とする
    Bring your UTokyo-Sci. badge to domestic radiation facilities.
  - 飛行機での手荷物検査によるバッジの被曝に留意
    Try to avoid X-ray survey of your badge.

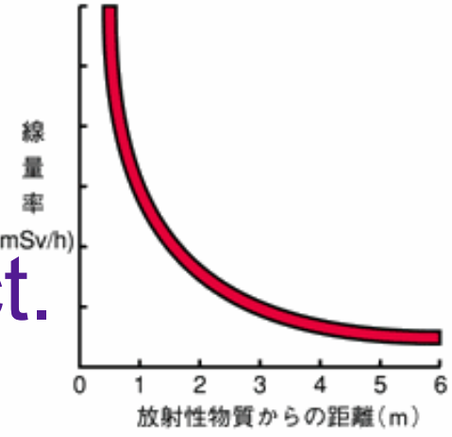
- 海外の放射線施設を利用する場合 **abroad**
  - 特に不要であれば、東大理学部のバッジは
    むしろ持参しないことを推奨する
    We recommend that you do not bring your badges abroad,
    As long as the facility abroad takes care of your radiation protection.
  - 持参する必要がある場合、手荷物検査や機内での被曝については、後から記録の修正が必要な場合がある
    If you need to bring it abroad, give us reports on possible radiation exposure of your badge at X-ray survey and during your flights.

Radiation protection

- **distance**

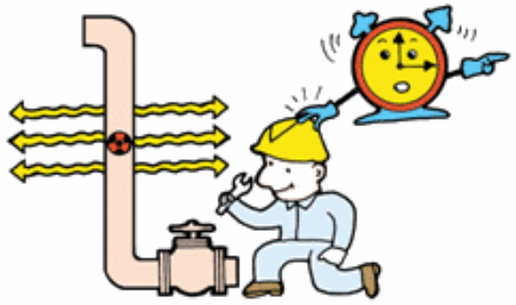
〔線量率〕＝〔距離〕^{2}に反比例

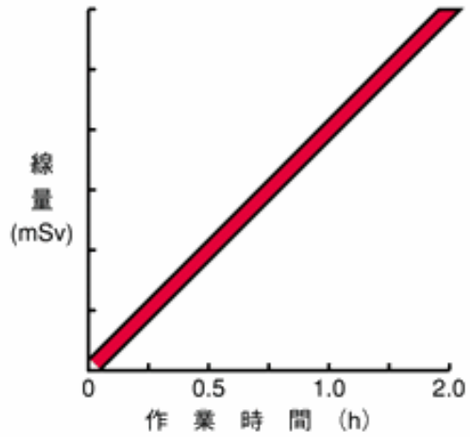




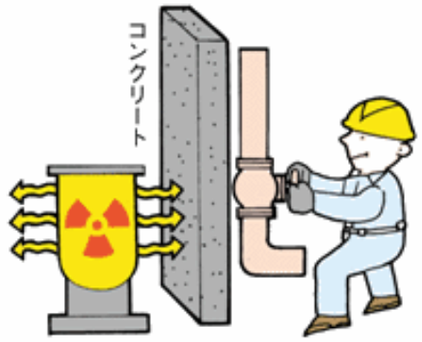
- **time**

〔線量〕＝〔作業場所の線量率〕×〔作業時間〕





- **shielding**



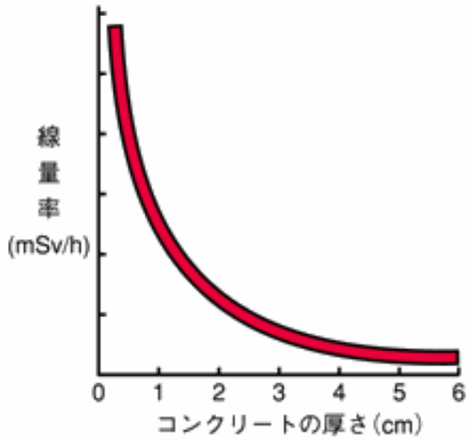


図1　遮へい3原則の図

［出典］電気事業連合会：「原子力・エネルギー」図面集2003−2004、p.130

Prevent deterministic effect.

Reduce stochastic effect.

Optimization : all exposures shall be kept as low as reasonably achievable, economic and social factors being taken into account.

（**ALARA** principle = As Low As *Reasonably Achievable*）

Dose limit : **1 mSv/yr** for general public (in addition to natural BG).

100 mSv/ 5 yrs and 50 mSv/yr max. for male radiation workers.

Dose limit for individuals

Occupational exposure for Radiation workers

Effective dose	100 mSv / 5 yrs and 50 mSv / yr
women	5 mSv / 3 mo.
pregnant women	1 mSv / period of pregnancy
Equivalent dose	(* from April 2021)
eye lens	100 mSv / 5 yrs and 50 mSv / yr
skin	500 mSv / yr
abdomen surface of pregnant women	2 mSv / period of pregnancy

Public exposure for General public

Effective dose	1 mSv / yr
Equivalent dose	
eye lens	—
skin	—

Protection by Jpn domestic law

線量限度の一覧表（作業者）

	1990勧告	1977勧告
実効線量	20mSv/年（5年平均）	50mSv/年
水晶体等価線量	150mSv/年	150mSv/年[2)]
皮膚等価線量	500mSv/年[1)]	500mSv/年
手・足の等価線量	500mSv/年	500mSv/年[3)]
その他の組織	—	500mSv/年

1）被ばく部位に関係なく，深さ7 mg/cm², 面積1 cm²の皮膚についての平均線量に適用される。

2）1980年のブライトン声明で300mSv（旧から45歳までの就業期間の被曝の場合で、65歳までのリスクの最大値）で適用された。

Annual Risk 1/1000 （18歳から65歳までの就業期間の被曝の場合で、65歳までのリスクの最大値）

線量限度の一覧表（一般公衆）

	1990 勧告	1977 勧告
実効線量	1 mSv/年	5 mSv/年[1)], 1 mSv/年（生涯の平均）
水晶体等価線量	15 mSv/年	50 mSv/年
皮膚等価線量	50 mSv/年[3)]	50 mSv/年
その他の組織	—	50 mSv/年[2)]

1）1985年のパリ声明で主たる限度を1年につき1 mSvとして、補助的な限度を5mSv/年とした。

2）1985年のパリ声明で実効線量当量の制限によって不要になった。

3）線量当量に関係なく、深さ7 mg/cm²の面積1 cm²の皮膚についての平均線量に適用される。

Annual Risk 1/10,000 （毎年被曝の場合、65歳までの最大値） ICRP recomm.

〔出典〕（1990年ICRP新勧告と1977年ICRP勧告における線量限度値対照表）
［「ICRP1990年勧告-その要点と考え方-」、草間朋子編、日刊工業新聞社、50ページ］

Radiation control area 放射線管理区域

H-20

Muon Blocker Controller

6501LP85

Blocker

OPEN

CLOSE

Key returned
Key locked
Blocker closed
Radiation

Pro-face

ON ON ON ON ON

扉開閉可

扉開

OPEN

扉閉

CLOSE

扉停止

STOP

DOOR CONTROLLER

6340LP02-3

D2−AREA

Door Operation

OFF

ON (LOCK)

Key Release

BEAM ON

非常停止ボタン

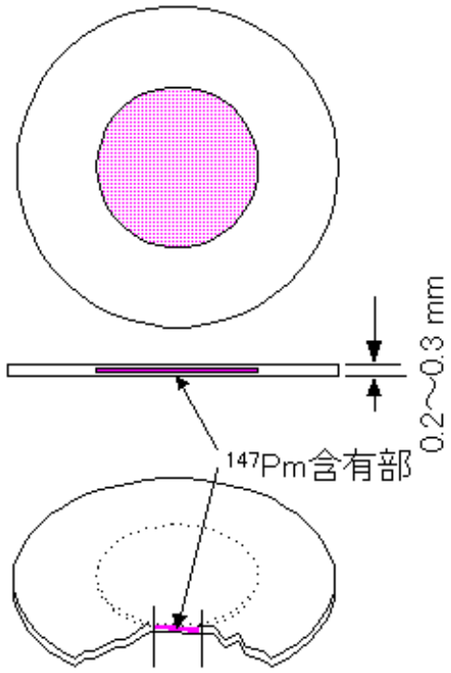
EMERGENCY STOP

H-21

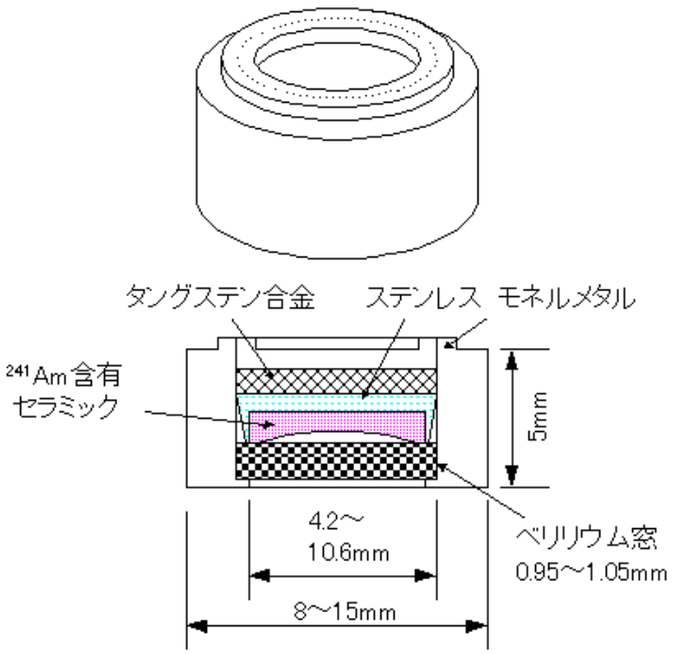
Sealed sources
密封小線源

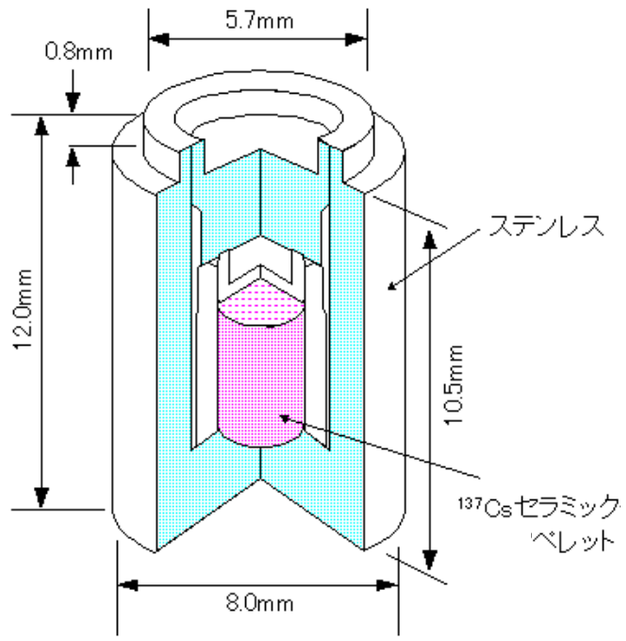
α-ray source

β-ray source



γ-ray source





Safe Usage of X-ray devices

エックス線装置の安全取扱

①X 線警告灯（黄色）
X 線の発生を防 X 線カバーの X 線警告灯の黄色 LED で表示します。

②防 X 線カバー（側面）
防 X 線カバーにより、ゴニオメータ等の光学系部が覆われています。

③防 X 線カバーの扉（インターロック） Interlock
前面パネルにロック機構が付いており、「DOOR」ボタン（黄色）が消灯している時は扉ロックが掛かり、防 X 線カバーは開けることができません。

④「DOOR」ボタン
防 X 線カバーを開ける時に使用します。

⑤HV ENABLE キー
キーを右に回し、装置ロックを解除し POWER ON を可能な状態にします。

東京大学における エックス線装置の分類

Classification of X-ray devices at UTokyo

密閉型 closed system	A	Completely sealed
	B	Interlock used all the time
非密閉型 non-closed system	C	Interlock used appropriately
	D	Equipments installed in a room
	E	Not fixed / mobile

エックス線装置の安全取扱

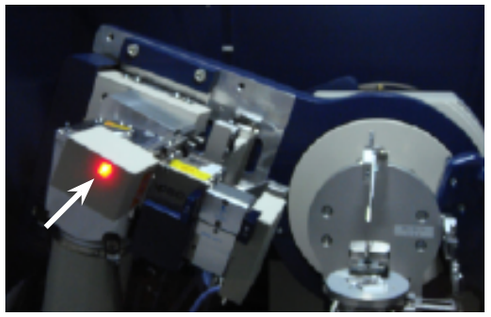


図２　シャッター付近の照射ランプ

図３　外部照射ランプ

図４　PC 上のシャッター状況

図５　装置制御板上の表示

Check open/close of the shutter with multiple indicators.

複数の表示で
シャッターの開閉状態を
意識して確認する。

Ｃ分類でインターロックを
解除するときは十二分に
確認する。

Be extremely careful when you unlock the interlock

ビームの調整やメンテナンス
等では、装置の電源を切り、
シャッターが閉じて
いることを確認する。

Turn off the power of the device before beam adjustment and/or maintenance.

使用記録を作成し、
整備すること。

Make records of usage

Safe Usage of X-ray devices

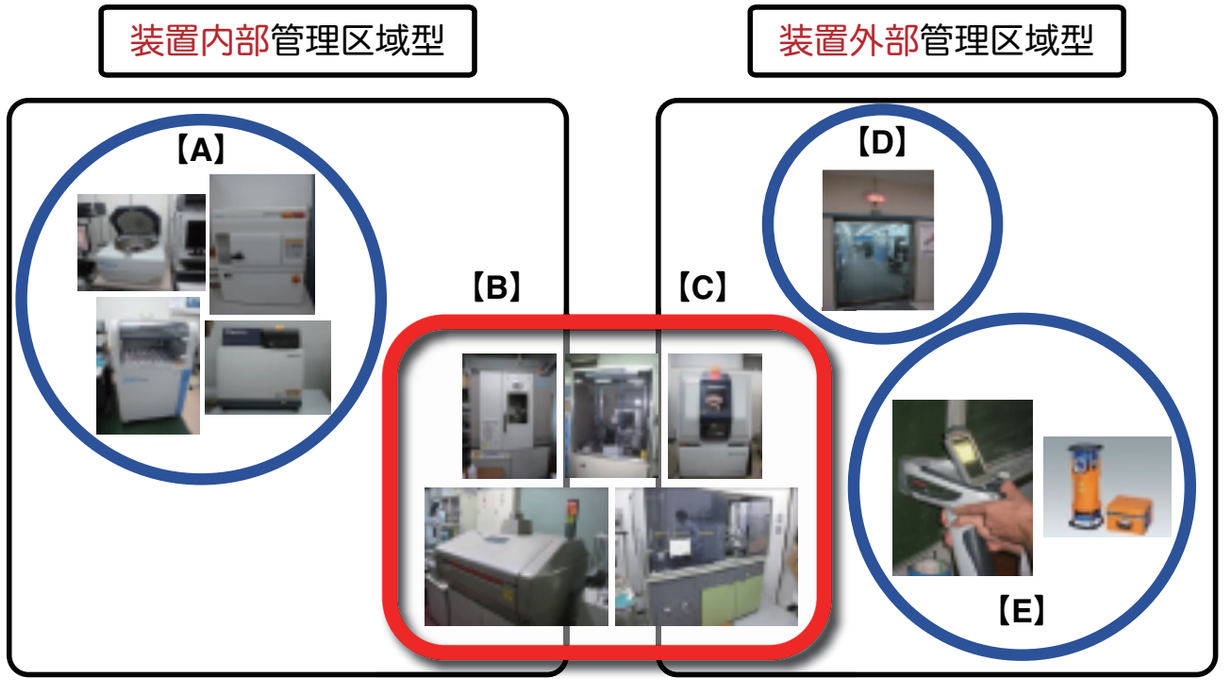


図１　東京大学における研究用エックス線装置の分類

東京大学におけるエックス線装置の分類

密閉型 closed system	A	Completely sealed
	B	Interlock used all the time
非密閉型 non-closed system	C	Interlock used appropriately
	D	Equipments installed in a room
	E	Not fixed / mobile

Classification of X-ray devices at UTokyo

Summary of Quizzes

#1 : There are three categories of radiation workers at School of Science, the University of Tokyo : “RI & Accelerators”, “X-CDE” and “X-AB”. One of these categories do not require medical check for authorization as a radiation worker. Answer which category.

#2 : This April, the equivalent dose limits to the lens of the eye were renewed to…

Annual average of ○○ mSv for 5 years

(With no single year > ○○ mSv)

#3 : Choose the physical process which contributes most to the attenuation of 100 keV X-rays in a shielding material of lead ?

- photoelectric effect
- Compton scattering
- pair production
- Rayleigh scattering

Write the answers in your Attendance Sheet for submission.