Safe Handling of Radiation

Basics of Radiation

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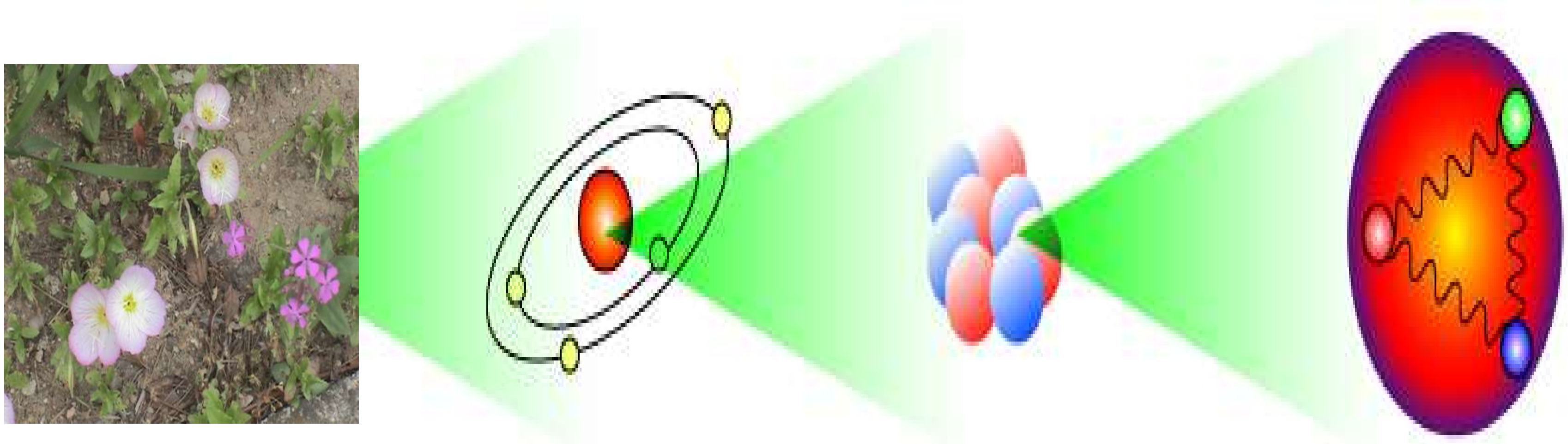
大学等放射線施設協議会

113-0032 東京都文京区弥生2-11-16
東京大学アイソトープ総合センター内
電話: 03-5841-3058 Fax: 03-5841-3050
E-mail: kyogikai@ric.u-tokyo.ac.jp

Radiation-Related Units

Item	Unit	Description	Definition
Exposure	Coulombs/kg (C/kg)	A measure of the ionization produced in air by X or gamma radiation.	1R (Roentgen) = 2.58×10^{-4} C/kg
Absorbed dose, D	Gray (Gy)	The fundamental dose quantity given by the mean energy imparted to matter of mass by ionizing radiation.	1Gy=1J/kg (=100rad)
Equivalent dose, H_T	Sievert (Sv)	The dose in a tissue or organ given by radiation-weighted (w_R) sum of the mean absorbed dose ($D_{T,R}$) from radiation (R).	$H_T = \sum_R w_R D_{T,R}$
Effective dose, E	Sievert (Sv)	The dose in a whole body given by tissue-weighted (w_T) sum of the equivalent doses (H_T) in all specified tissues and organs (T).	$E = \sum_T w_T H_T$
Radioactivity	Becquerel (Bq)	The number of nuclear transformations (decays) occurring in a given quantity of material per unit time.	1Bq=1 decay/sec (1Ci=3.7×10^{10}Bq)
Radiation Energy	Electron Volt (eV)	The energy gained by an electron in passing through a potential difference of 1 V.	1eV=1.6×10^{-19}J

Microscopic world



All Materials

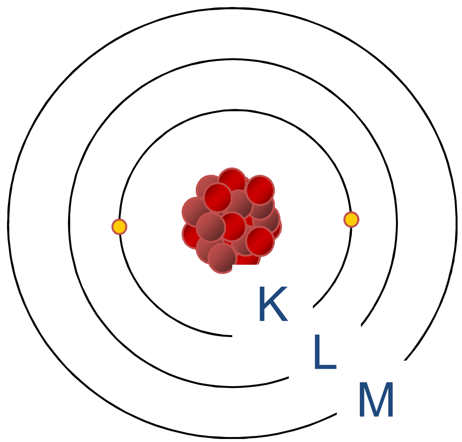
Atom
(electron, nucleus)
10^{-10}m

Nucleus
（proton，neutron)
10^{-15}m

Nucleon
（Quark)
10^{-16}m

Atomic Structure

Component	Approximate Diameter (m)	Charge
Atom	1×10^{-10}	
Nucleus	1×10^{-15}	positive
Electron		negative
Proton	1×10^{-16}	positive
Neutron	1×10^{-16}	neutral



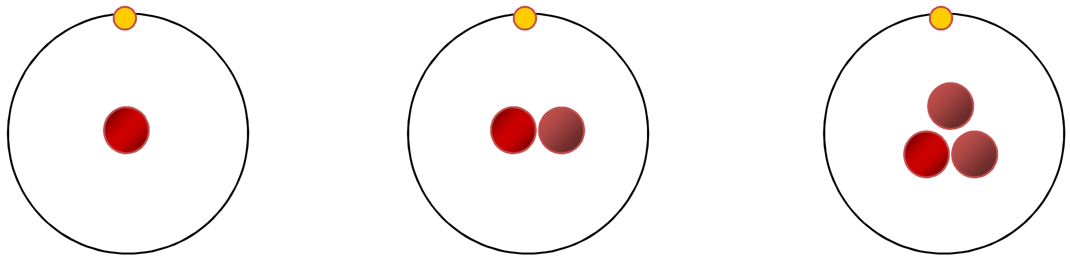
Notation of Isotope

Mass Number ^{32} Element

Atomic Number $_{15}$ Neutron Number $_{17}$

$$^{32}_{15}\mathrm{P}_{17}$$

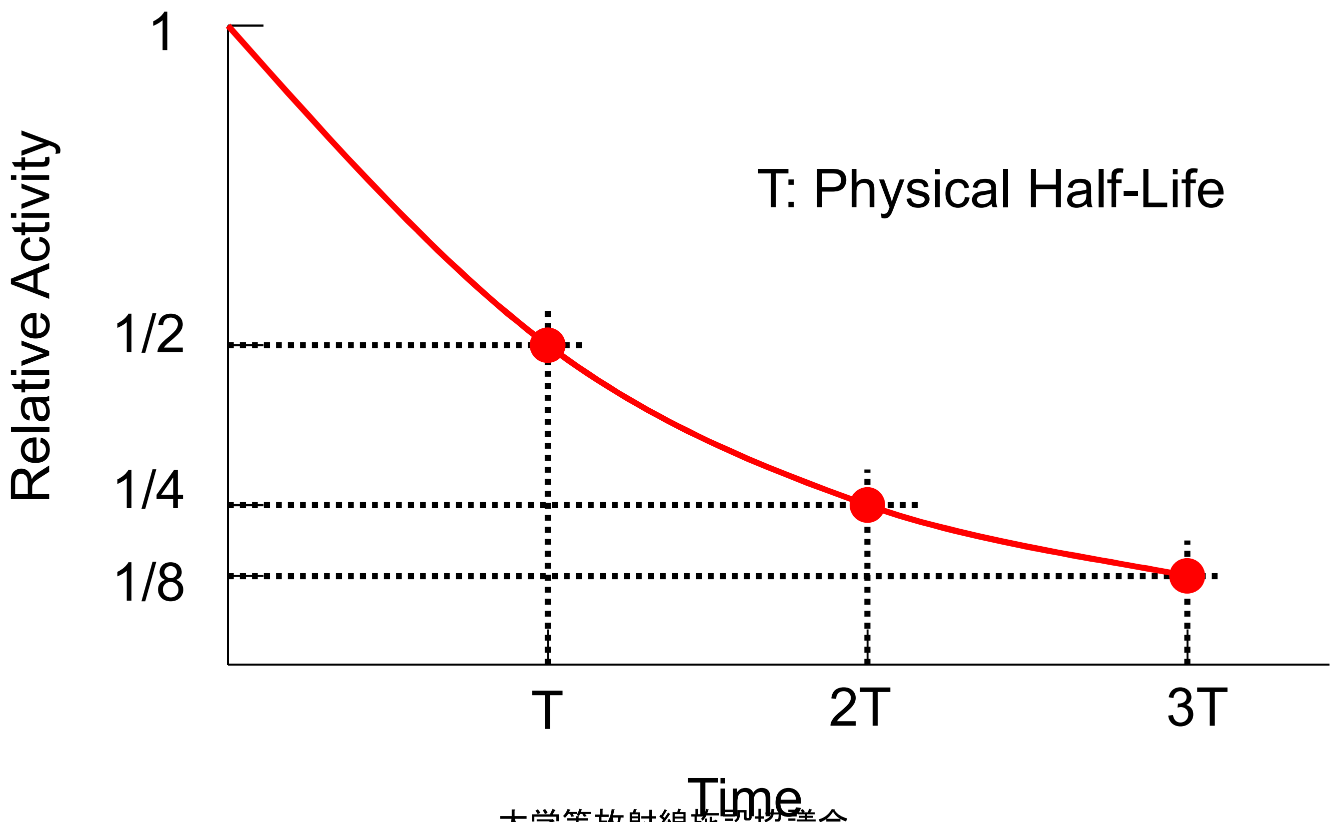
Isotopes of Hydrogen



Term	Hydrogen	Deuterium	Tritium
Number of Protons	1	1	1
Number of Neutrons	0	1	2
Natural Abundance [%]	99.9885	0.0115	none
Radioactivity	no	no	yes

Radioactive decay

Radioactive decay is the disintegration of the nucleus of an unstable nuclide by spontaneous emission of charged particles and/or photons. Every decay process has a specific half-life.



Activity (A)

The number of nuclear decay occurring in a given amount of material per unit time

N	: number of nuclei
t	: a short period of time
λ	: decay constant
N_0	: number of nuclei at t=0
A_0	: activity at t=0
$T_{1/2}$	: half life

$$-\frac{dN}{dt} = \lambda N \equiv A$$

$$N = N_0 e^{-\lambda t}$$

$$\lambda = \frac{\ln 2}{T_{1/2}} = \frac{0.693}{T_{1/2}}$$

$$A(t) = \lambda N(t) = \lambda N_0 e^{-\lambda t} = \lambda N_0 e^{-0.693\, t / T_{1/2}} = A_0 e^{-0.693\, t / T_{1/2}}$$

alternatively

$$A(t) = \lambda N(t) = \lambda N_0 e^{-\lambda t} = \lambda N_0 \left(\frac{1}{2}\right)^{\frac{t}{T_{1/2}}} = A_0 \left(\frac{1}{2}\right)^{\frac{t}{T_{1/2}}}$$

Example: Decay of Phosphorus-32

$T_{1/2}$	: 14.3 days
A_0	: 1 MBq
t	: 7 days

$$A = A_0 e^{-0.693\,t/T_{1/2}} = 1 \times e^{-0.693 \times 7/14.3} = 1 \times e^{-0.339} = \mathbf{0.712}$$

$$A = A_0 \left(\frac{1}{2}\right)^{\frac{t}{T_{1/2}}} = 1 \times \left(\frac{1}{2}\right)^{\frac{7}{14.3}} = \mathbf{0.712}$$

Major types of radiation

Charged particle	α-ray (helium nucleus)	emitted from radionuclides
	β^--ray (electron)	
	β^+-ray (positron)	
	protons	generated by accelerators
	deuterons	
	electron rays	
	heavy ions	
Uncharged particle	neutrons	generated by reactors, accelerators and radionuclides
Electromagnetic wave	X-ray - Characteristic X-ray - Bremsstrahlung	generated outside atomic nucleus
	γ-ray	emitted from atomic nucleus

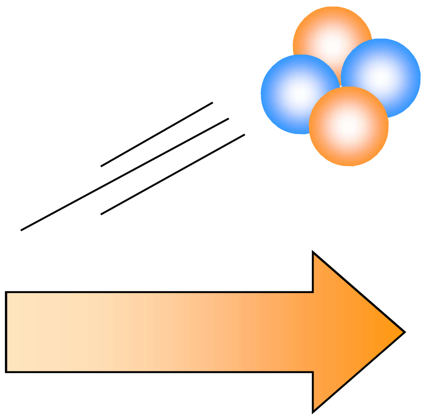
Major types of radioactive decay

Decay processes undergone by unstable nuclides to become more stable

α-decay	emission of helium nucleus (α-ray)
β^--decay	emission of electron (β^--ray)
β^+-decay	emission of positron (β^+-ray)
Electron capture	capture of an orbital electron by nucleus
Other types	emission of electromagnetic wave (γ-ray)
	emission of conversion electron (internal conversion)
	emission of electron and positron (internal pair production)

α-decay (α-ray)

α-particle
= helium nucleus
= α-ray

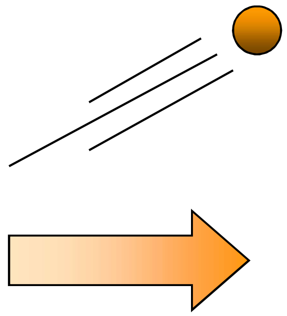


Radium-226
proton 88
neutron 138

Radon-222
proton 86
neutron 136

β⁻–decay (β⁻–ray)

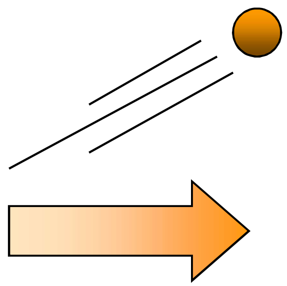
electron
= β⁻ particle
= β⁻-ray



Tritium
proton 1
neutron 2

Helium-3
proton 2
neutron 1

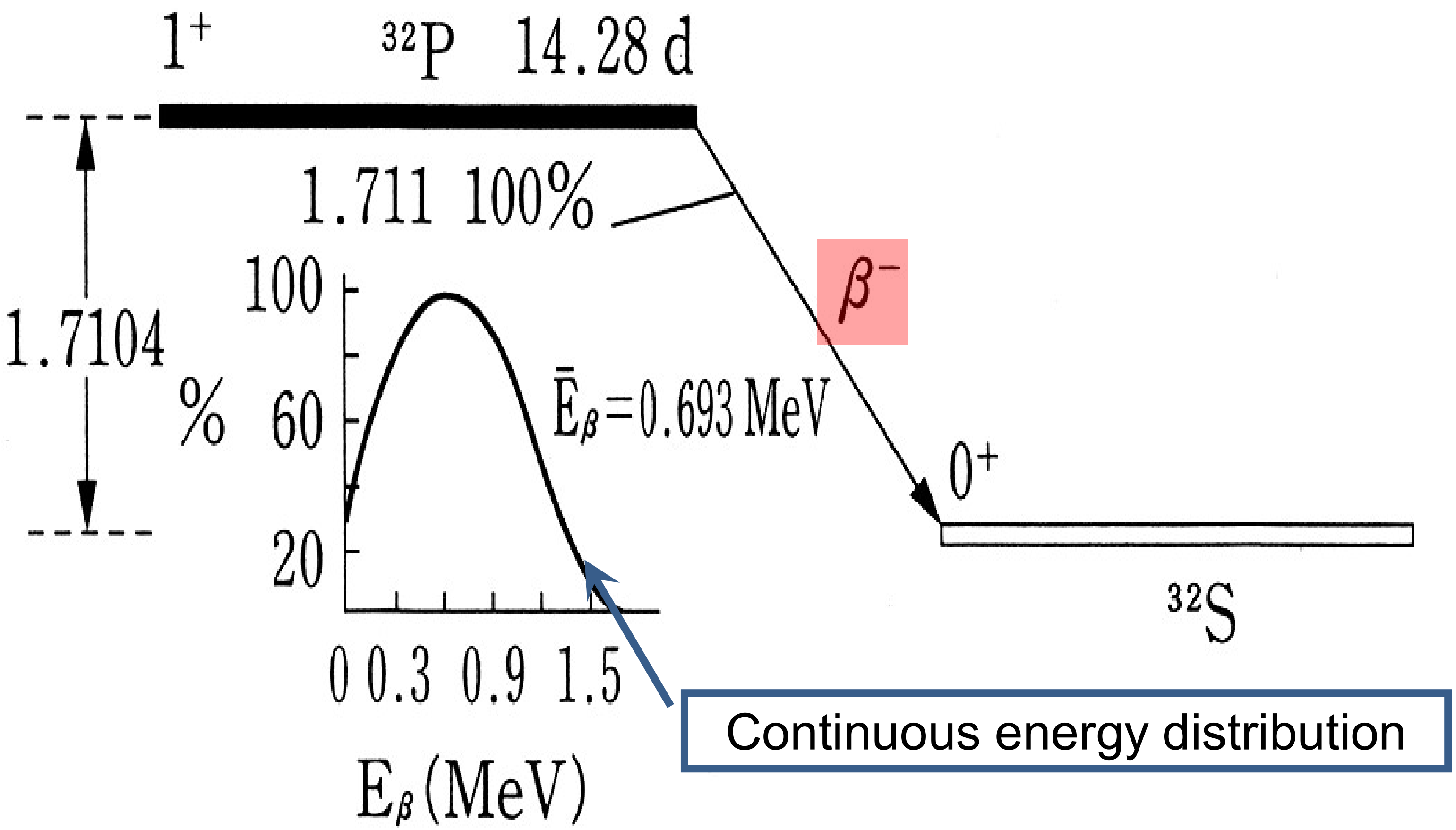
electron



Phosphorous-32
proton 15
neutron 17

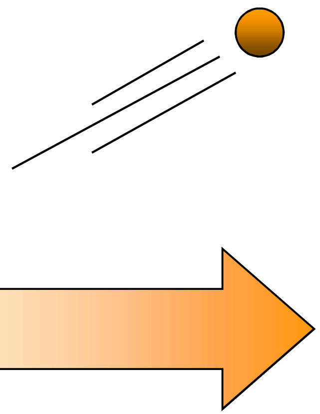
Sulfur-32
proton 16
neutron 16

Decay scheme for ^{32}P



β^+-decay

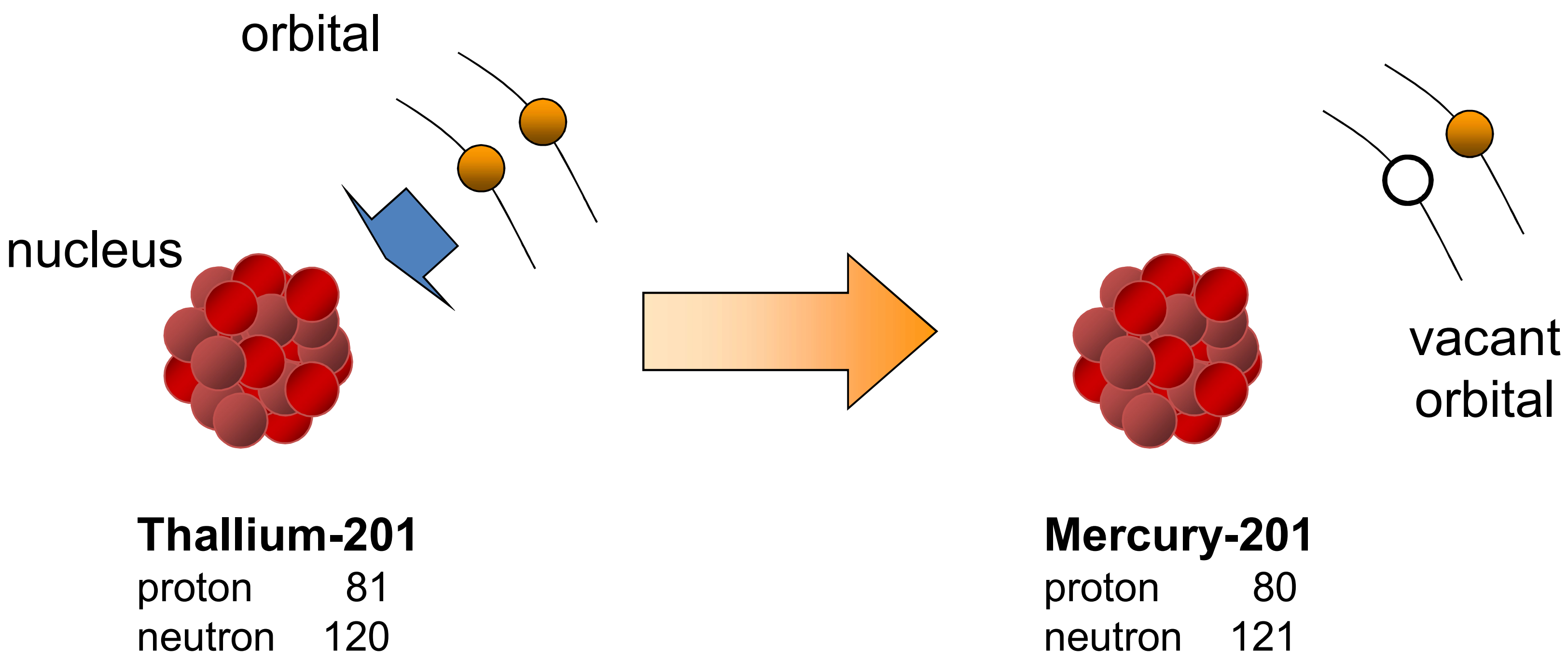
positron
= β^+ particle
= β^+-ray



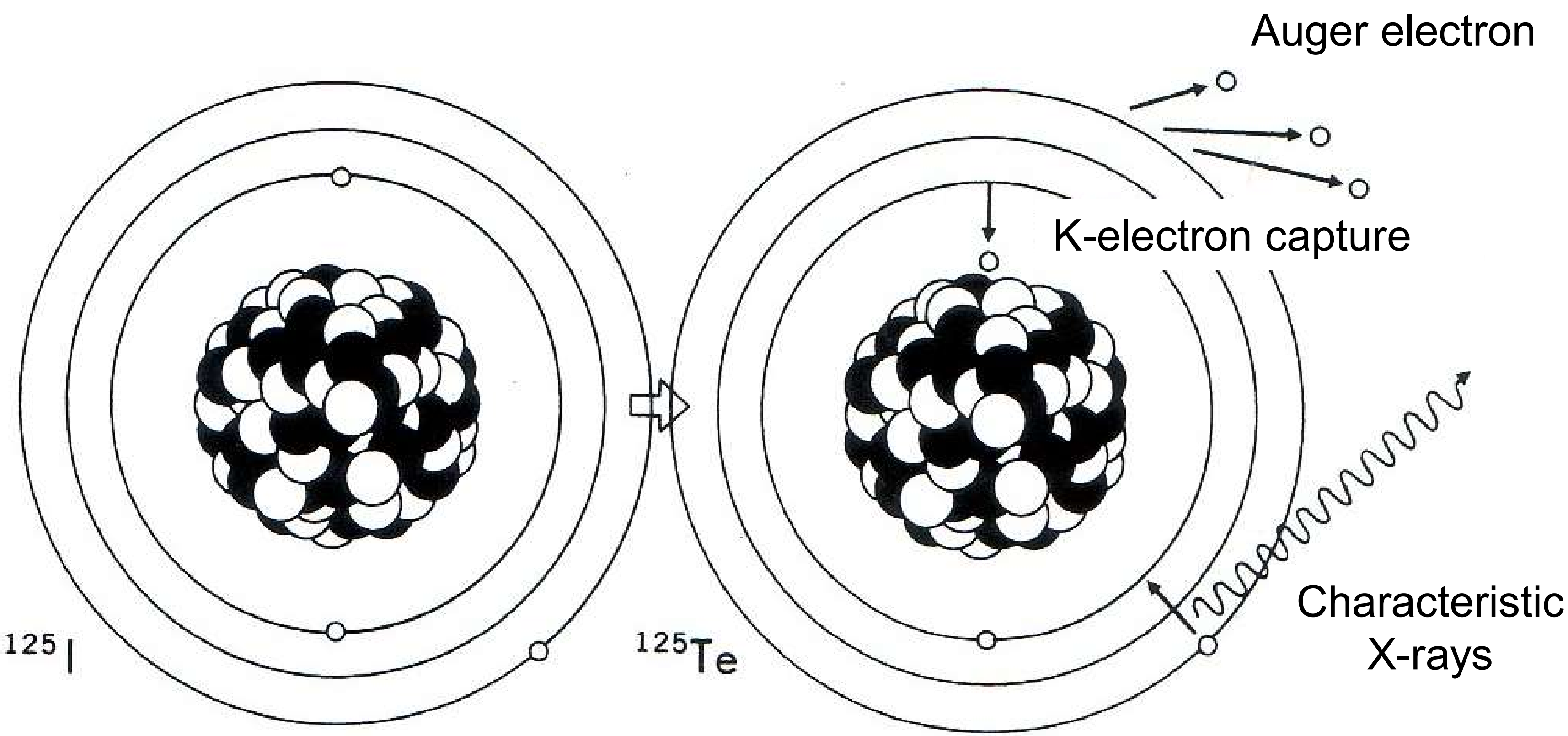
Carbon-11
proton 6
neutron 5

Boron-11
proton 5
neutron 6

Electron capture



Emission following electron capture



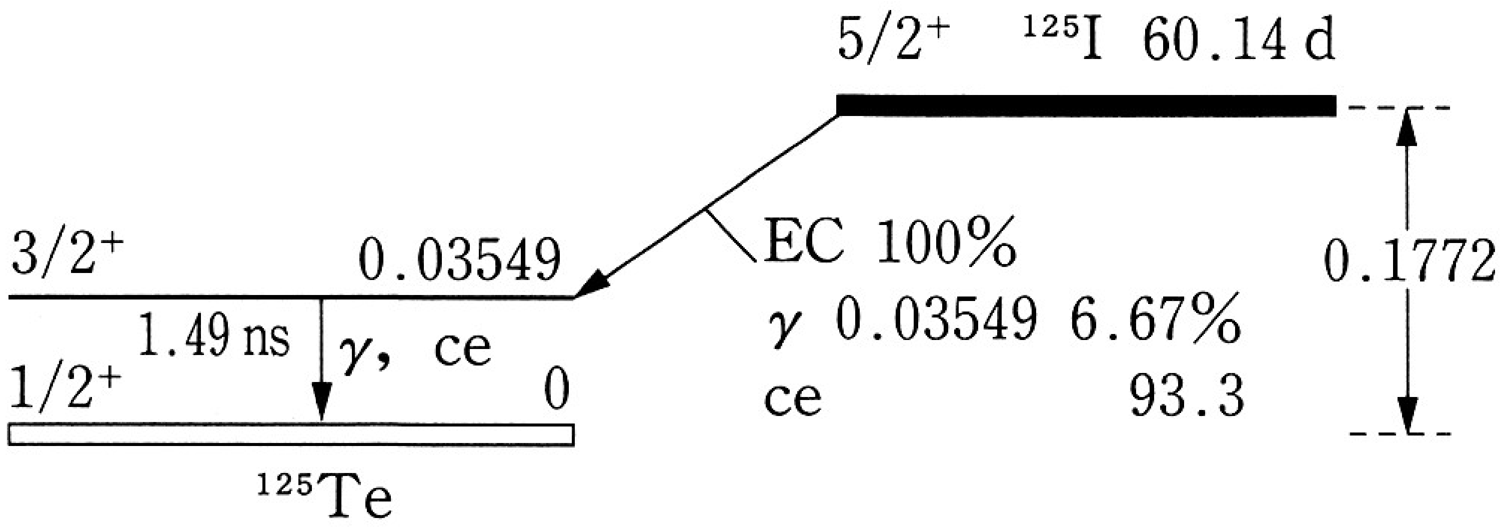
Other types of energy dissipation from unstable nuclei

Gamma emission (γ-ray)
Emission of highly-energetic, short-wave electromagnetic radiation from the nucleus of an atom. In general, α– and β- decays and always the fission process are accompanied by gamma emission.

Internal conversion
Direct transfer of excess energy to one of its own orbital electrons, thereby ejecting the electron from the atom (conversion electron). It always accompanies the predominant process of gamma emission.

Internal pair production
Direct conversion of energy within the electromagnetic field of a nucleus into an electron and a positron that are emitted together. This requires that the excess energy of the unstable nucleus be at least equivalent to the combined masses of an electron and a positron (in excess of 1,020,000 electron volts).

Decay scheme for ^{125}I



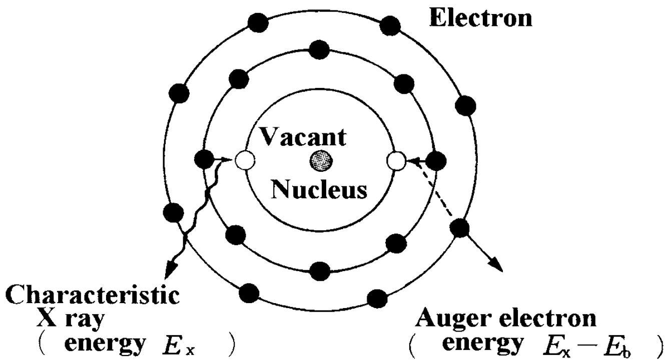
Electromagnetic radiations

Gamma-rays (γ-rays)
These are defined as mono-energetic electromagnetic radiations that are emitted from nuclei of excited atoms following radioactive transformations. In most cases, following α- or β- decay processes, gamma emission is the mechanism by which a nucleus loses energy going from a high energy excited state down to a low energy stable state.

X-ray
These are defined as electromagnetic radiations generated outside the atomic nucleus. There are two distinct types of X-ray.

- **Characteristic X-ray**
- **Bremsstrahlung**

Characteristic X-rays

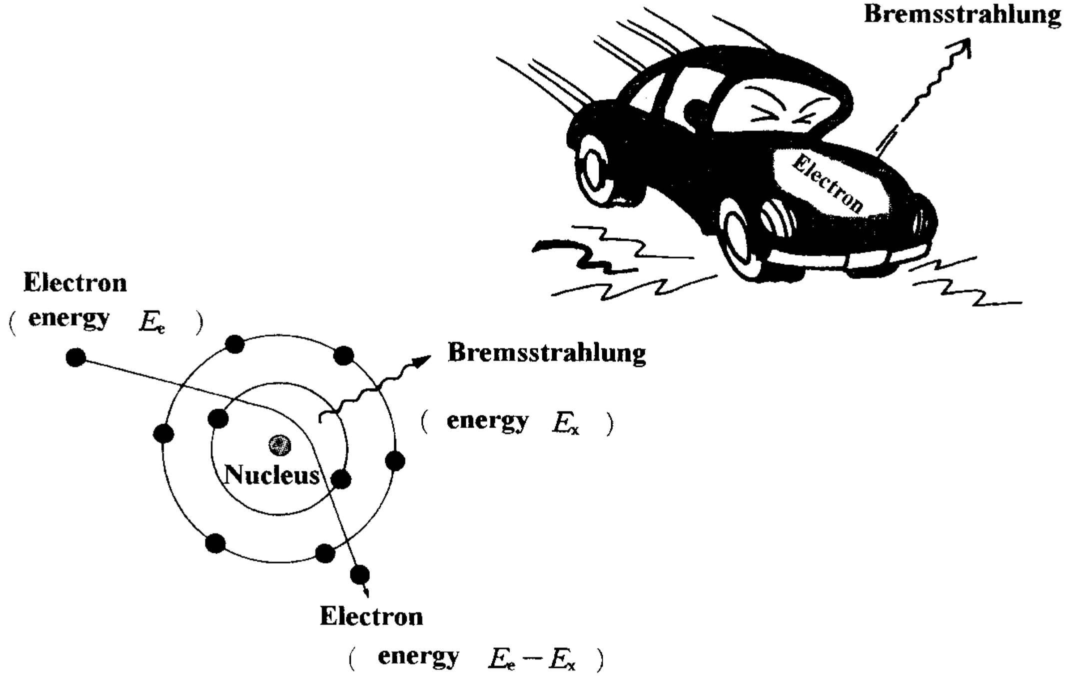


A collision of fast-moving electrons with an atom first causes a tightly bound inner-shell electron to be ejected from the atom; a loosely bound outer-shell electron then falls into the inner shell to fill the vacancy. In the process, a single photon (characteristic X-ray) is emitted by the atom with an energy equal to the difference between the inner-shell and outer-shell vacancy states. This energy difference (*Ex*) usually corresponds to the photon wavelengths in the X-ray region of the spectrum.

Alternatively, one of the orbital electrons is given excitation energy and kicked out of the atom. This electron is called an Auger electron. The energy of Auger electron is given by '*Ex* - *Eb*' where *Eb* is binding energy (energy necessary to release electron from the atom).

Bremsstrahlung

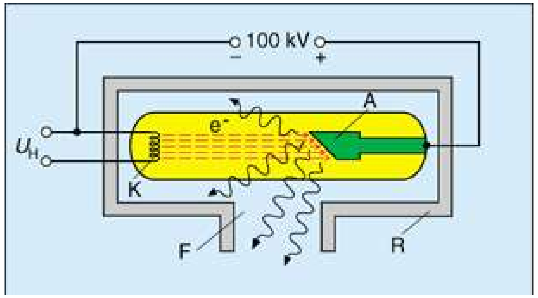
(German: Breaking radiation)



Bremsstrahlung is emitted when electrons (*Ee*) are quickly decelerated by an interaction with the electric fields surrounding atomic nuclei. The energy of the resultant photon (*Ex*) is related to the energy of the incident electron as well as the electric field strength. These forces are greater in nuclei with a high atomic number.

Generation of X-rays

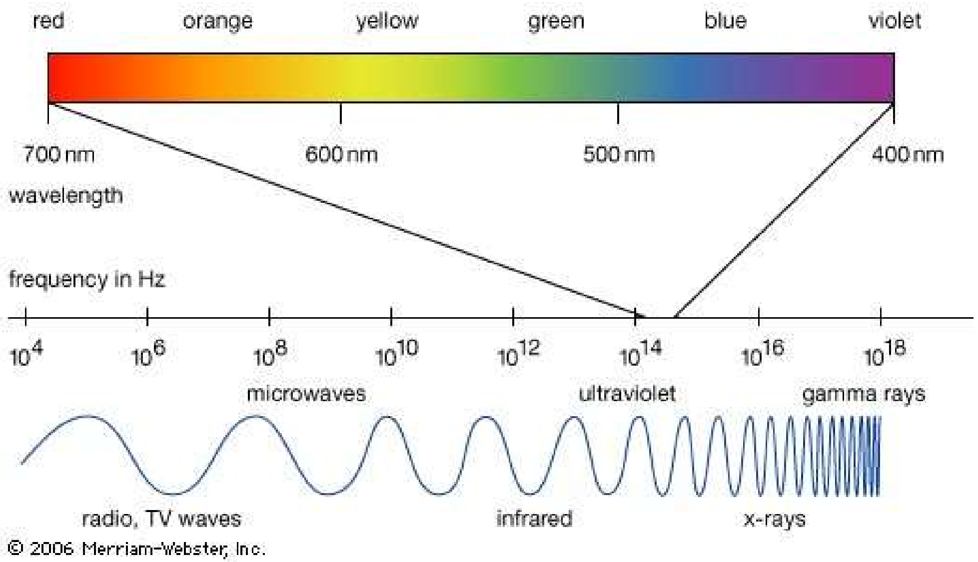
X-rays are generated by slowing-down electrons or heavy charged particles (Characteristic X-rays, Bremsstrahlung). In an X-ray tube, electrons are accelerated by means of high direct voltage to bombard a metal electrode.



Simplified sectional drawing of an X-ray tube (UH: heater voltage, K: cathode, A: anode, e: electrons exiting in the cathode and accelerated to the anode, R: x-ray shielding, F: beam hole)

http://www.euronuclear.org/info/encyclopedia/x/x-radiation.htm

Electromagnetic wave spectrum



"Electromagnetic wave spectrum." Online . Britannica Student Encyclopedia. 6 Apr. 2009

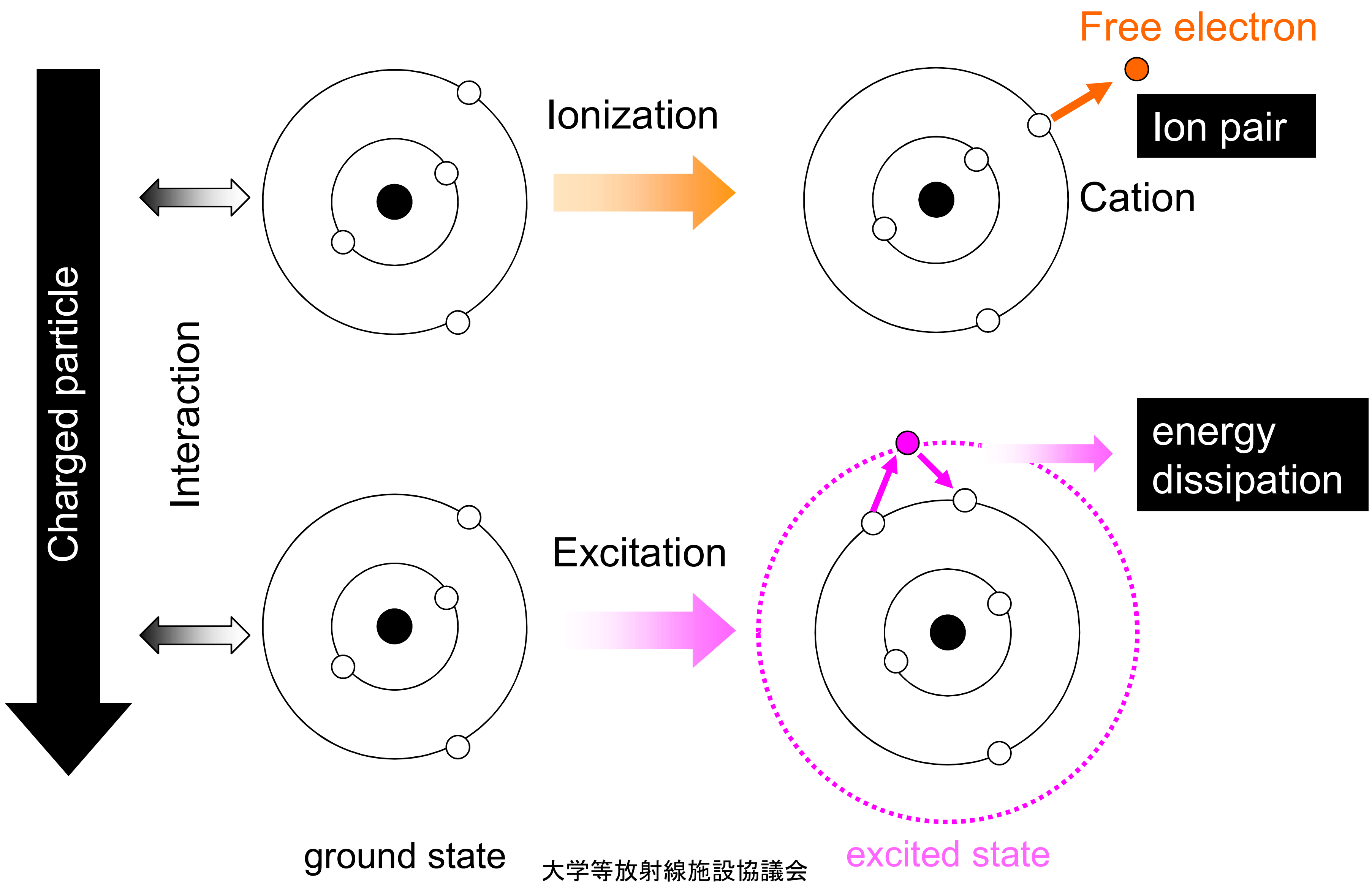
Relationships among radioactivity, radiation and radioisotopes

Radioactivity
The spontaneous decay of disintegration of a radionuclide, an unstable atomic nucleus, accompanied by the emission of radiation.

Radioisotope
A radioactive isotope. A common term for a radionuclide.

Suppose aroma from coffee is radiation, coffee itself has radioactivity and is a radioisotope.

Ionization and excitation



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Radiation interaction with matter
α-particles

- Electrostatic attraction on the outer orbital electrons of atoms near which α-particles pass
  - resulting that some electrons will be attracted away from their parent atoms and that ions will be produced (ionization).

- A double positively charged and low velocity due to their large mass
  - cause α-particles to lose their energy over a distance as short as 4cm in air in straight lines.

Radiation interaction with matter
β^--particles (electron)

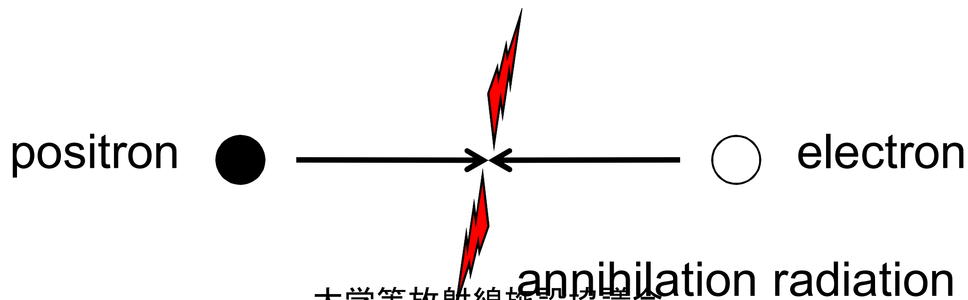
- Negative charge of β^--particles interacts with the negative charge of orbital electrons
  - ejecting orbital electrons from their orbits (producing ion pairs) or causing excitation until the electron has lost enough energy to be captured by a nucleus.

- Small mass, high velocity and single negative charge
  - enable β^--particle to travel through the matter further than an α-particle before producing an ionizing effect, resulting in longer range in air from up to 790cm.
  - cause large deflection with each interaction, resulting in many path changes and scattering.

Radiation interaction with matter
β^+-particles (positron)

- Positive charge of positron interacts with the negative charge of orbital electrons
  - losing its kinetic energy through ionizations and excitations, similar to β^--particle.

- In addition, a positron will also combine with an electron. Then two particles are annihilated
  - producing two 0.511 MeV gamma rays called annihilation radiation in exactly opposite directions.



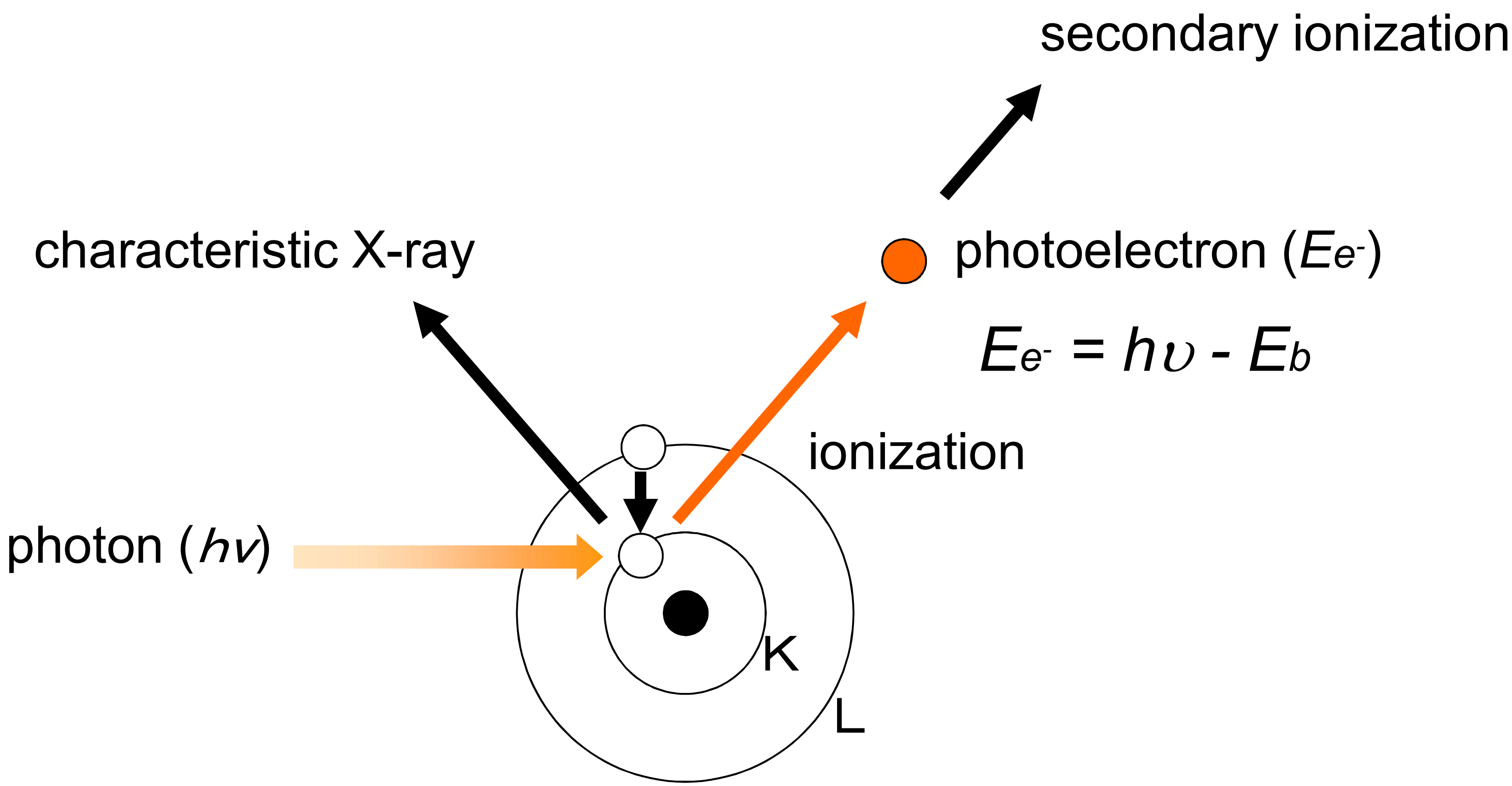
Radiation interaction in matter
electromagnetic radiation

- **Photoelectric effect**
  - A photon imparts all its energy to an orbital electron and then vanishes.
  - If the energy of the photon is greater than the binding energy of the electron, an electron will be ejected from the atom.

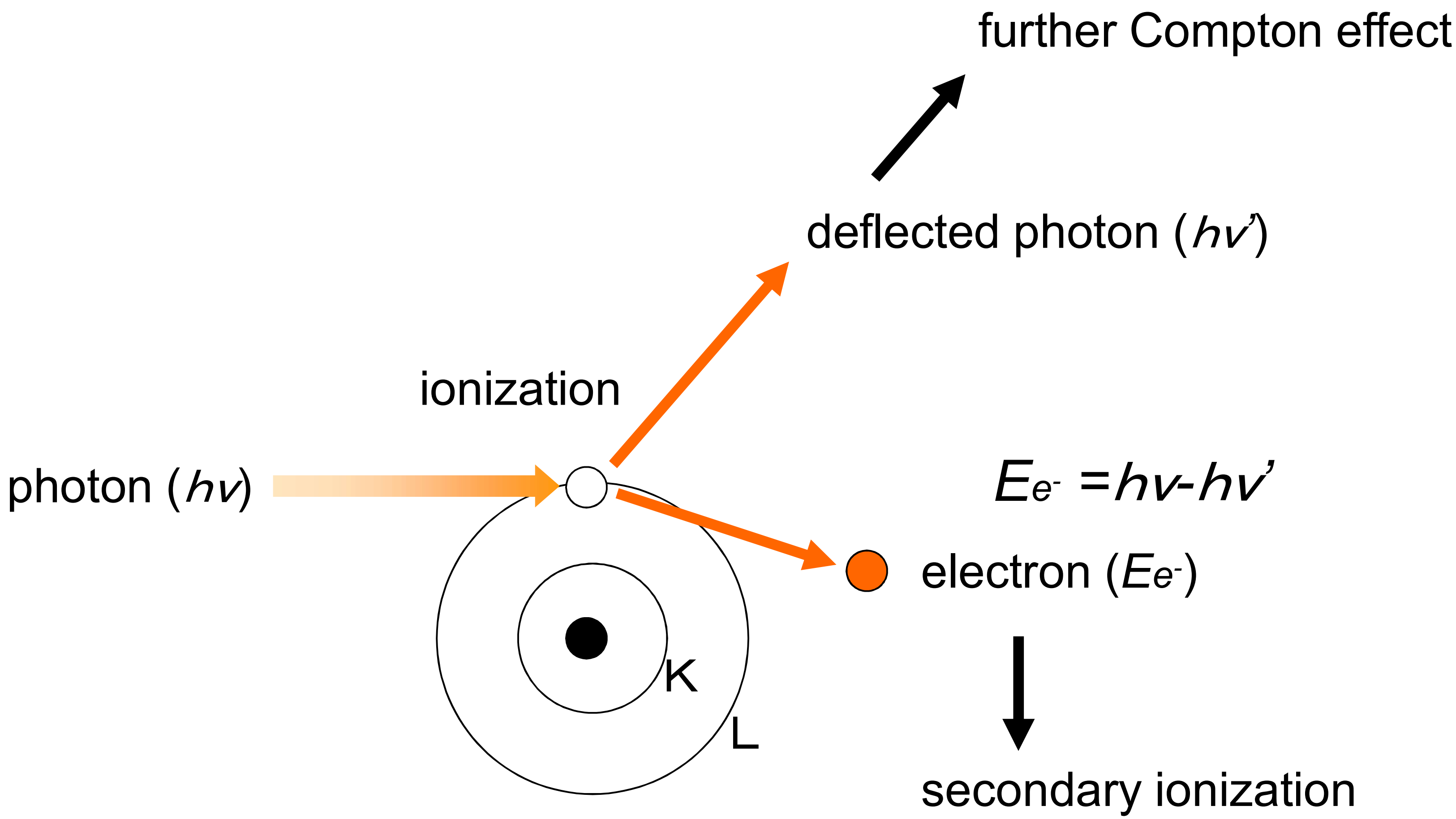
- **Compton effect (scattering)**
  - A photon transfers only a portion of its energy to an orbital electron and then continues in an alternate direction.

- **Pair production**
  - A photon passing through an atom in the region of the nucleus undergoes a conversion into a positron and an electron.

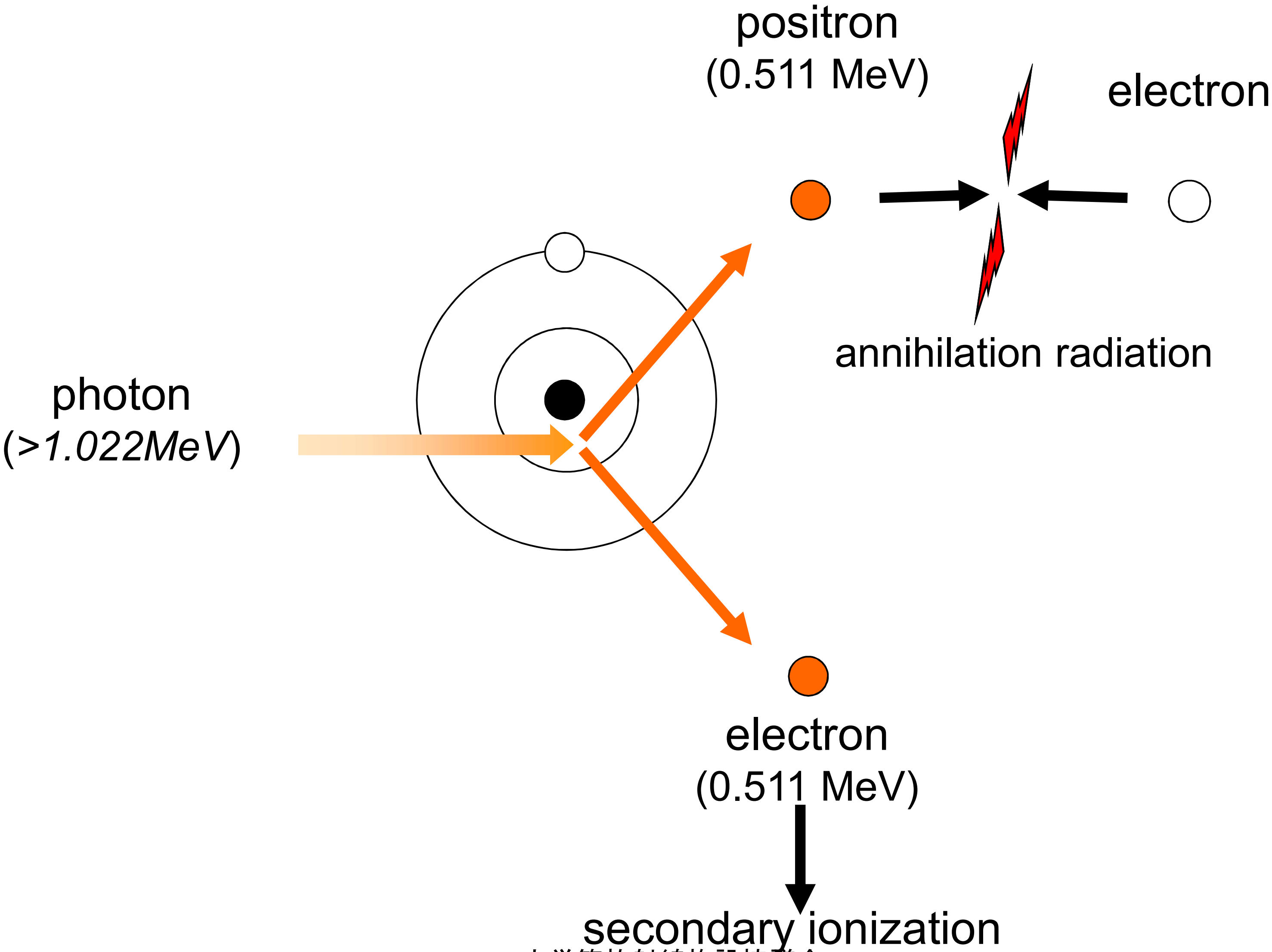
Photoelectric effect



Compton effect (scattering)



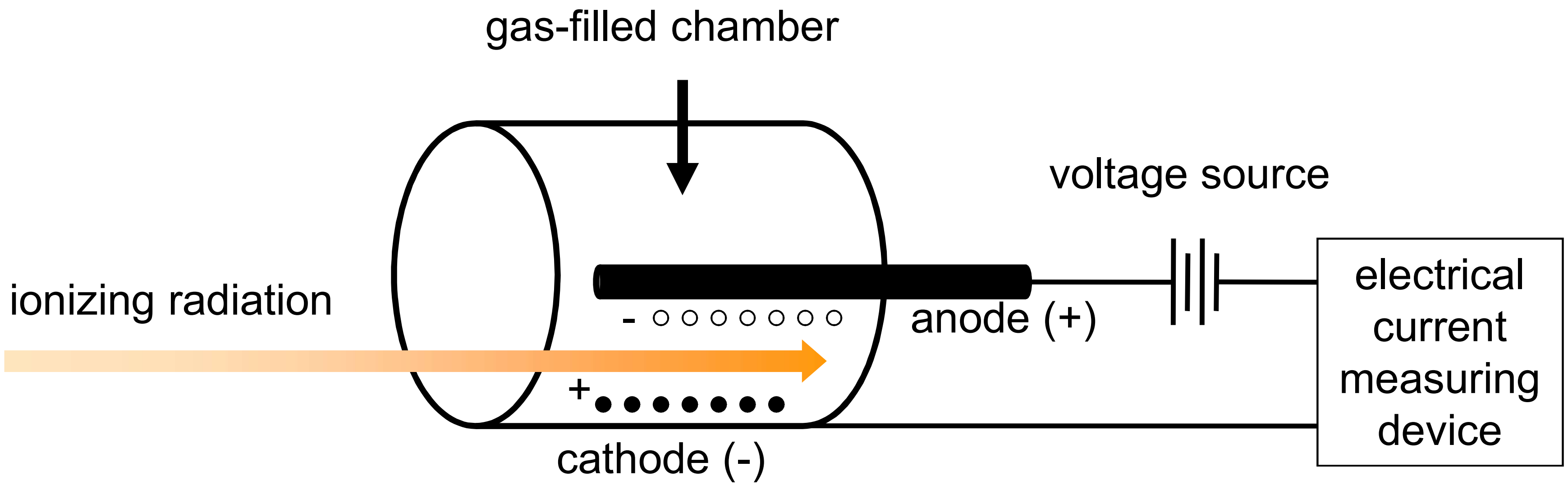
Pair production



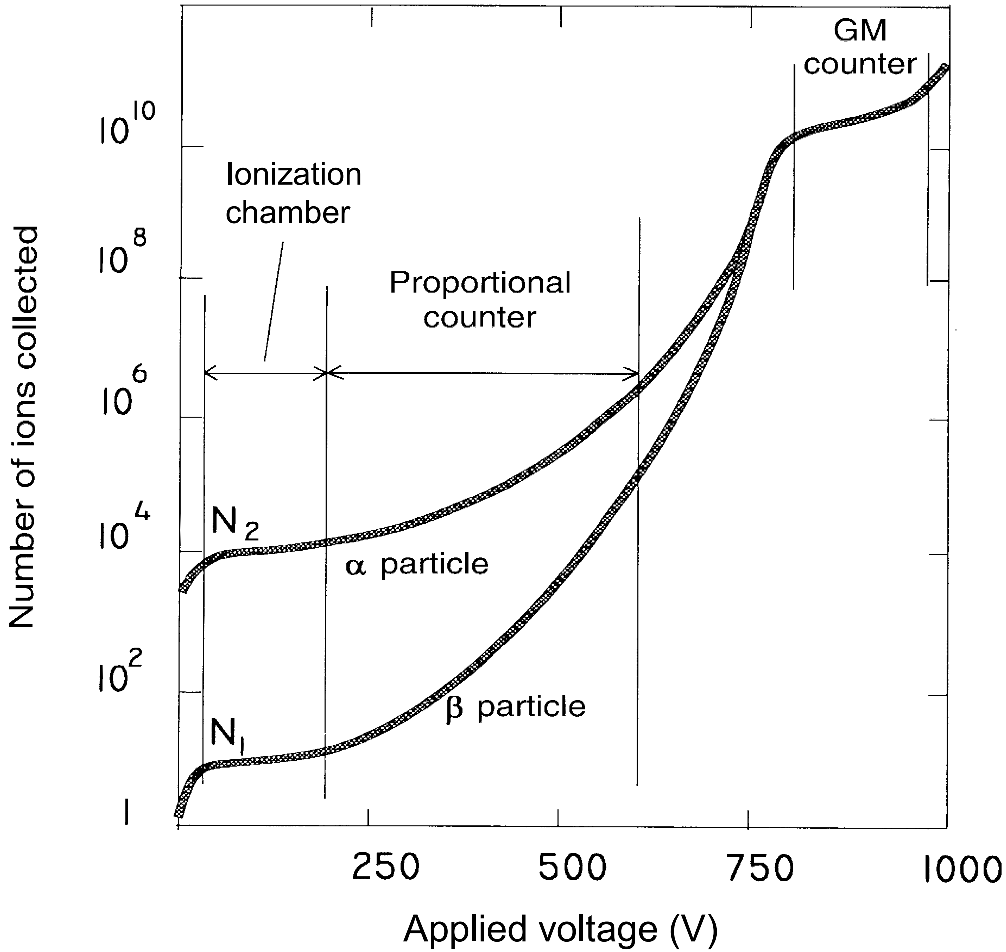
Radiation detectors

- **Gas-filled detectors**
  - Ionization chamber
  - Proportional counter
  - Geiger-Mueller (GM) counter
- **Scintillation detectors**
  - Crystal scintillation counter
  - Liquid scintillation counter
- **Semiconductor detectors**
  - Silicon (Si(Li)) detector
  - Germanium (Ge(Li)) detector
- **Other luminescence-based detectors**
  - Thermoluminescence (TLD) dosimeter
  - Radiophotoluminescence (RPL) dosimeter
  - Optically stimulated luminescence (OSL) dosimeter
  - Photostimulated luminescence detector (Imaging plate)

Gas-filled detectors



Operating voltages for gas-filled detectors



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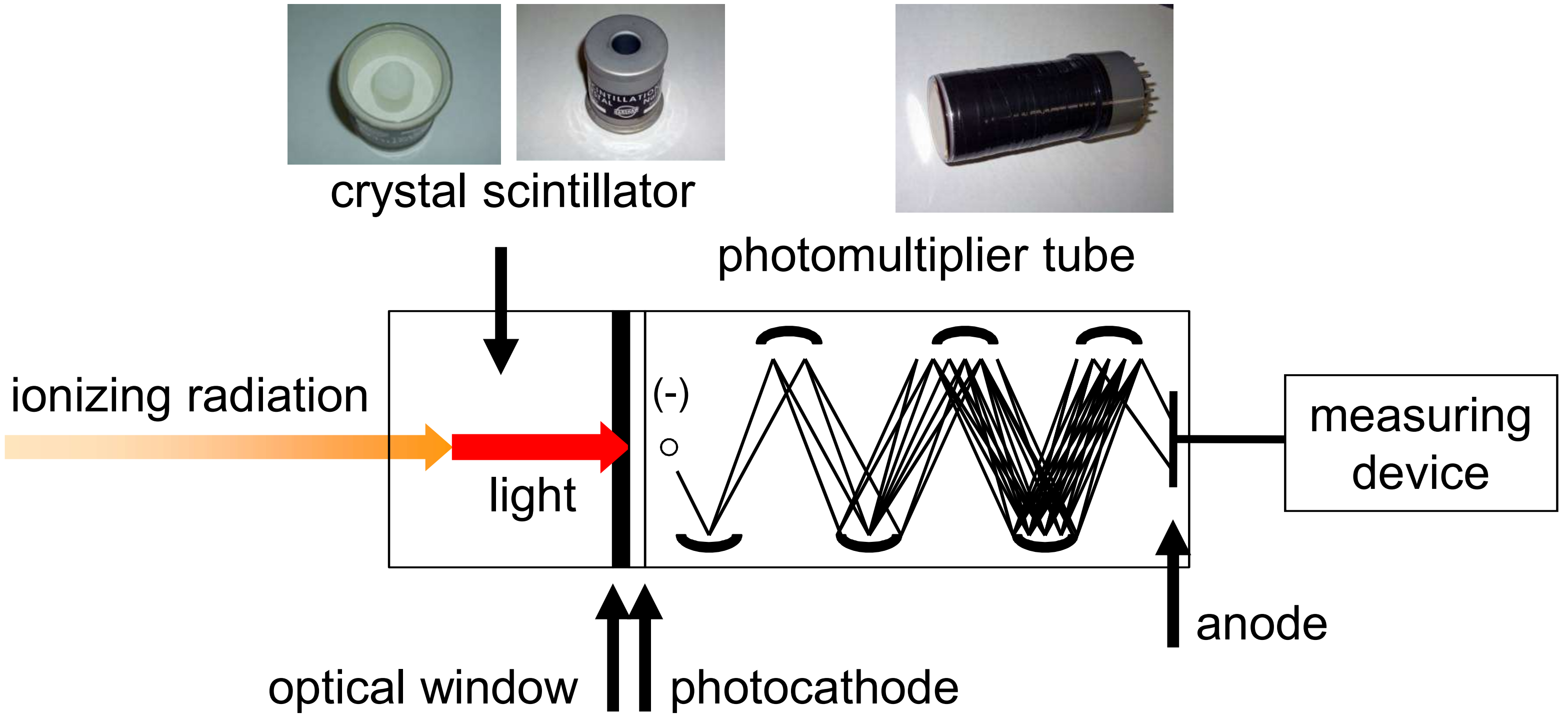
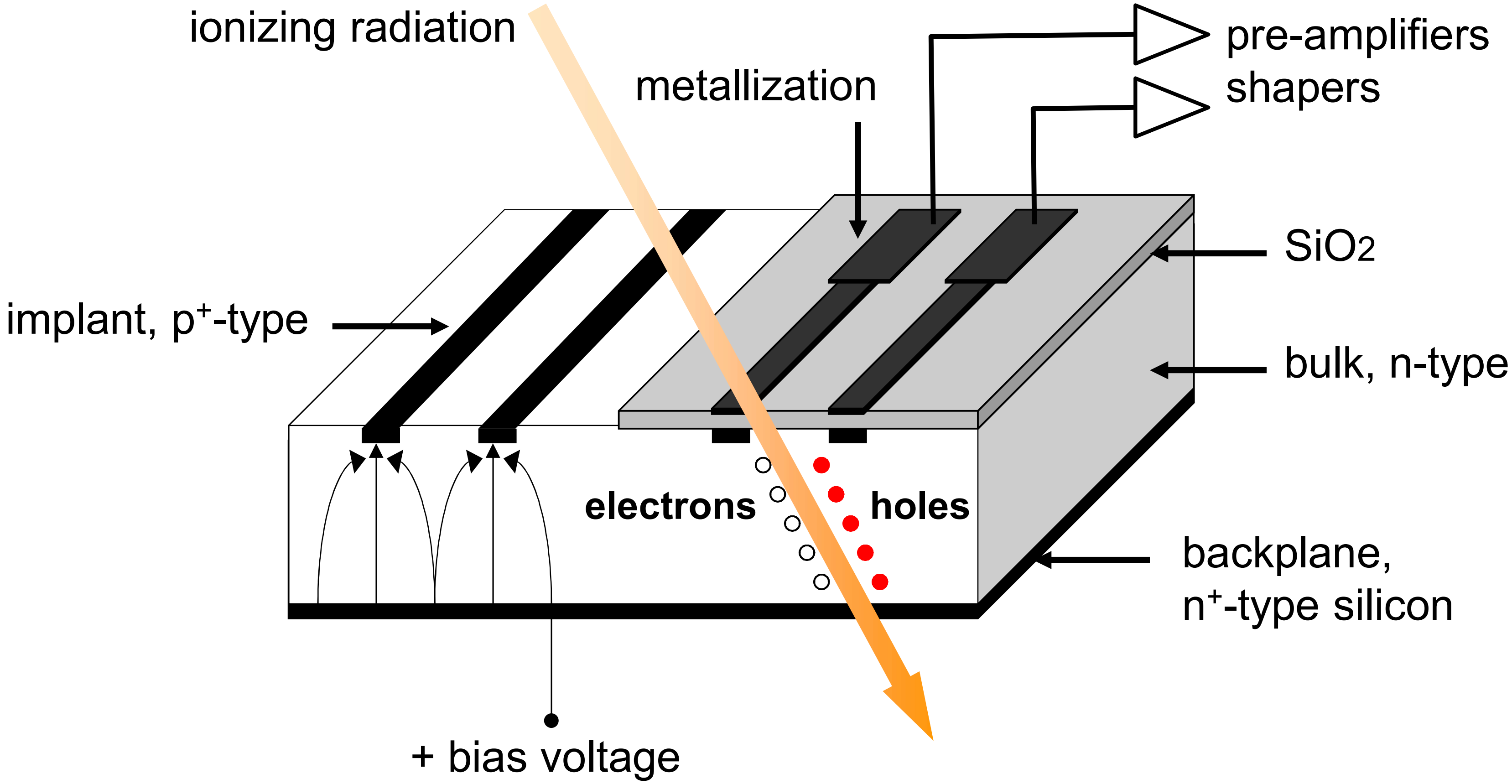
Scintillation detectors

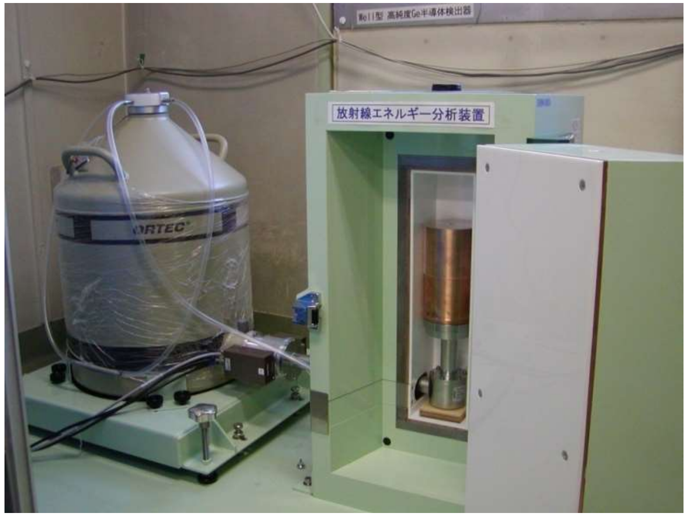


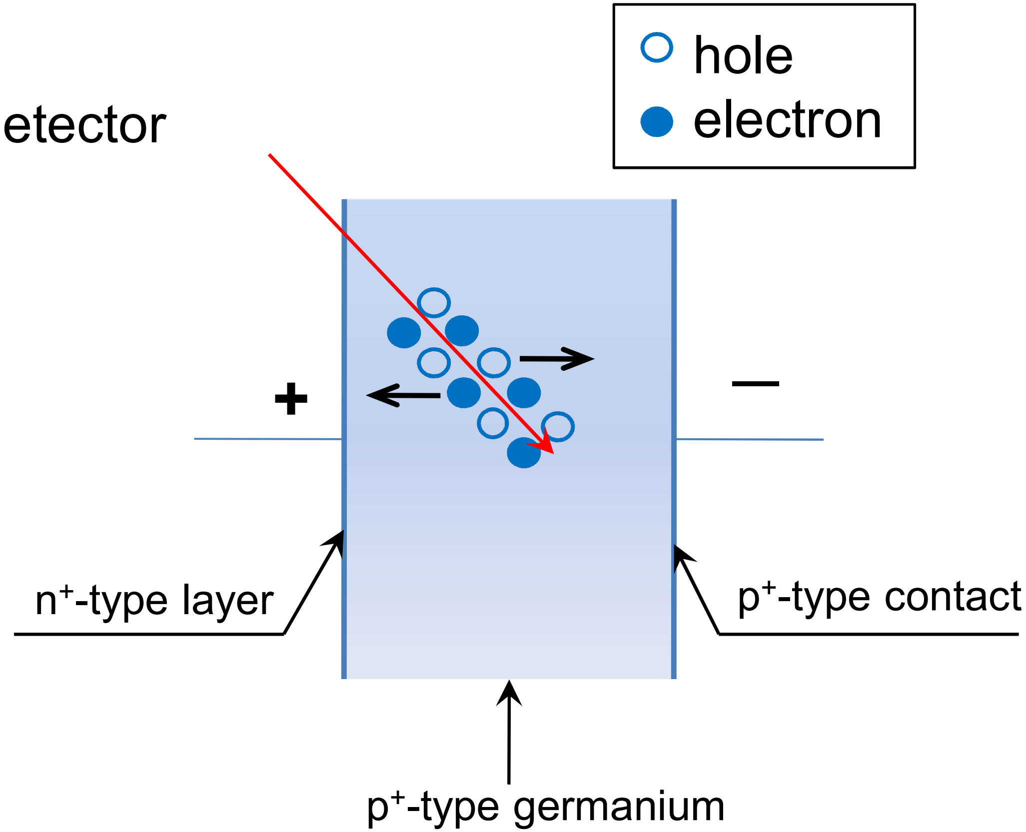
Semiconductor detector



Semiconductor detector

HPGe（High Purity Germanium）detector





Luminescence-based detectors
for personnel monitoring for external radiation

Thermoluminescence
- TLD badge

Radiophotoluminescence (RPL)
- GLASS badge

Optically stimulated luminescence (OSL)
- LUXEL badge