Introduction to Radiation Physics, Quantities and Units

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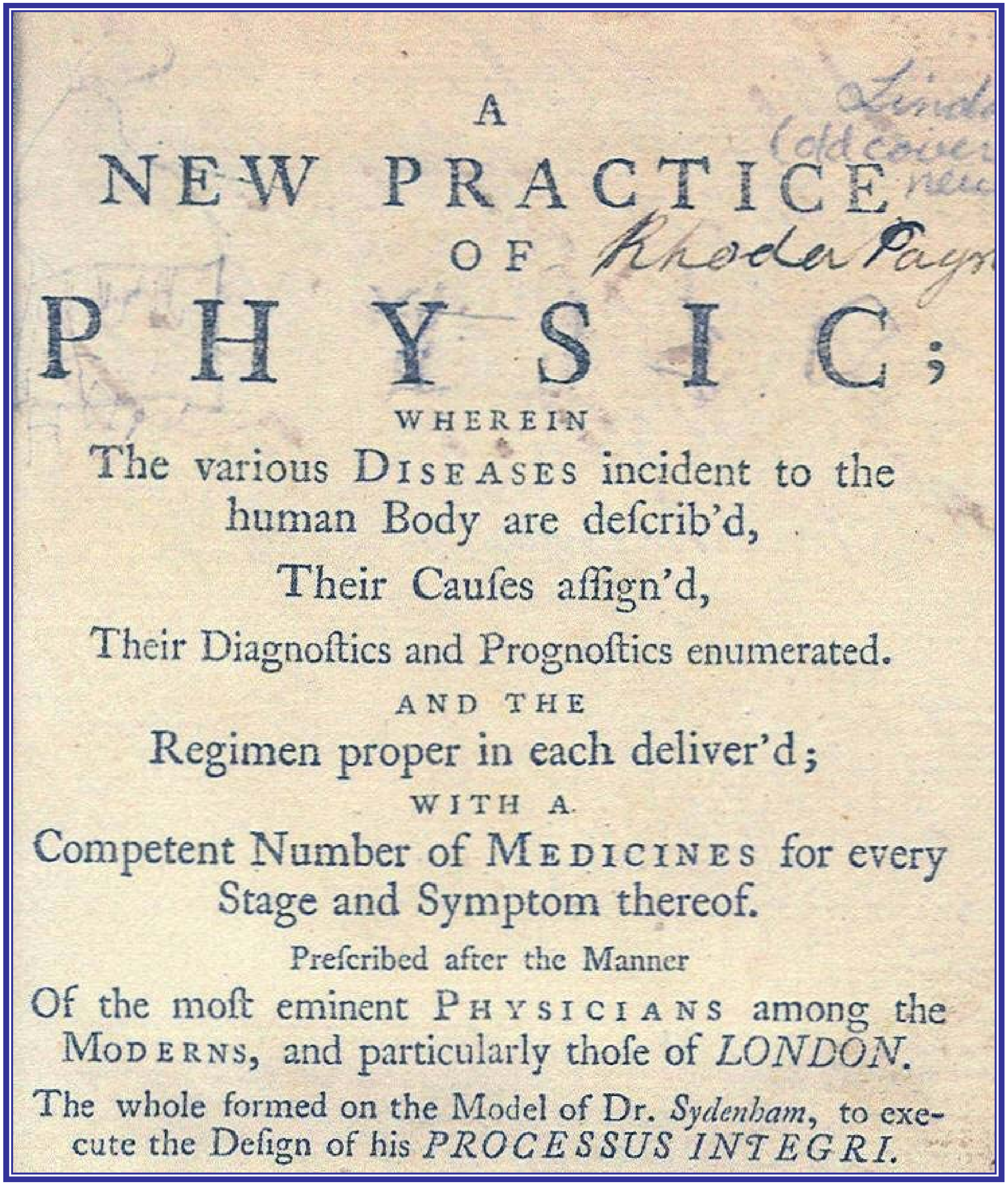
Course Objectives

Participants Should Be Able To:

- Understand the basic physics of the electromagnetic and particulate forms of ionizing radiation.
- Understand the distinctions between the units of radiation quantity, exposure and dose.
- Be familiar with some of the methods used to measure radiation dose.



A

NEW PRACTICE

OF

PHYSIC;

WHEREIN

The various DISEASES incident to the human Body are deſcrib'd,

Their Cauſes aſſign'd,

Their Diagnoſtics and Prognoſtics enumerated.

AND THE

Regimen proper in each deliver'd;

WITH A

Competent Number of MEDICINES for every Stage and Symptom thereof.

Preſcribed after the Manner

Of the moſt eminent PHYSICIANS among the MODERNS, and particularly thoſe of *LONDON*.

The whole formed on the Model of Dr. *Sydenham*, to execute the Deſign of his *PROCESSUS INTEGRI.*

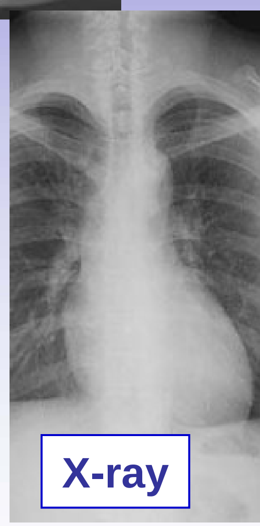
Physics from a Doctor's Point of View

What is "Radiation"?

- Radiation can be thought of as the transmission of energy through space.
- Two major forms of radiation:
  - Electromagnetic (EM) radiation
  - Particulate radiation
- Both forms can interact with matter, and transfer their energy to the matter.

Shorter Wavelengths

Longer Wavelengths



Higher Frequencies and Energies

Lower Frequencies and Energies

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Electromagnetic Radiation

- <u>Electromagnetic</u> <u>radiation</u> has no mass, and moves through space at the speed of light (3.0 x10^8 meters per second).
- Electromagnetic radiation can be described by two models:
  - <u>Wave</u> Model
  - <u>Photon</u> Model

EM Radiation: Wave Model

- **EM radiation is a pair of perpendicular, time-varying electric and magnetic fields traveling through space with the <u>velocity</u> of light (c).**
- **The distance between maxima of the EM fields is the <u>wavelength</u> (λ).**
- **The <u>frequency</u> (ν) of the wave is given by:**

$$\nu = c / \lambda$$

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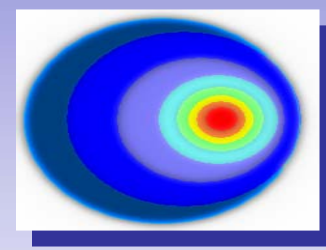
EM Radiation: Photon Model

$$E = h\,c\,/\,\lambda$$



Electromagnetic radiation can also be described as discrete packets of energy called <u>photons</u>. The energy (E) is related to the wavelength (<u>λ</u>) in the wave model through Planck’s Constant (<u>h</u>) and the speed of light (<u>c</u>).

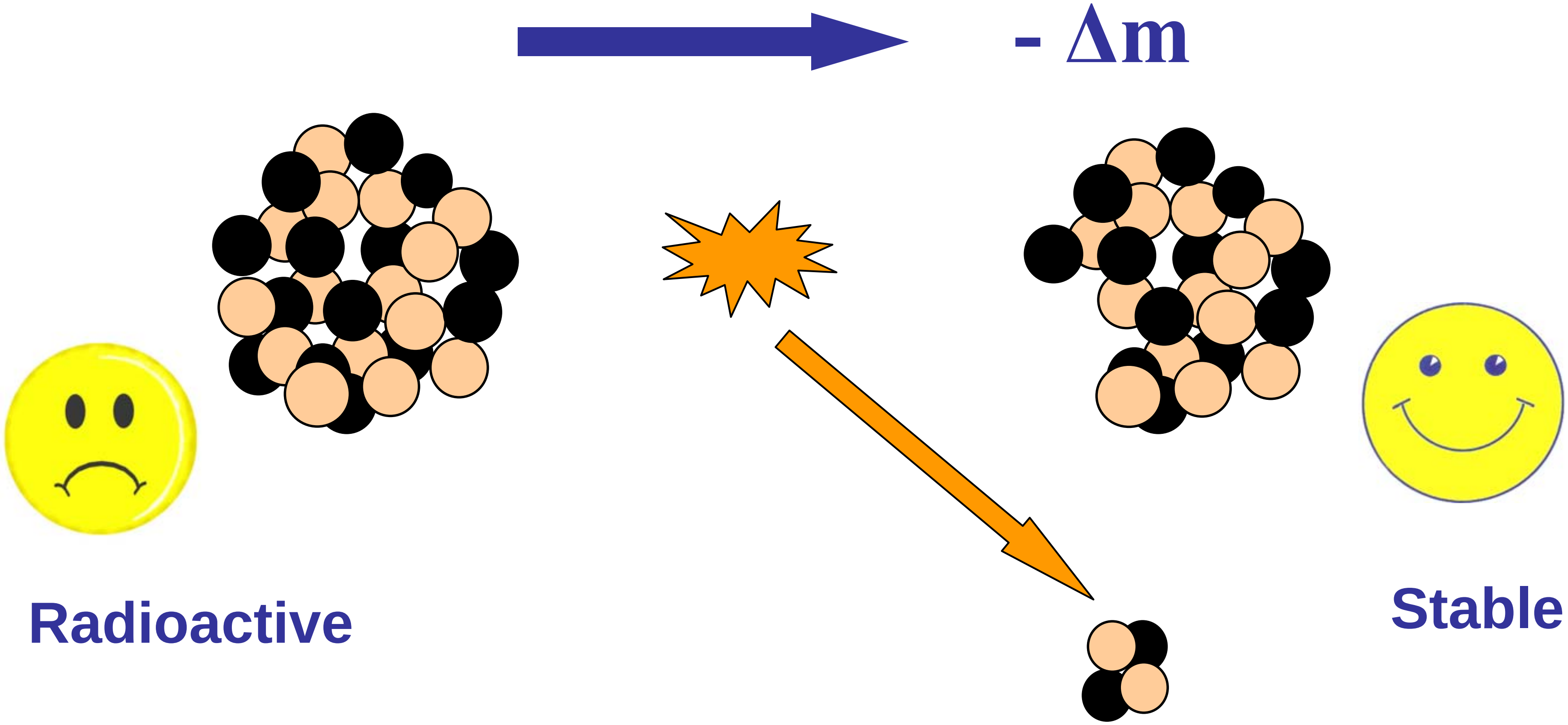
Ionizing EM Radiation

- **EM radiation with wavelengths shorter than 100 nanometers can remove electrons from the outer atomic shells.**
- **This process produces <u>ions</u>.**
- **Ions can interact with living tissue to produce biological damage.**
- **A major source of ionizing radiation is <u>nuclear transformation</u>.**

Human Transformation

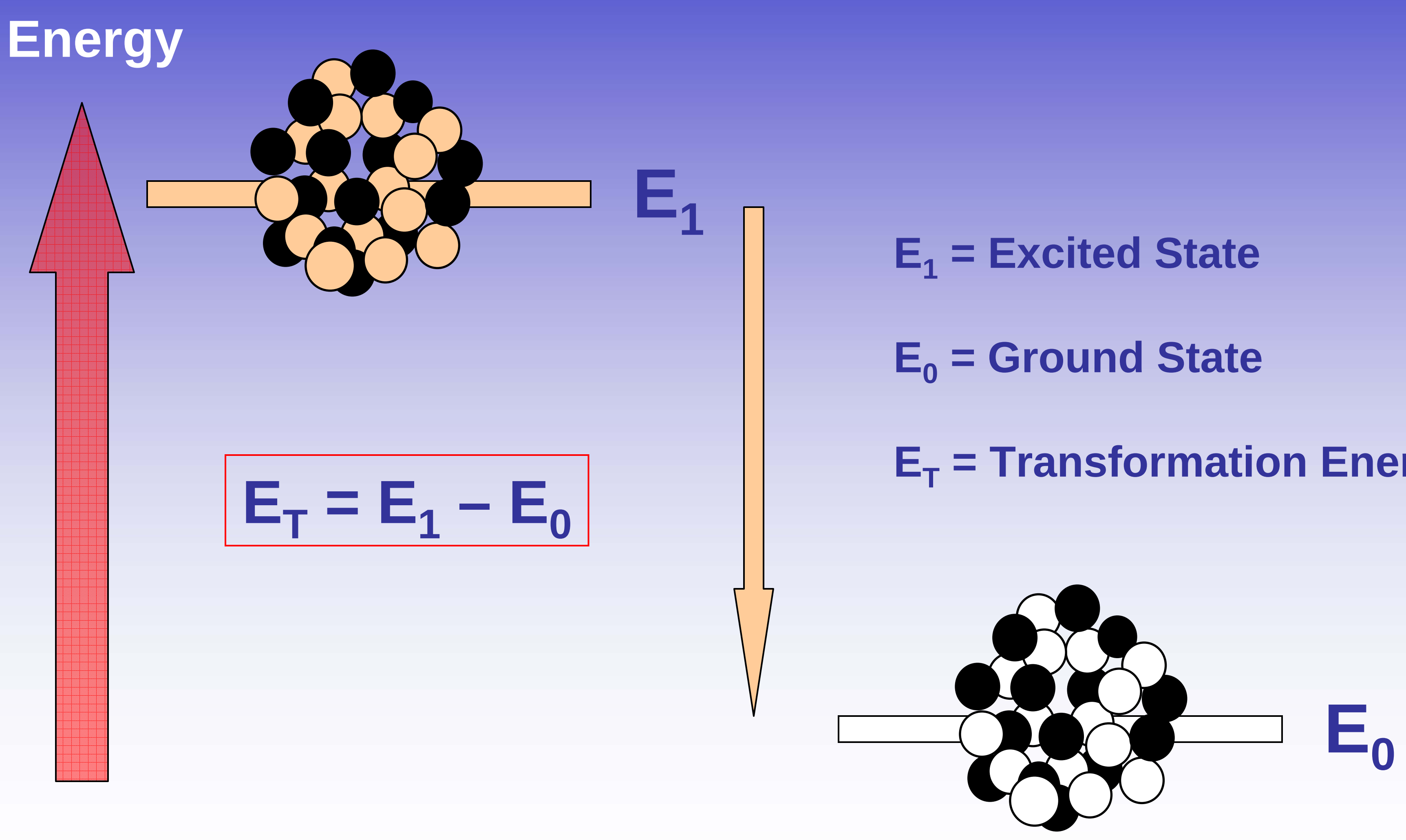
→ **- Δm**

Nuclear Transformation



<u>Ionizing</u> <u>Radiation</u>: α, β, or γ

Nuclear Transformation



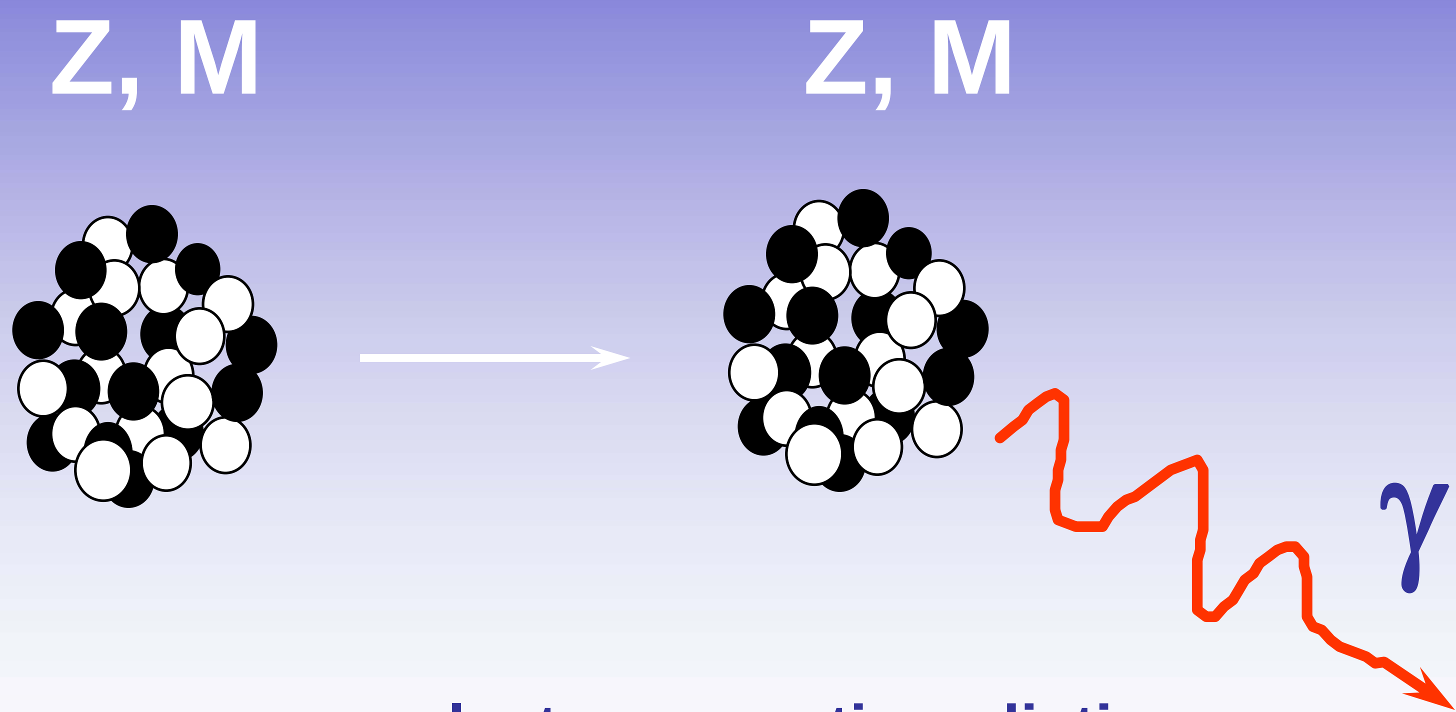
$$E_T = E_1 - E_0$$

E_1 = Excited State

E_0 = Ground State

E_T = Transformation Energy

Gamma Rays



Gamma rays are electromagnetic radiation resulting from nuclear transformation.

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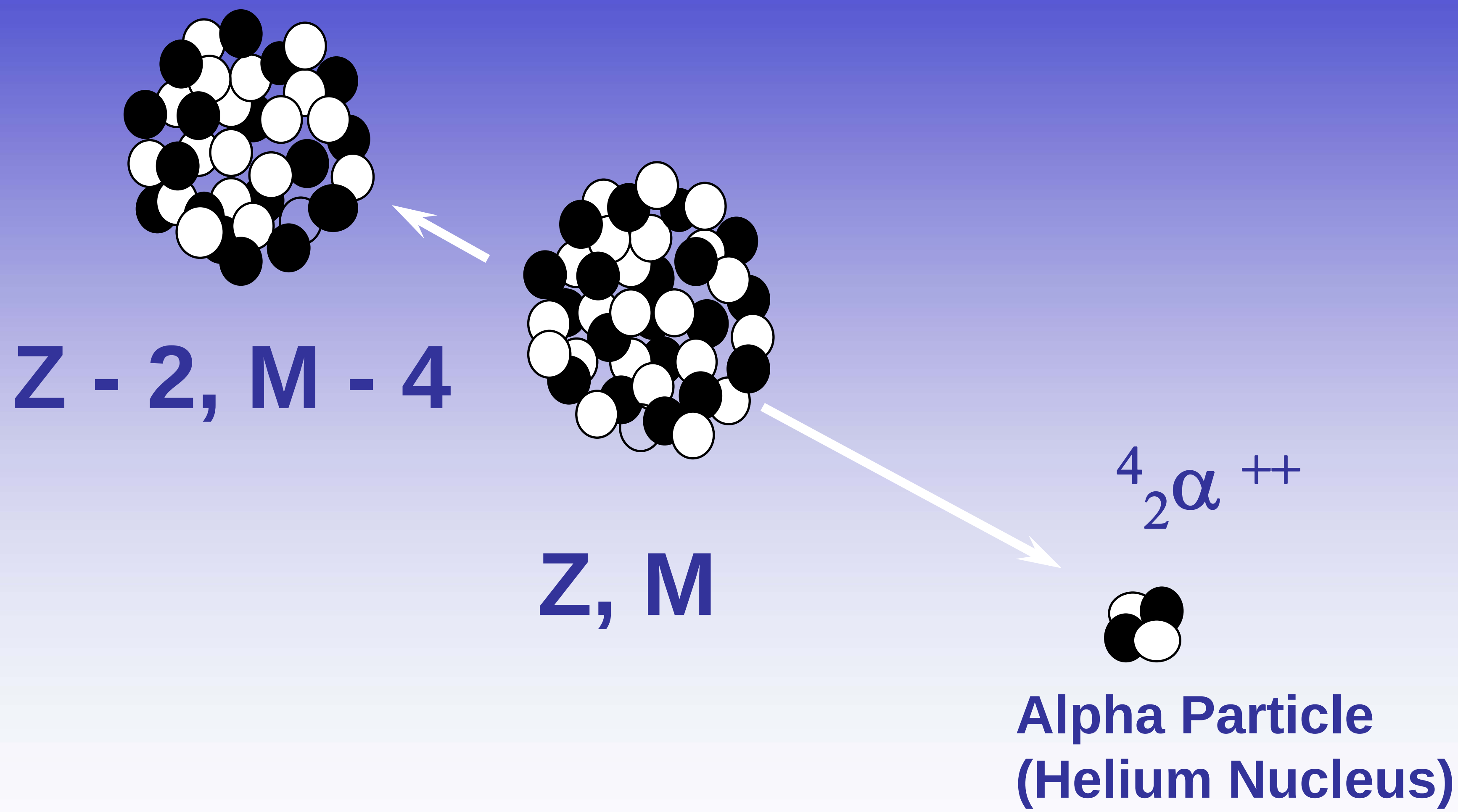
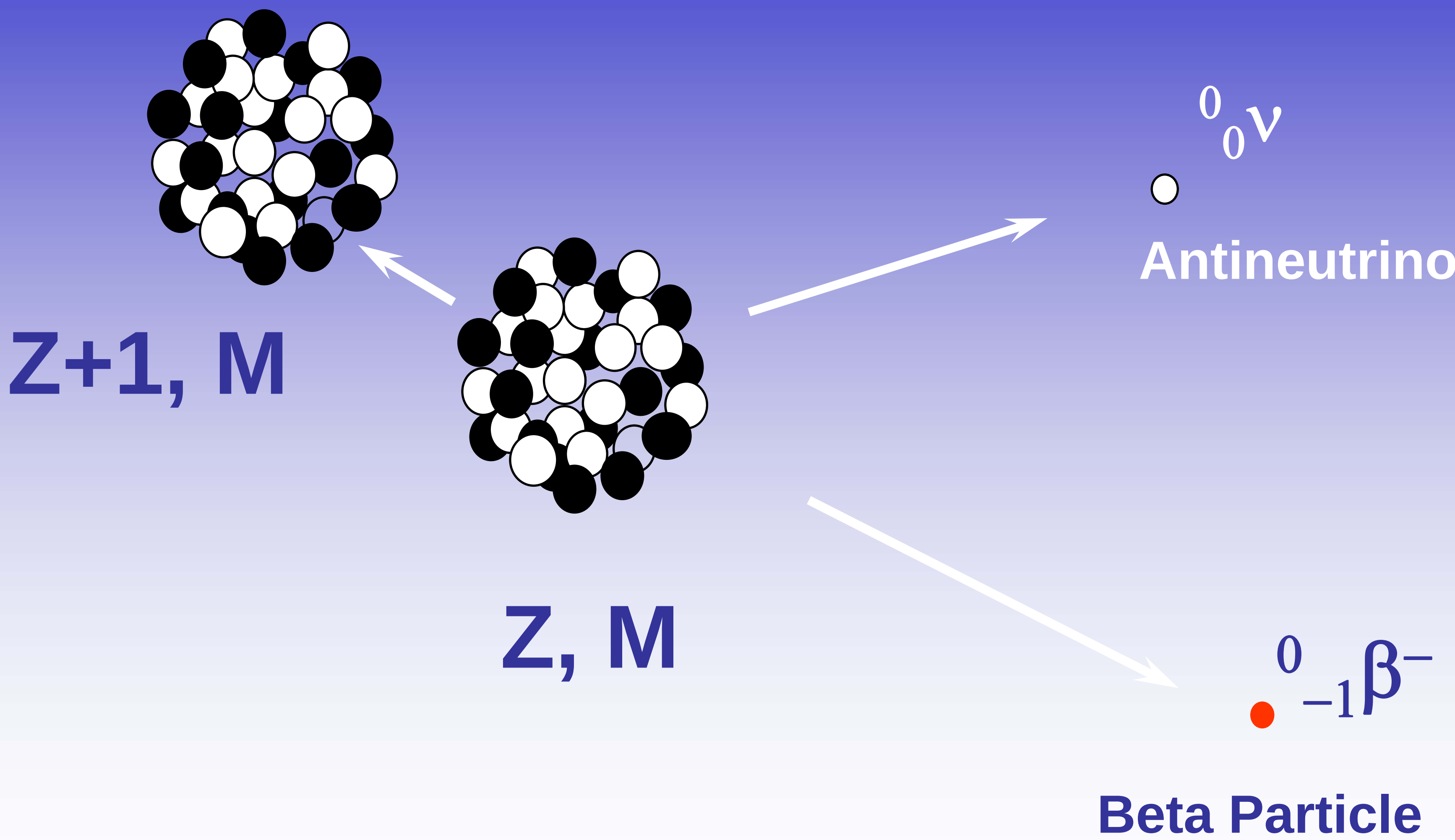
Particulate Radiation

- Charged particles are emitted from the atomic nucleus at high energy in some nuclear transformations. These include alpha and beta particles.
- Uncharged particles (neutrons) are produced by fission or other nuclear reactions.
- Both types of particles produce ionization.

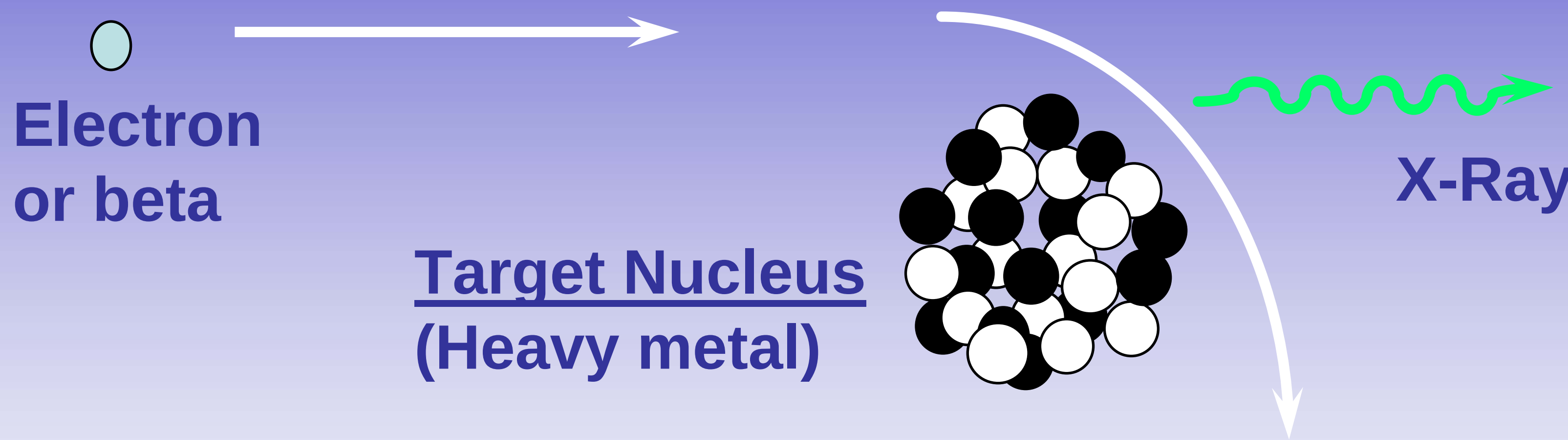
Alpha Particles



Beta Particles



Production of X-Rays

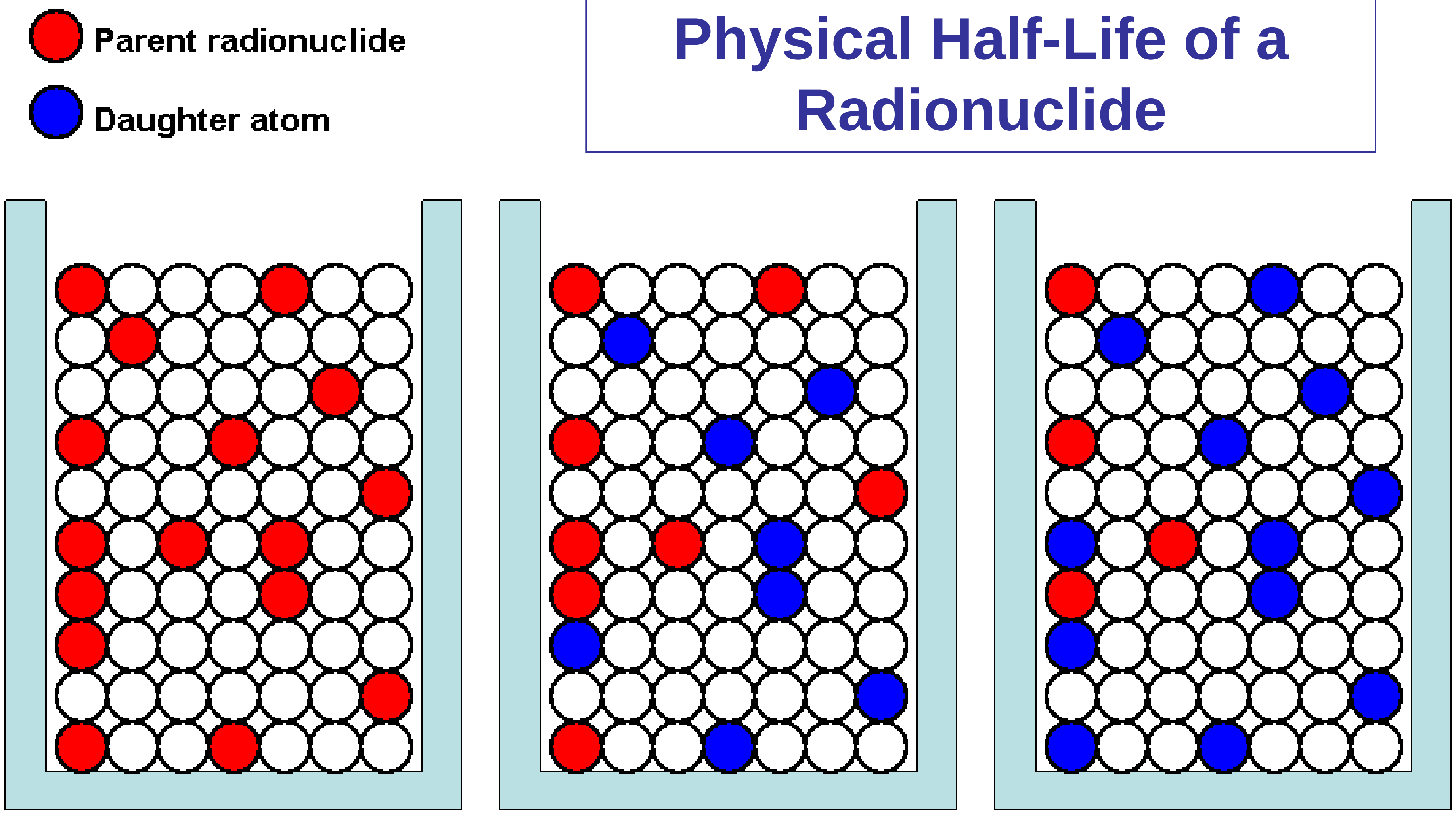


<u>X-rays</u> are produced when a charged particles (electrons or betas) are decelerated by a strong electrostatic field, such as that found near the nuclei of heavy metals (tungsten, lead).

Physical Half-life

- **Radioactive nuclei undergo disintegration at a rate that is proportional to the number of untransformed nuclei present.**
- **The <u>physical</u> <u>half-life</u> is the time required for one-half of the remaining nuclei to transform.**
- **The half-life is characteristic of the radionuclide.**

Simple Model of the Physical Half-Life of a Radionuclide



T = 0
16 Parents

After One Half-life
8 Parents, 8 Daughters

After Two Half-lives
4 Parents, 12 Daughters

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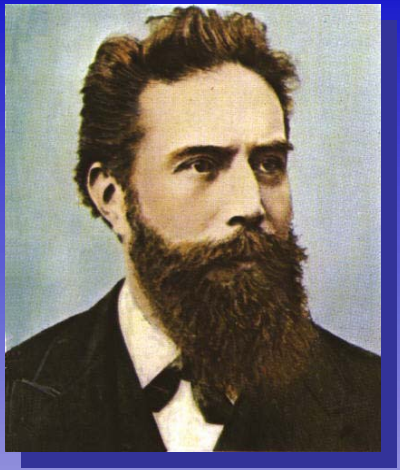
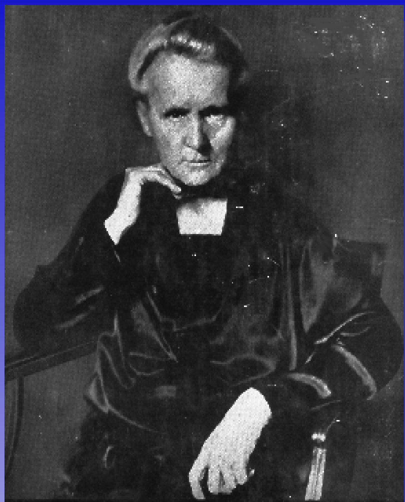
Radioactive "Half-Life"

Radionuclide	Half-Life
Americium-241	432 years
Cesium-137	30 years
Cobalt-60	5.3 years
Iridium-192	74 days
Iodine-131	8 days



Radiation Exposure

- Exposure is an index of the ability of a radiation field to ionize air.
- Radiation passing through a gas liberates ion pairs.
- If the gas is in an electric field, movement of ion pairs can be measured as a current, which is proportional to exposure rate.



Quantity of Radioactive Material

- **<u>Quantity</u> of radioactive material is expressed as the number of nuclear transformations (or disintegrations) that occur in a sample per unit time.**
- **The term for quantity of radioactive material is <u>activity</u>.**

Radiation Absorbed Dose

- <u>Absorbed</u> <u>Dose</u> is a measure of the energy imparted to matter when an ionizing radiation field interacts with matter.
- Absorbed dose is expressed as energy absorbed per unit mass of material.

Equivalent Dose

- **For the <u>same</u> <u>absorbed</u> <u>dose</u> (deposited energy) in tissue, different forms of ionizing radiation can have <u>different</u> biological effects.**
- **"Equivalent Dose" attempts to normalize these differences.**

Equivalent Dose

- **Equivalent Dose is the product of the dose and a modifying factor called the quality factor (QF), which reflects the relative biological effectiveness of the radiation:**

$$H_T = D \times QF$$

Quality Factors (QF)

- **QF are <u>indices</u> of the "relative biological effectiveness" (RBE) of a radiation. RBE is a complicated function of type of radiation, energy and the biological system under consideration.**
- **QF are not measured. They are determined by a committee.**

Some Values of QF

Radiation	QF (ICRP 60)
Photons, electrons (all energies)	1
Thermal neutrons (< 10 keV) and neutrons > 20 MeV	5
Neutrons 10 keV – 200 keV Neutrons 2 – 20 MeV	10
Alphas, neutrons (100 keV- 2 MeV), protons, fission fragments	20

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Effective Dose Equivalent

- <u>Effective Dose Equivalent (EDE)</u> is intended to reflect the total biological effect of a given exposure on a human. It is a <u>weighted</u> <u>average</u> of the individual doses to a number of important tissues:

$$H_E = \Sigma (H_T \times W_T)$$

(sum is over all tissues)

Effective Dose Equivalent

- **Effective Dose Equivalent (EDE) is a <u>derived</u> quantity, not a measurable quantity.**
- **Applies to situation where irradiation of organs and tissues is <u>non-uniform</u>.**
- **EDE yields the same "radiation detriment" as a numerically-equivalent whole-body dose.**
- **W_T values are assigned by a committee.**

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Some Tissue Weighting Factors

Tissue / Organ	ICRP 26	ICRP 60*
Gonads	0.25	.20
Red Marrow	0.15	.12
Colon	0.05	.12
Lung	0.12	.12
Breast	0.12	.05
Thyroid	0.03	.05
Bone Surfaces	0.03	.01

***When ICRP 60 weighting factor and algorithm are used, result is expressed as "effective dose" as opposed to "effective dose equivalent" in the ICRP scheme.**

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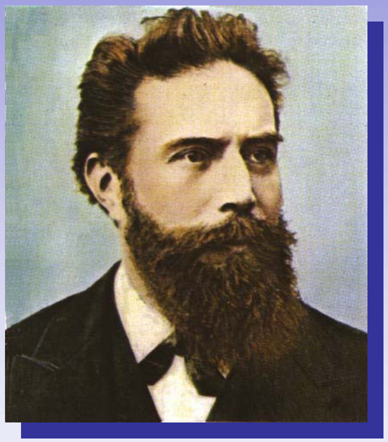
Radiation Units

- **Two systems are in common use:**
  - **Special Units**
  - ***System Internationale* (SI) Units**
- **Special units are used by most regulatory agencies in the U.S.**
- **SI units and are used in the rest of the world, and are based on “MKS”**

Units of Exposure and Quantity

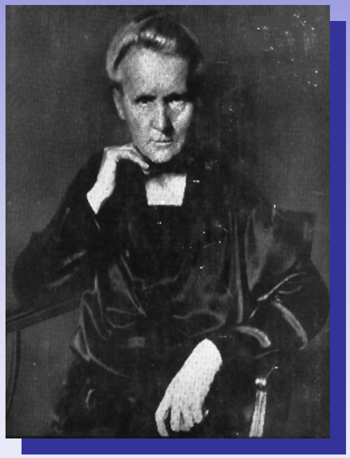
Special Units

Roentgen (R)



2.58 x 10^{-4} coulombs / kg dry air at STP

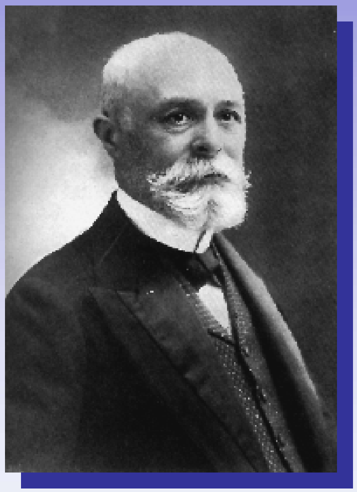
Curie (Ci)



Disintegrations per second in 1 gm radium (3.7 x 10^{10} dps)

SI Units

Becquerel (Bq)



1.0 dps

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Units of Absorbed Dose

Special Units

rad

radiation absorbed dose (100 erg/gm)

SI Units

gray (Gy)

S.I. unit: 1.0 J/kg (100 rads)

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Units of Equivalent Dose and EDE

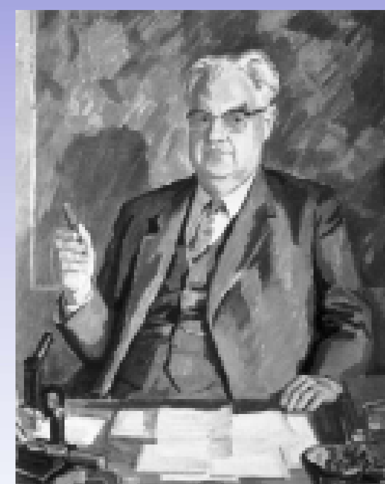
Special Units

rem (rem)

roentgen **e**quivalent **m**an
(rad x quality factor)

SI Units

sievert (Sv)



Gy x quality factor

Computing Exposure Rate

- **If the activity of a source of gamma rays is known, the exposure rate as a given distance from the source can be computed.**
- **Exposure rate at 1 centimeter and activity are related by a quantity called the <u>specific gamma constant</u> (Γ).**
- **Assumes that source is a point source.**

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Computing Exposure Rate

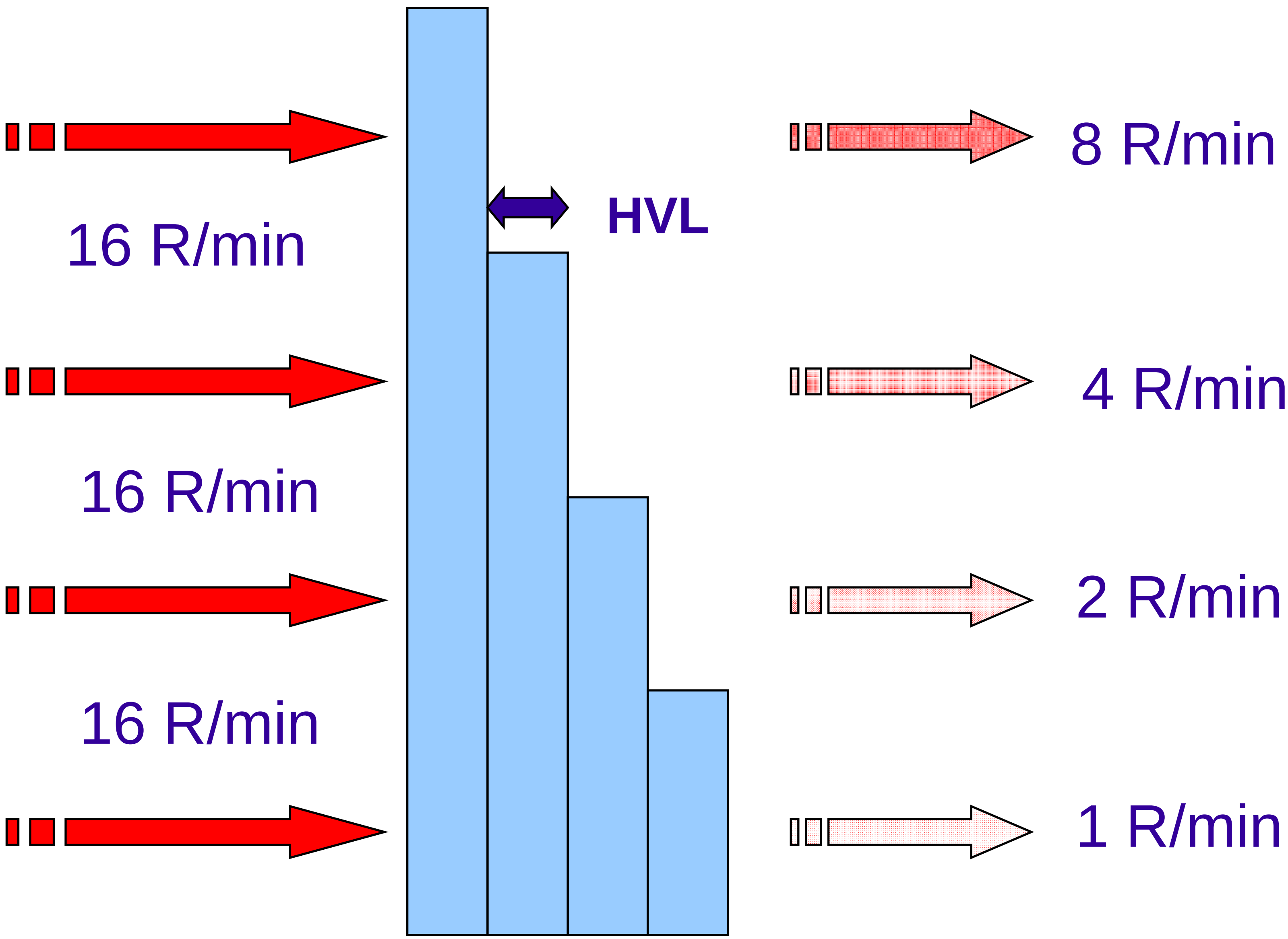
$$R = \Gamma A / r^2$$

R = exposure rate (roentgens/hr)
Γ = specific gamma constant (R/hr-mCi at 1 cm)
A = source activity (mCi)
R = distance from source (cm)

Half Value Layer (HVL)

- **Is the thickness of a material required to reduce the transmitted exposure rate (R) to <u>one</u> <u>half</u> the incident exposure rate (R_0).**
- **HVL depends upon the material's atomic number and density, and upon the energy spectrum of the incident photons.**

Photon Attenuation by Adding HVLs



Half Value Layer (HVL)

Energy (kVp)	Lead (cm)	Concrete (cm)
50	0.005	0.432
70	0.015	0.838
100	0.024	1.524
125	0.027	2.032
150	0.029	2.235

Attenuation of Photons by Shielding

$$R = R_0 \left(\exp \left(-\, 0.693\ t \,/\, HVL \right) \right)$$

R = Attenuated exposure rate
R_0 = Primary Exposure Rate
t = thickness of shielding (cm)
HVL = "Half Value Layer" (cm)

Attenuator Blocks to Modify Irradiator Dose Rate

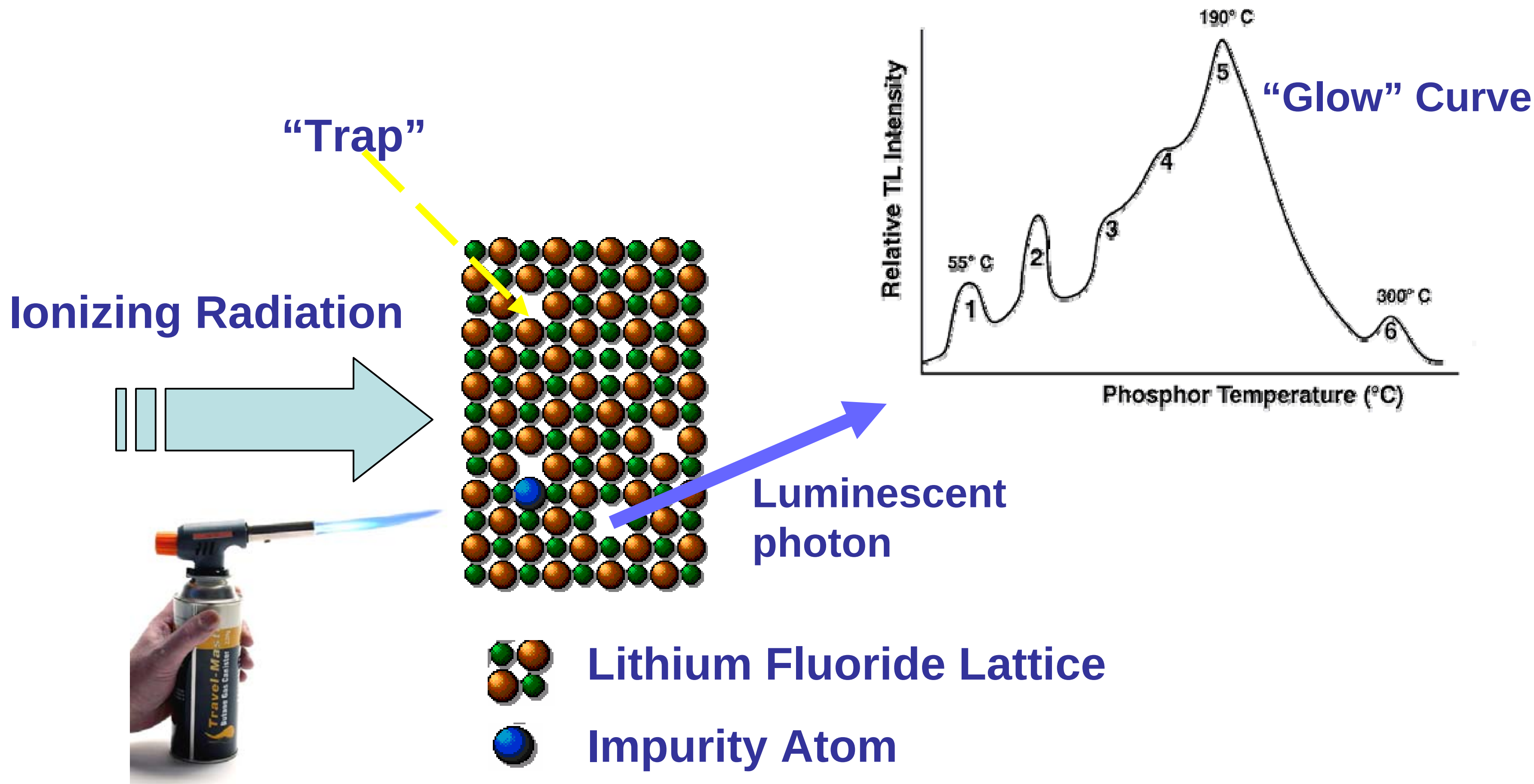
“Stacking” lead attenuator blocks can incrementally reduce the dose-rate and shape the dose profile inside the irradiation chamber

Calorimetric Dosimetry

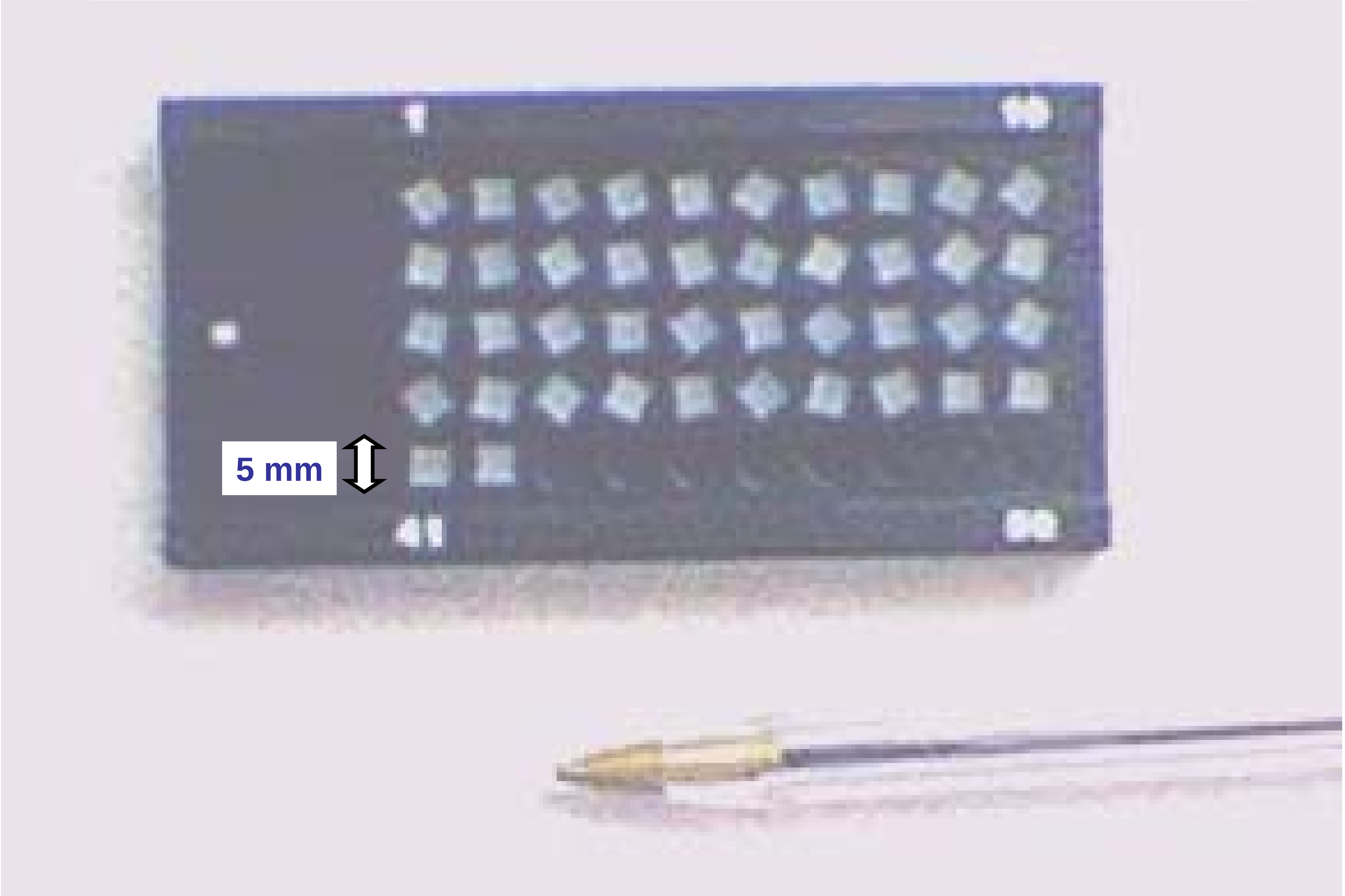
- **Energy released in a medium by ionizing radiation ultimately degraded to thermal energy.**
- **Thermal energy will raise the temperature of the medium.**
- **For water, 1.0 Gy increases the temperature by 0.24 mK (0.00024 degree centigrade)**

Thermoluminescence Dosimetry

Radiation produces free electrons in the crystal, which fall into “traps” at the sites of lattice imperfections. Later, the crystal is heated, which liberates the “trapped” electrons. This process releases light, in proportion to the original radiation dose.

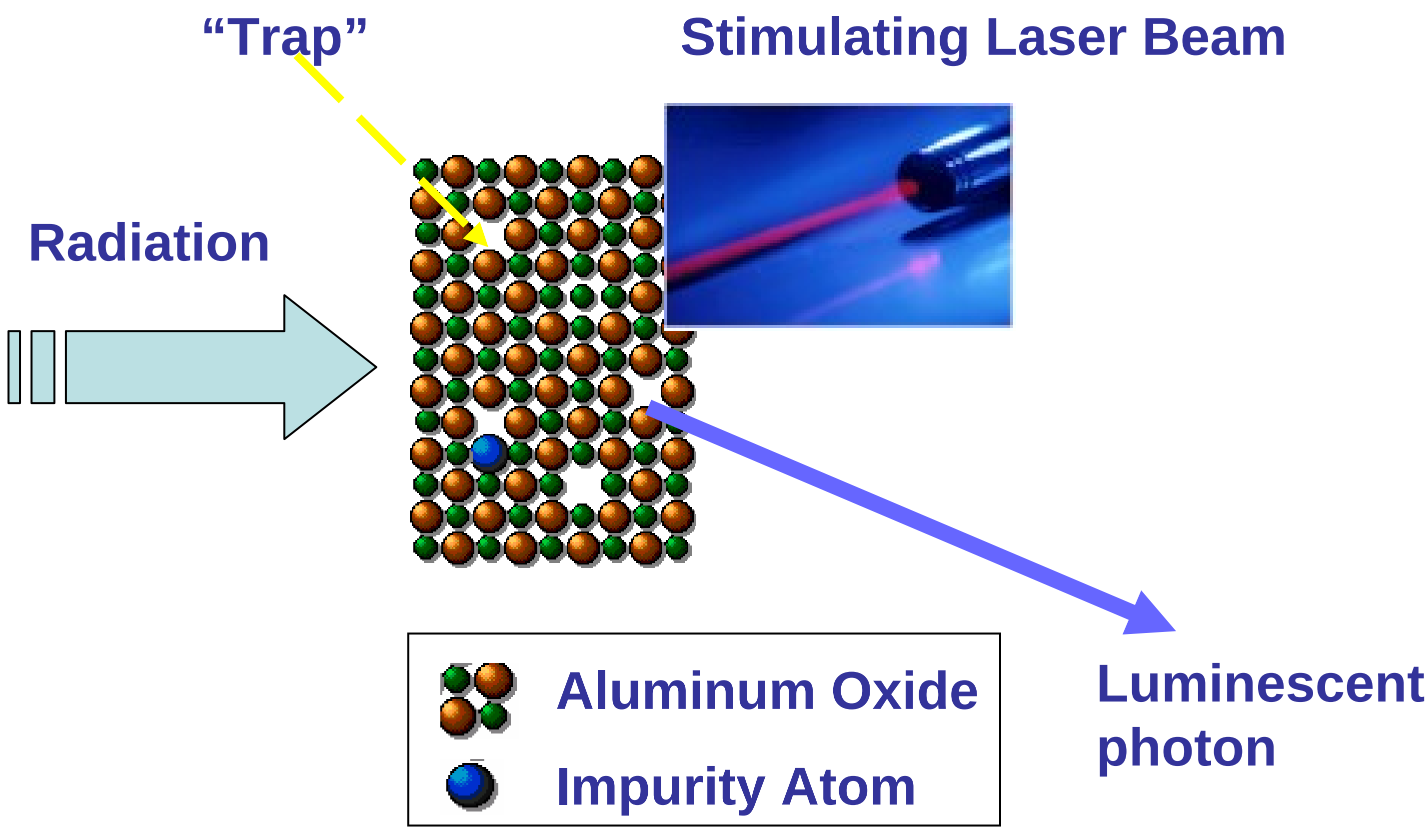


TLD “Chips” are Tissue Equivalent and Can be Miniaturized

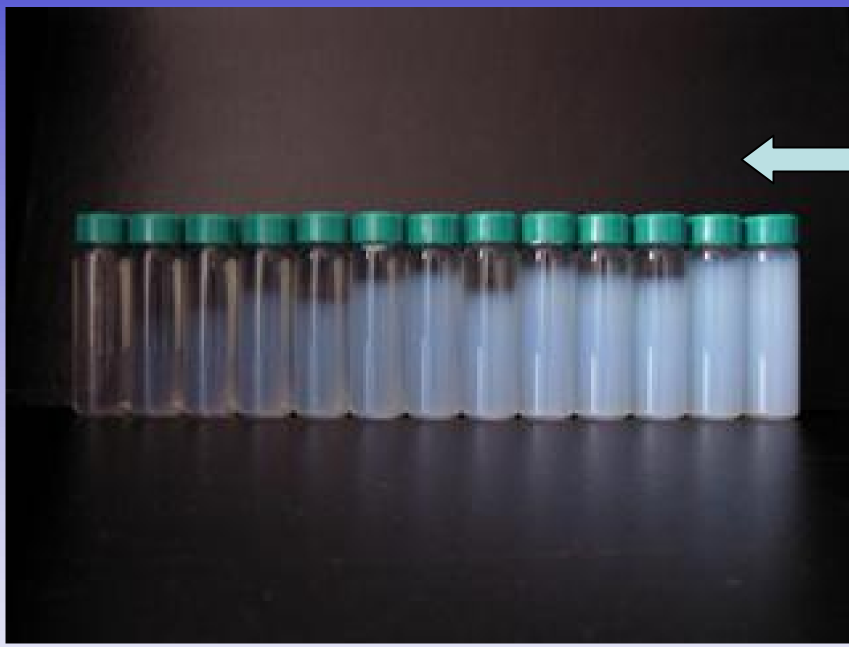


Optically Stimulated Luminescence Dosimetry

Radiation produces free electrons in the crystal, which fall into "traps" at the sites of lattice imperfections. Later, the crystal is exposed to a burst of laser light, which liberates the "trapped" electrons. This process releases light, in proportion to the original radiation dose.

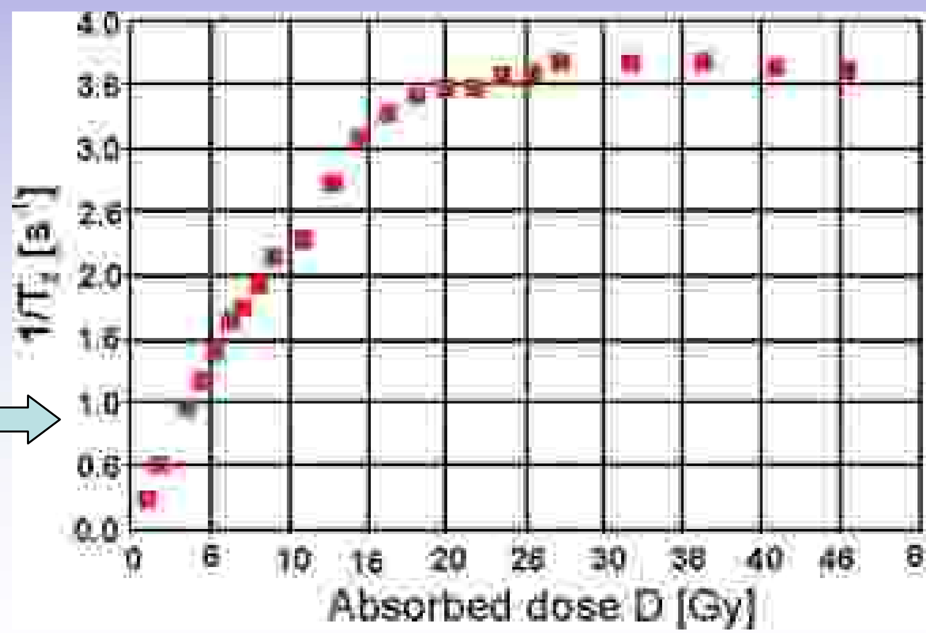


Polyacrylamide Gel Dosimetry



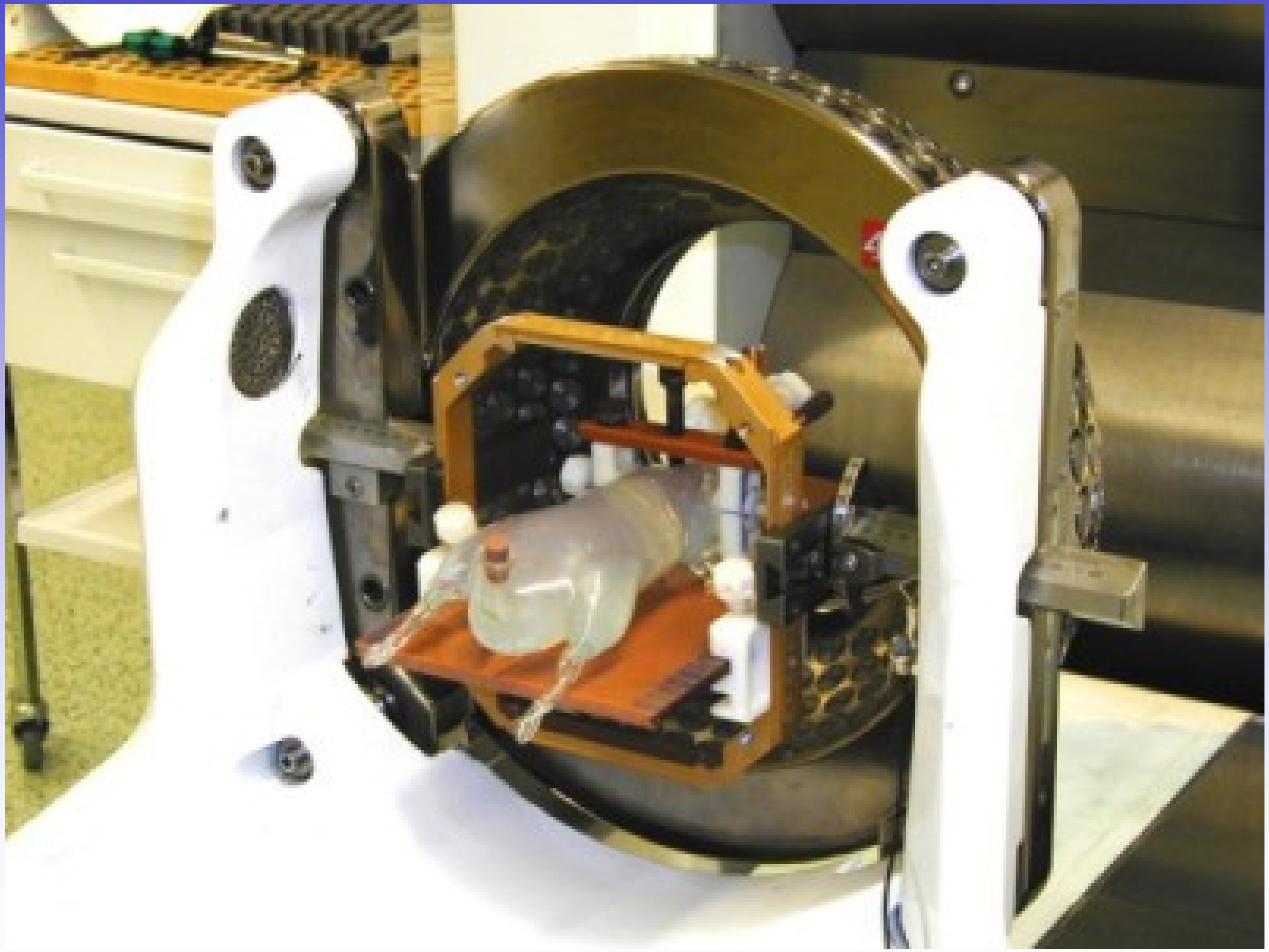
When irradiated, polyacrylamide polymer gels change chemical characteristics. Tubes have been irradiated with 0 (left) to 11 (right) Gy.

Chemical changes can be quantified by MRI scanning. Changes in T1 can calibrate absorbed dose.



Source: Prague 3D Gel Dosimetry Group (http://3dgeldos.fjfi.cvut.cz/results/)

Polyacrylamide Gel Dosimetry



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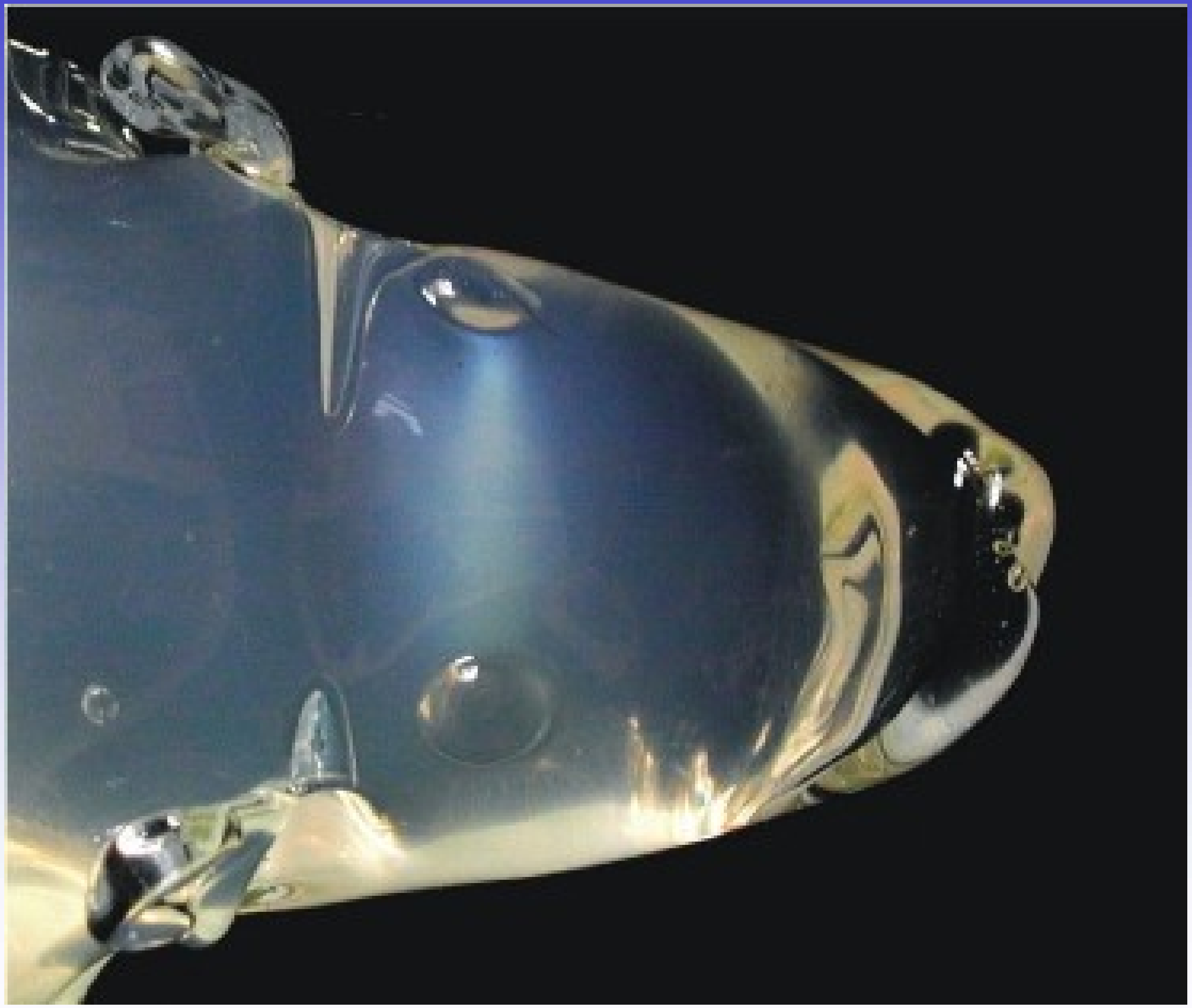
Polyacrylamide Gel Dosimetry



Source: Prague 3D Gel Dosimetry Group (http://3dgeldos.fjfi.cvut.cz/results/)

MOSFET Dosimetry

MOSFET detectors are semiconductors that generate measurable electric current when irradiated. Current is proportional to dose rate.