PHILLIP WU. JANUARY 5, 2021

Modern Physics

Topics in Medical Physics

X-ray Absorption coefficients of different elements and biological tissue

± From considering Beer-Lambert law, $I=I_0e^{-\alpha*x}$

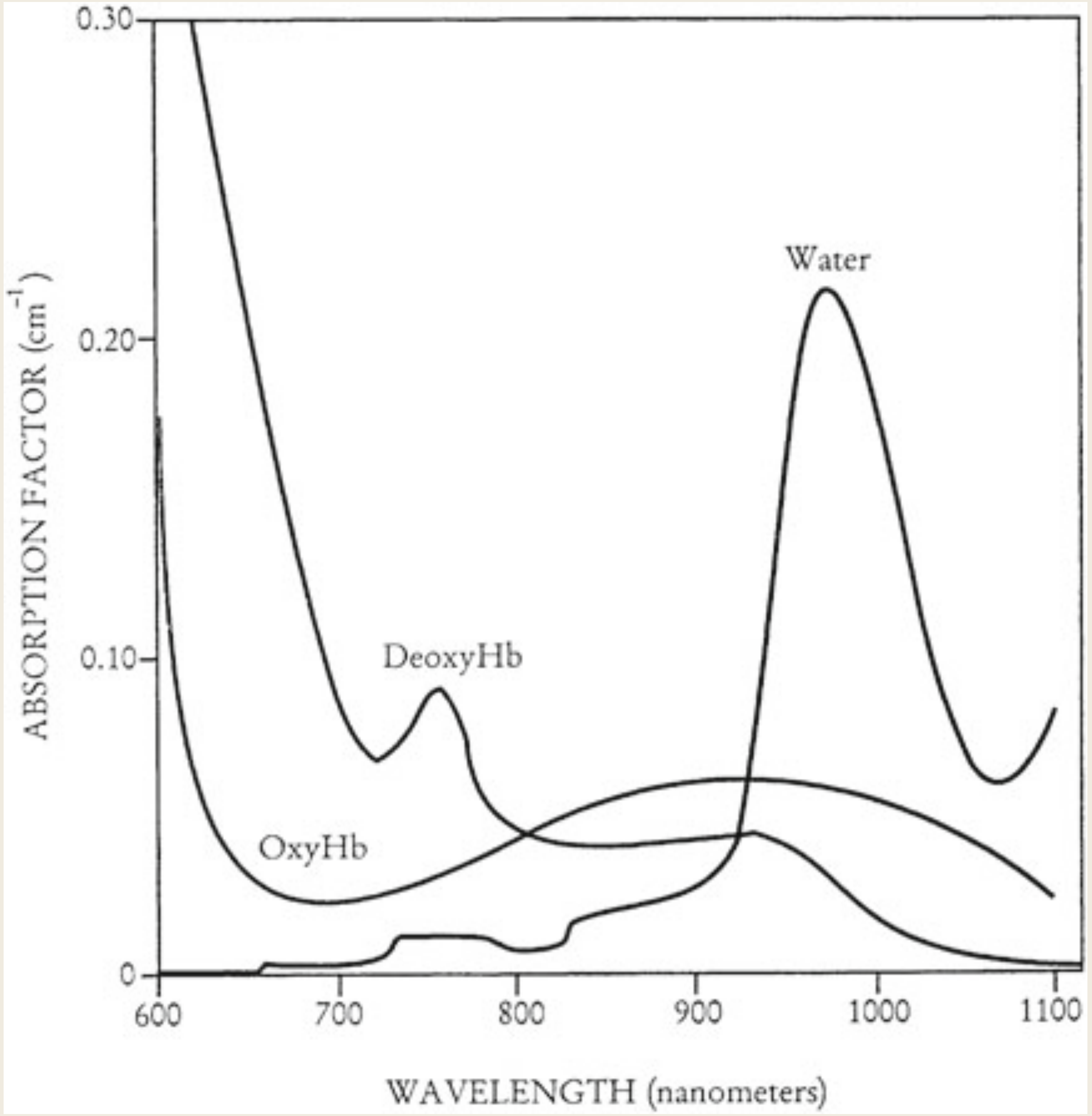
Material	Atomic #	Absorption	Specific Absorption
		Coefficient, α (cm^{-1})	Coefficient, α/ϱ (cm^2/g)
Fat	–	0.1788	0.196
Muscle	–	0.2045	0.2045
Brain		0.2061	0.2061
Bone		0.466–0.548	~0.28 cm^2/g since bone ϱ correlates with α
Al	13	131	48.7
P	15	132	73
Ca	20	266	172
Cr	24	1.86×10^3	259
Fe	26	2.55×10^3	324
Co	27	3.19×10^3	354
Pb	82	2.73×10^3	241

Attenuation Coefficients

With atoms and light, the attenuation coefficient helps us greatly to understand the light matter interaction. Considering the average number of photons scattered or absorbed

$N(z) = N_0 e^{-(\mu_s + \mu_a)z}$

We also consider the probability of interaction per target entity when a light beam has Φ photons per unit area, $p = \sigma\Phi$.



Infrared Radiation from the Body

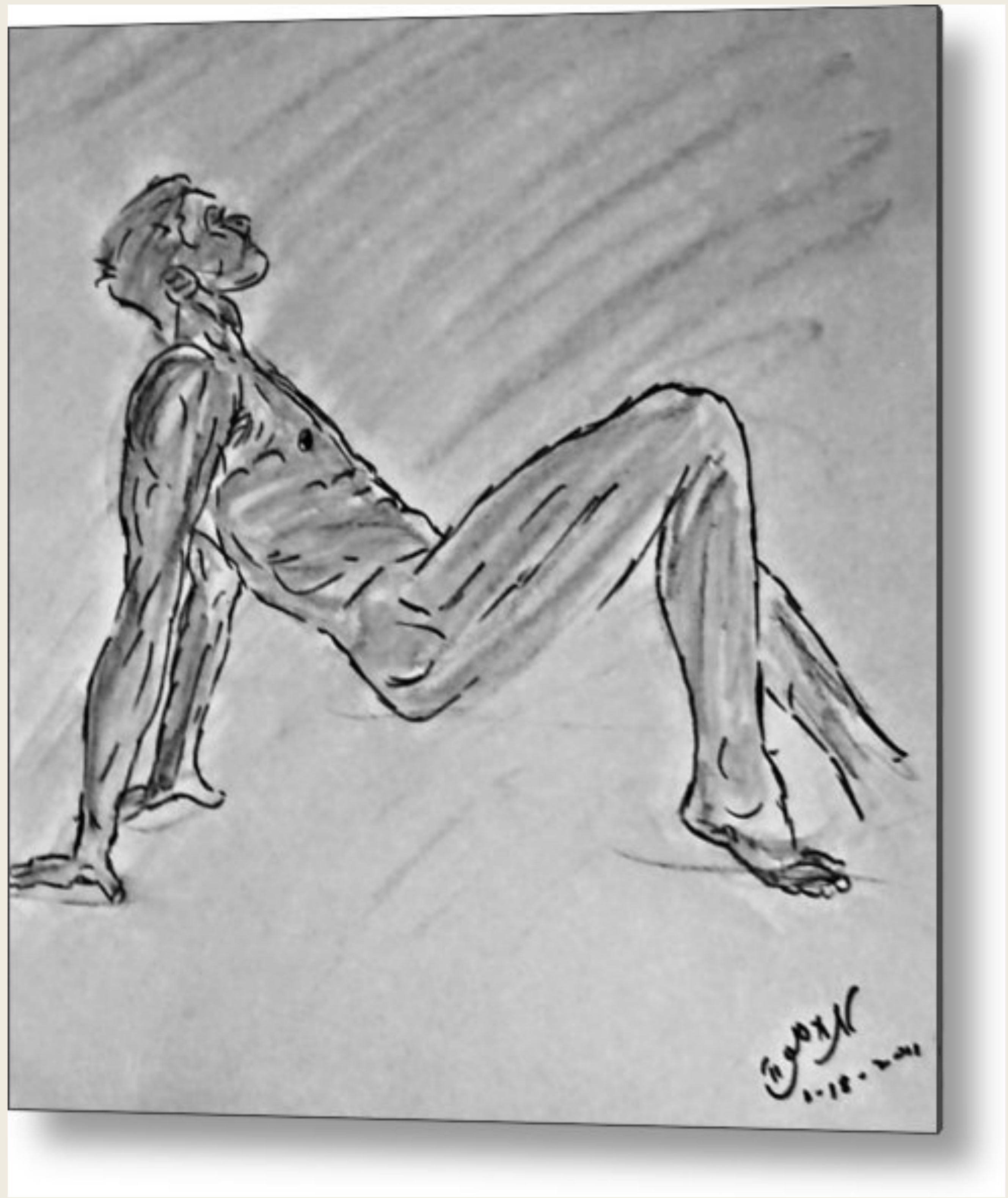
Consider the blackbody radiation formula.

$w_{T0t} = S\sigma_{SB}(T^4 - T_s^4) = (1.73)(5.67 * 10^{-8})(306^4 - 293^4) = 137W$

We assume the total surface area of a male adult is 1.73 m^2 and that the room in which the body is, is at room temperature.

Thus, a nude subject surrounded by walls of 20 degrees Celsius would have to exercise to maintain body temperature.

This technique is noninvasive and may also be used to image oxygenated or deoxygenated blood ~2 to 3 mm below skin surface when illuminating with 700 to 900 nm light.



Ultraviolet Light

From the sun can be classed into the following:

UVA 315-400 nm

UVB 280-315 nm

UVC 200-280 nm

Far UV 120-200 nm

Extreme UV 10-120 nm

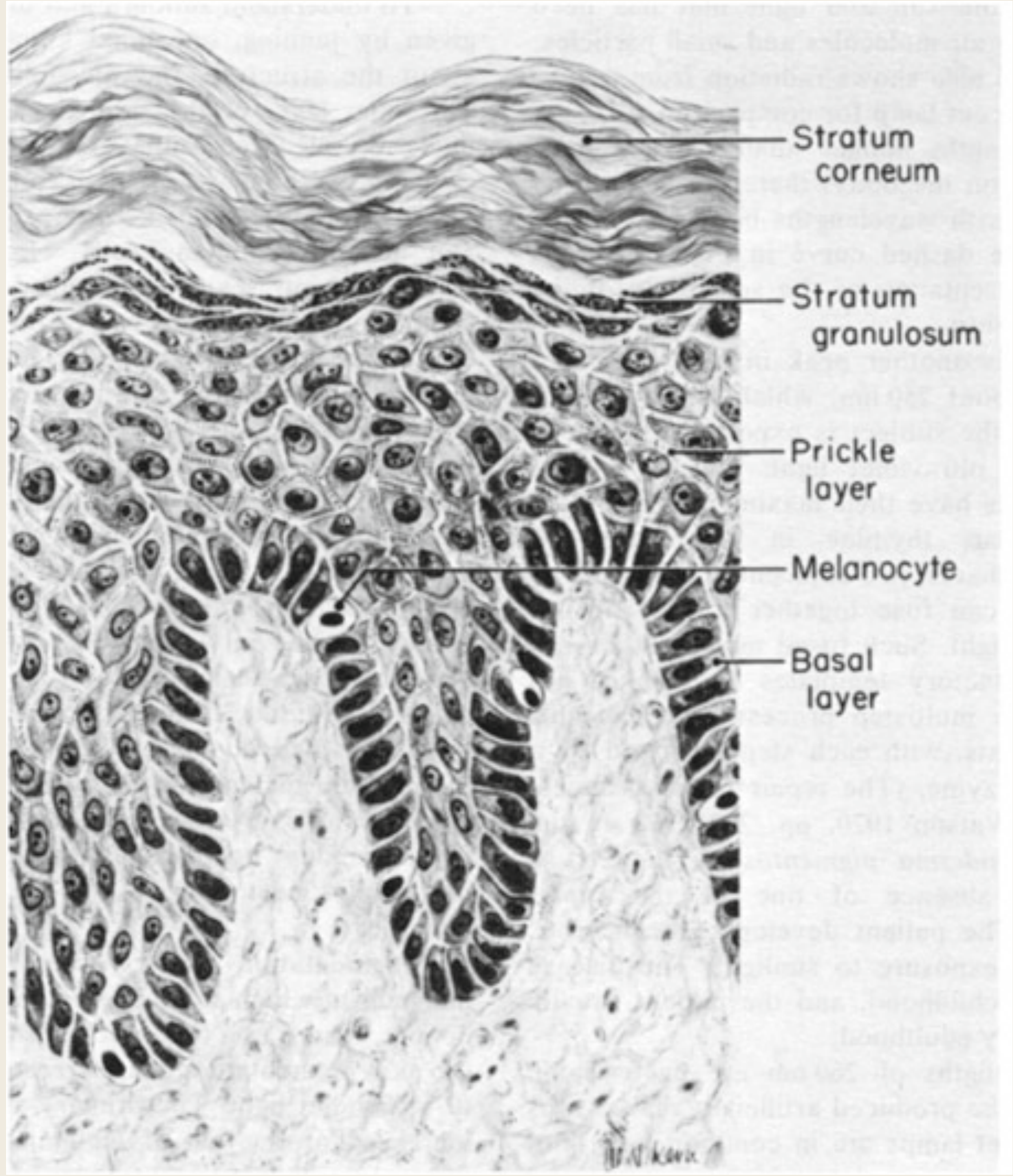


Fig. 14.29 The epidermis. The basal layer contains the cells from which the other layers are derived. As the cells move toward the surface they become the prickle layer and the stratum granulosum. The stratum corneum is dead cellular debris. The melanocytes, which produce melanin granules, are in the basal layer. (Reprinted from Pillsbury and Heaton 1980 with permission from Elsevier.)

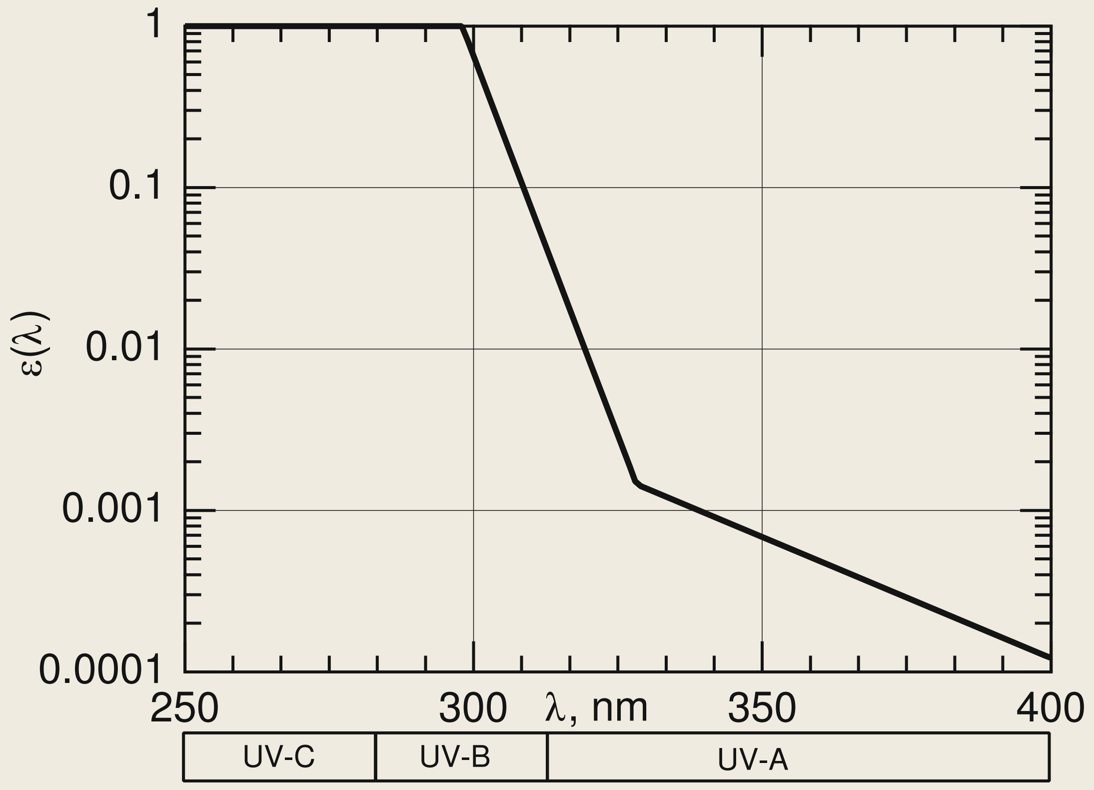


Fig. 14.30 The erythema action spectrum $\epsilon(\lambda)$ for ultraviolet light, as adopted by the CIE in 1987

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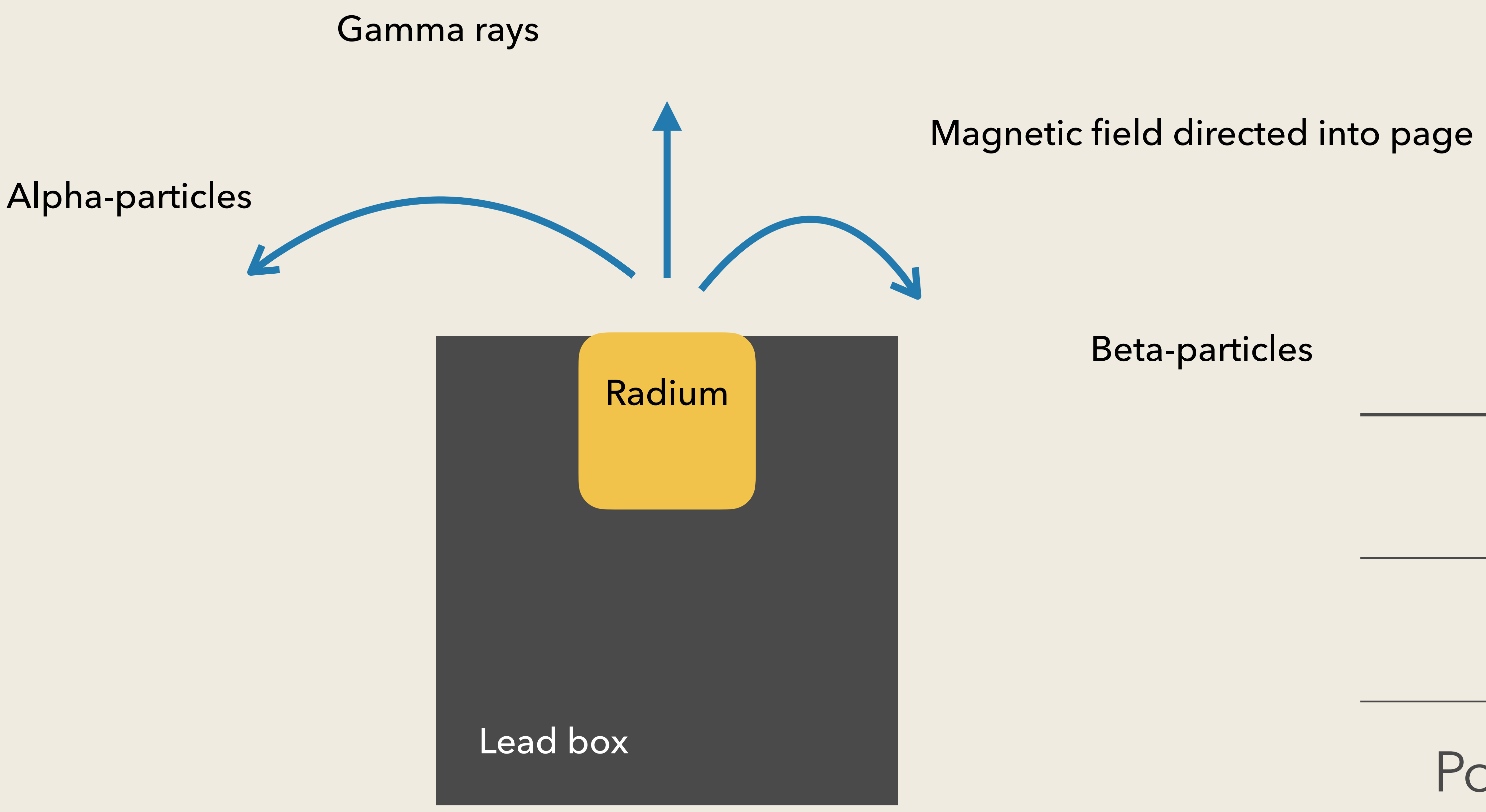
Radioactive Decay



Decay type	Transformation	Example
Alpha decay	${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He$	${}^{238}_{29}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He$
Beta decay	${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^{-}$	${}^{14}_{6}C \rightarrow {}^{14}_{7}N + e^{-}$
Positron emission	${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + e^{+}$	${}^{64}_{29}Cu \rightarrow {}^{64}_{28}Ni + e^{+}$
Electron capture	${}^{A}_{Z}X + e^{-} \rightarrow {}^{A}_{Z-1}Y$	${}^{64}_{29}Cu + e^{-} \rightarrow {}^{64}_{28}Ni$
Gamma decay	${}^{A}_{Z}X^{*} \rightarrow {}^{A}_{Z}X + \gamma$	${}^{87}_{38}Sr^{*} \rightarrow {}^{87}_{38}Sr + \gamma$

Radioactive Decay

On the Earth for example, we would have the radioactivity defined as

$$R = -\frac{dN}{dt}$$

Here the units in SI for the activity is Becquerel = 1 Bq = 1 decay/second

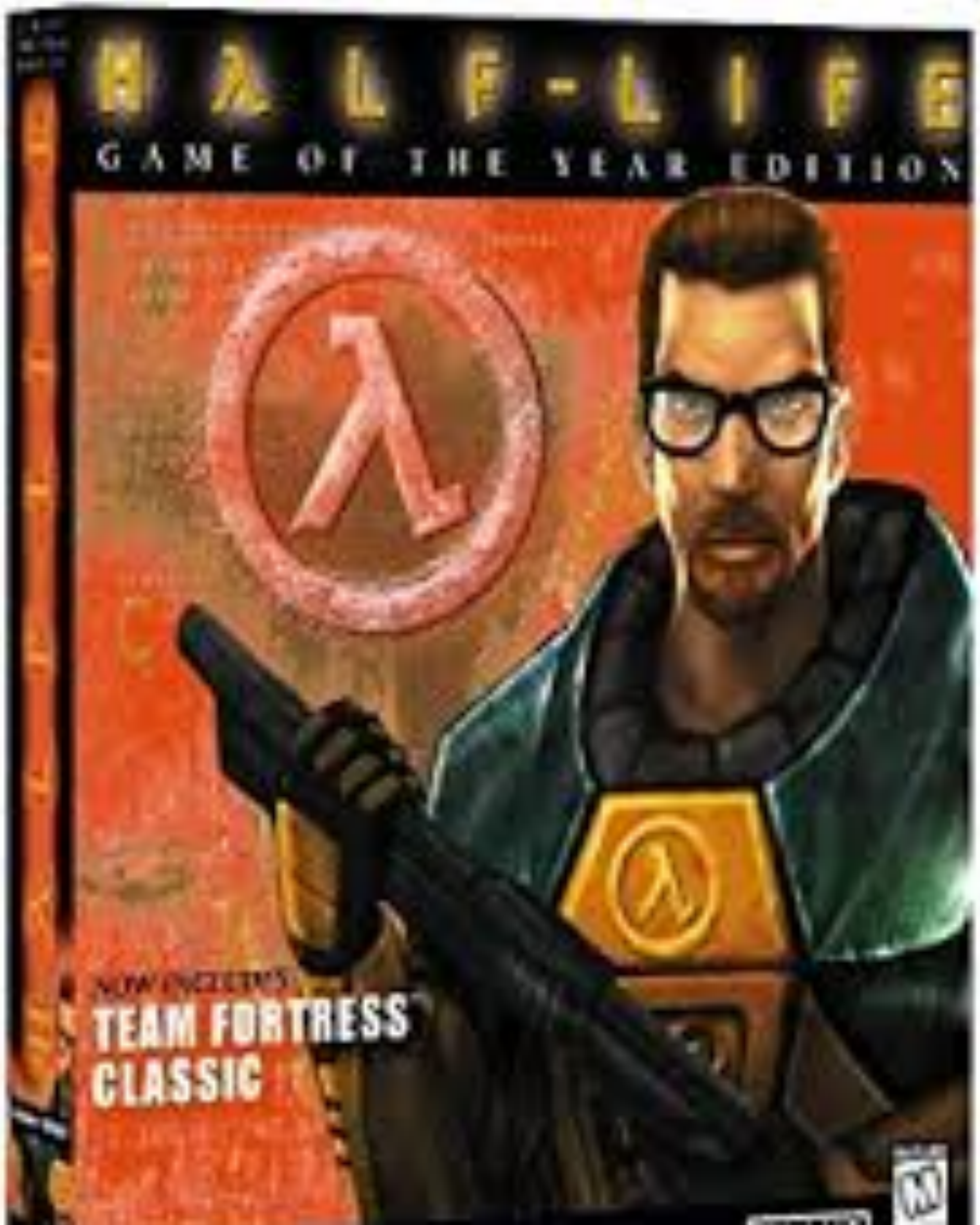
For reference, most radioactivities are in the megabq to to gigabq range.

As an example, 1 gram of radium, ${}^{226}_{88}Ra$ is 1 Curie (a traditional unit) = 1 Ci = 3.7 * 1010 decays/s = 37 GBq

As a comparison, potassium has activity of 0.7 microCi per kilogram, mainly from ${}^{40}_{19}K$.

Importantly for medical physics, the dosage is measured in Sieverts, Sv, the amount of radiation absorbed equivalent to 1 kg of body tissue absorbing 1 Joule of x-rays or gamma rays.

Average risk factors are placed at 0.05 /Sv so that the chance of dying from cancer as a result of radiation are 1 in 20 for a dose of 1 Sv, 1 in 20,000 for a dose of 1 mSv and so on.



The Half-Life

“Less and less but always some left”

$$R = R_0 e^{-\lambda t}$$

For example, the activity of radioactive elements reduces to the following at half its life

$$\frac{1}{2} R_0 = R_0 e^{-\lambda T_{1/2}}$$

$$e^{\lambda T_{1/2}} = 2$$

Radioactive Decay

Example: Find the activity of 1.00 mg of radon, ^{222}Rn, with atomic mass of 222 u. In 1 mg of radon,

$$\lambda = \frac{0.693}{T_{1/2}} = \frac{0.693}{(3.8d)(86{,}400s/d)} = 2.11 * 10^{-6}/s$$

$$N = \frac{1 * 10^{-6}kg}{(222u)(1.66 * 10^{-27}kg/u)} = 2.71 * 10^{18}atoms$$

$$R = \lambda N = (2.11 * 10^{-6}/s)(2.71 * 10^{18}nuclei) = 5.72 * 10^{12}decays/s = 5.72TBq = 155Ci$$

Example: 1 week later, the activity of this radon sample will then be,

$$\lambda t = (2.11 * 10^{-6}/s)(7days)(86{,}400s/day) = 1.28$$

$$R = R_0 e^{-\lambda t} = (155Ci)e^{-1.28} = 43Ci \longleftarrow$$ Very bad

The Effects of Nuclear Weapons

The primary dangers after nuclear weapon fallout is from long lived isotopes.

Radioactivity

Biological effects:

We can use this method to estimate the cumulative activity from radioactive substances

$$\tilde{A}_h = A_h \int_0^\infty e^{-\lambda t} dt = \frac{A_h}{\lambda} = \frac{F_h A_0}{\lambda}$$

$$\tau_h = \frac{\tilde{A}_h}{A_0} = \frac{F_h}{\lambda} \approx T_{1/2}$$

Nuclear binding, fission and fusion

The (inverse) process of binding is to release nuclear energy.

Nuclear energy can be released by fission of a heavy nucleus or fusion of two light nuclei.

Energy is produced because the end product of a more tightly bound nucleus than the initial state is formed.

$$\Delta E = (m_i - m_f)c^2 = \Delta mc^2$$

$$^{1}_{0}n + ^{238}_{92}U \rightarrow ^{239}_{92}U \rightarrow ^{239}_{93}Np + e^- + \bar{\nu}$$

20 minutes

$$^{239}_{93}Np \rightarrow ^{239}_{94}Pu + e^- + \bar{\nu}$$

2 days

This reaction typically occurs for a 40 ton mass with a rate given as the thermal power/ energy released per fission at $3*10^{19}$ /s, and the estimated electric power for such a mass of 3% enriched Uranium is approximately 1GW-year.

Radiation Safety

As an example: consider the fission from the Uranium reactor.

Supposing the fission rate is $3*10^{19}$ /s, meaning the radioactive intensity of a nuclear reactor core is around 10^9 Ci.

Without shielding, from $N(t) = N_0 e^{-t/\tau}$, the flux at a distance of 100 m would be 10^5 rem/hour.

Exposure times of $\Delta t = 6*10^{-3}$ hour = 20 seconds or so would be 600 rem, a lethal dose.

Some numbers for reference:

10 rem - detectable blood changes

200 rem - injury and some disability

400 rem - 50% deaths in 30 days

600 rem - 100% deaths in 30 days

Nuclear Weapons

The enrichment process enhances probability that a neutron will cause fission.

For comparison, 1kg of TNT (trinitrotoluene) releases 1000 kcal of energy or $4*10^6$ J (the energy consumed by a 40 W light bulb in a whole day).

A Uranium nuclear weapon releases 200 MeV or 10^7 times more energy.

The Hiroshima bomb was ~12 kt of TNT.

Note that average household energy needs ( )

The Effects of Nuclear Weapons

The primary dangers after nuclear weapon fallout is from long lived isotopes.

6% of fissions leads to this →

	Lifetime tau	Retention	Limit of safe concentration
90Sr	28 years	36 years	20 microCi
137Cs	30 years	70 days	30 microCi
14C	5600 years	10 days	400 microCi
239Pu	24400 years	180 years	0.4 microCi

In the event of major nuclear exchange, the other dangers are potential atmospheric changes.

Potentially, with the atmospheric temperatures swinging to -37 deg Celsius!

Radiation Safety

Safety standards typically set the limit for public occasional exposure at 0.5 rem/year = 0.005 Sv/year

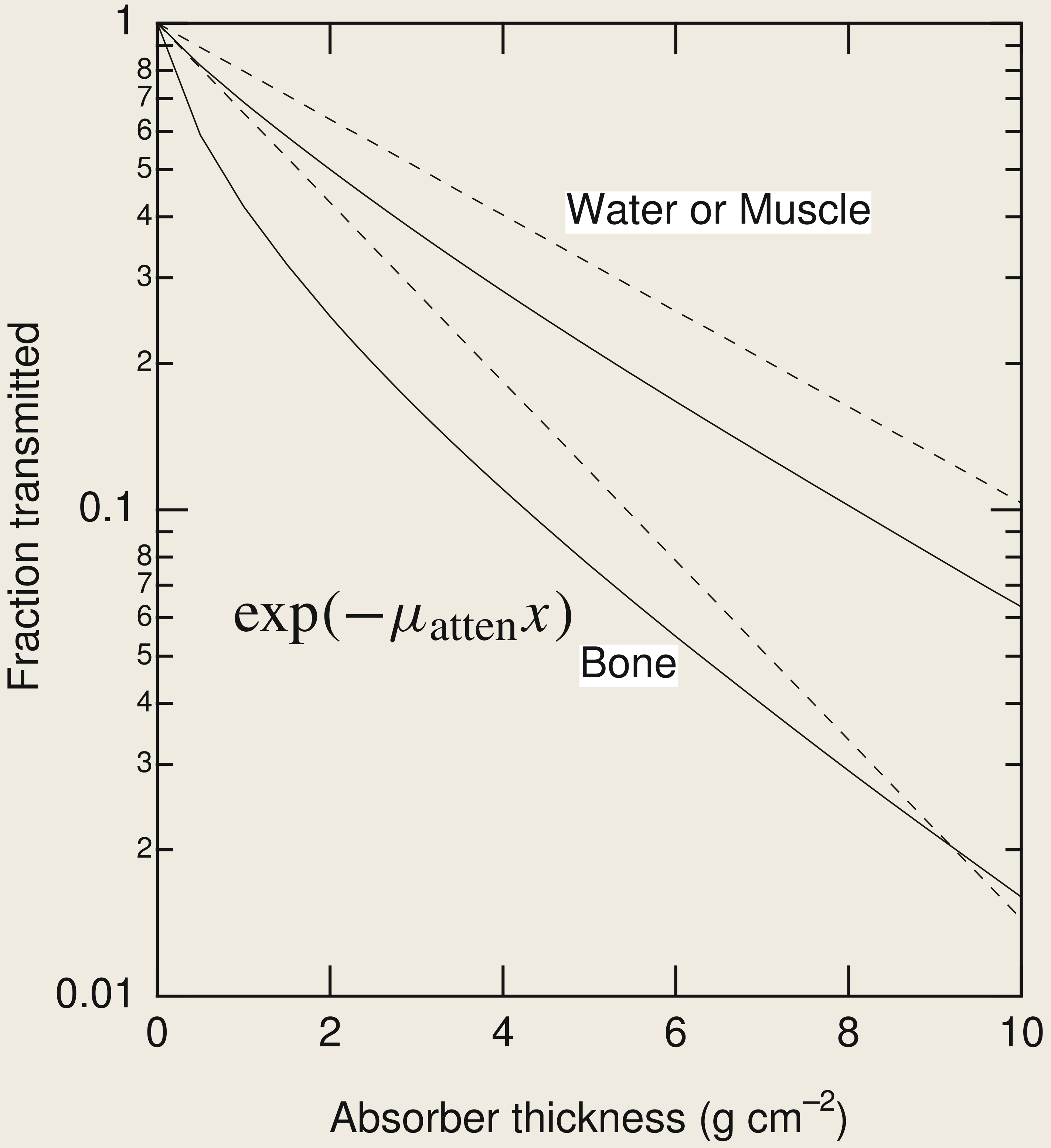
For radiation workers the limit is 3 rem in any consecutive 13 weeks and less than 5 rem/year

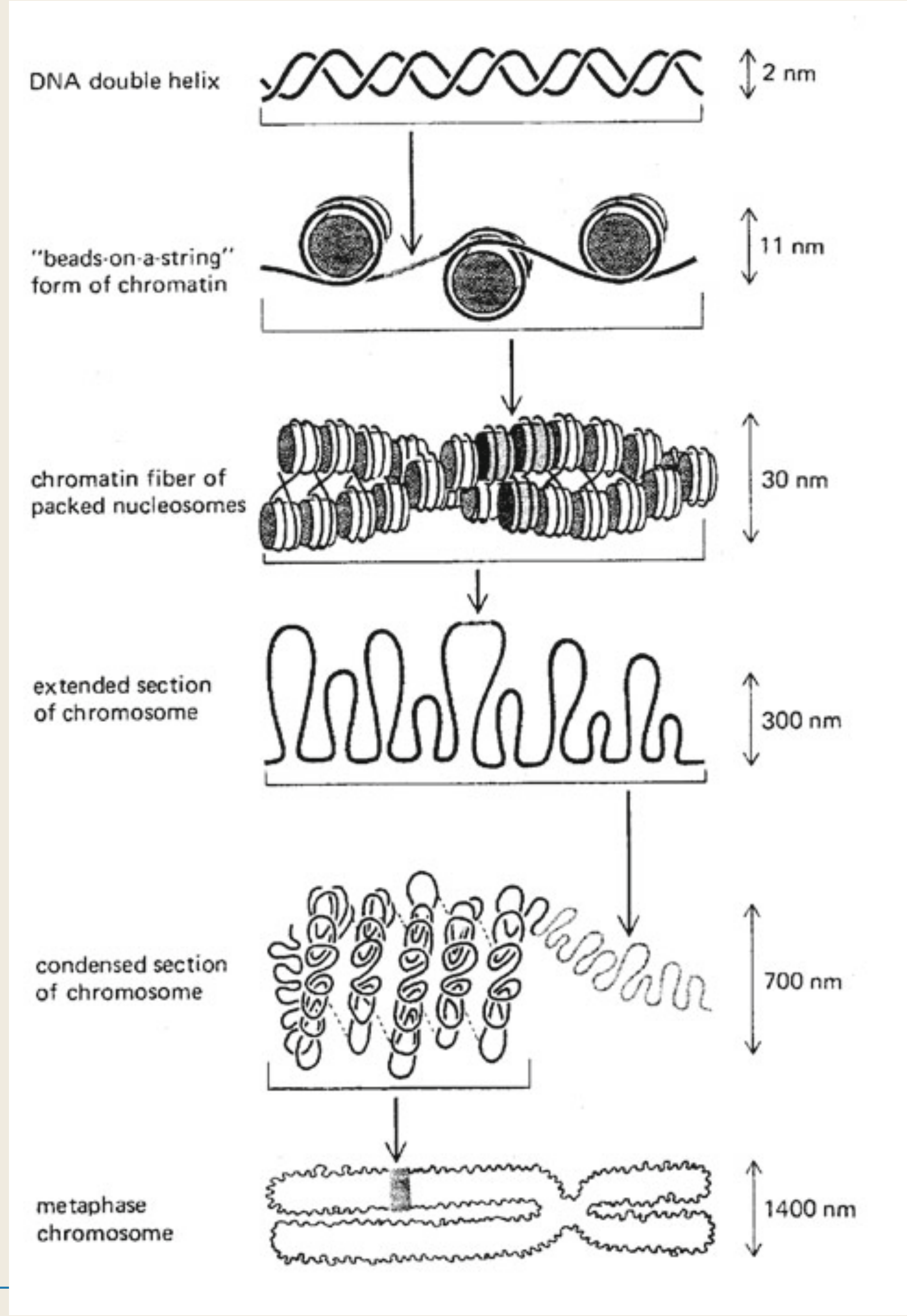
Cosmic rays and natural radioactivity contribute about 100 mrem/year while man-made sources contribute 70 mrem/year.

Maximum permissible quantities of ingested radioisotopes (depend on lifetime) and are ~10-100 microCi.

Good rules of Thumb from Principles of Modern Technology

Survive!





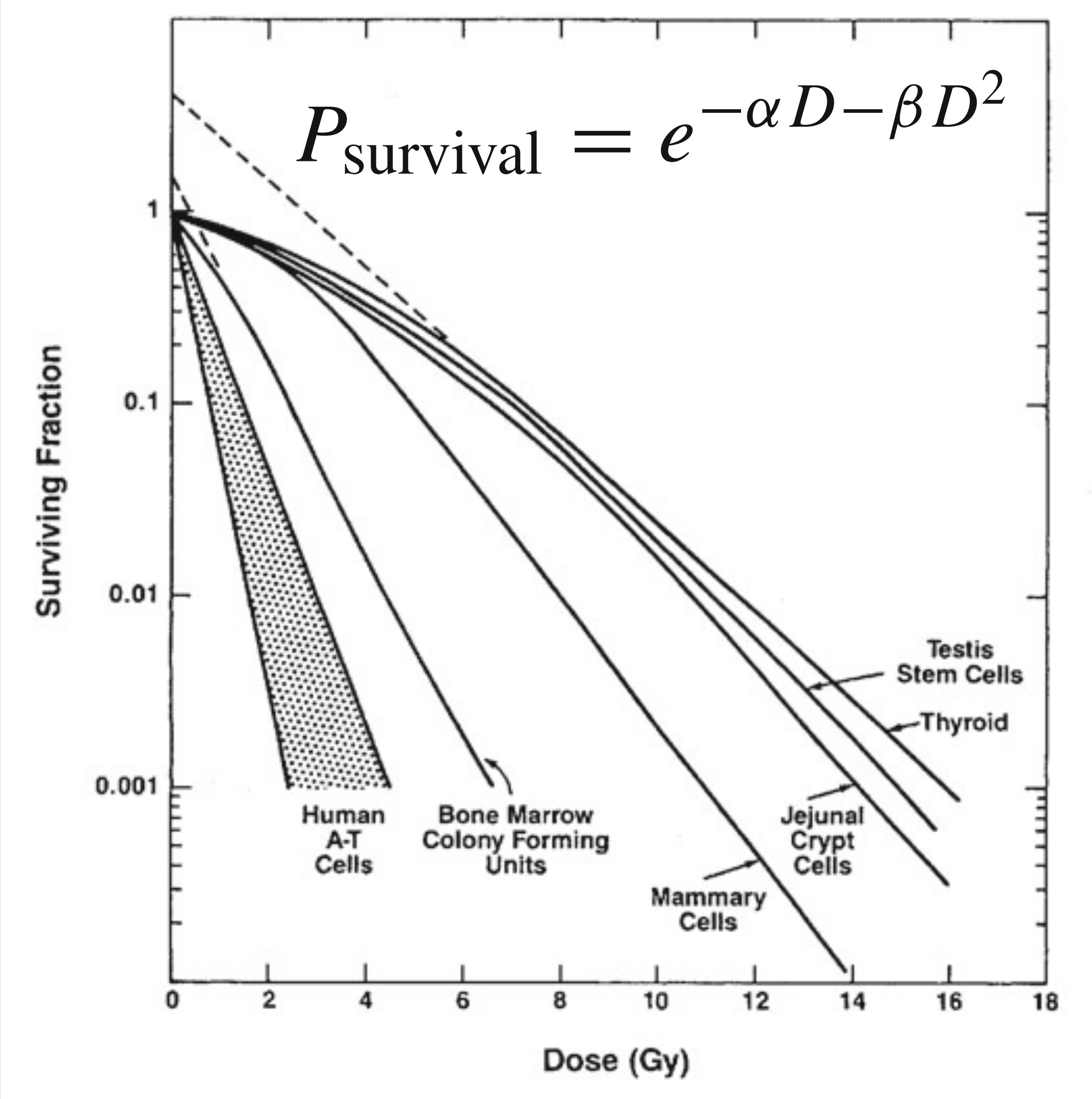
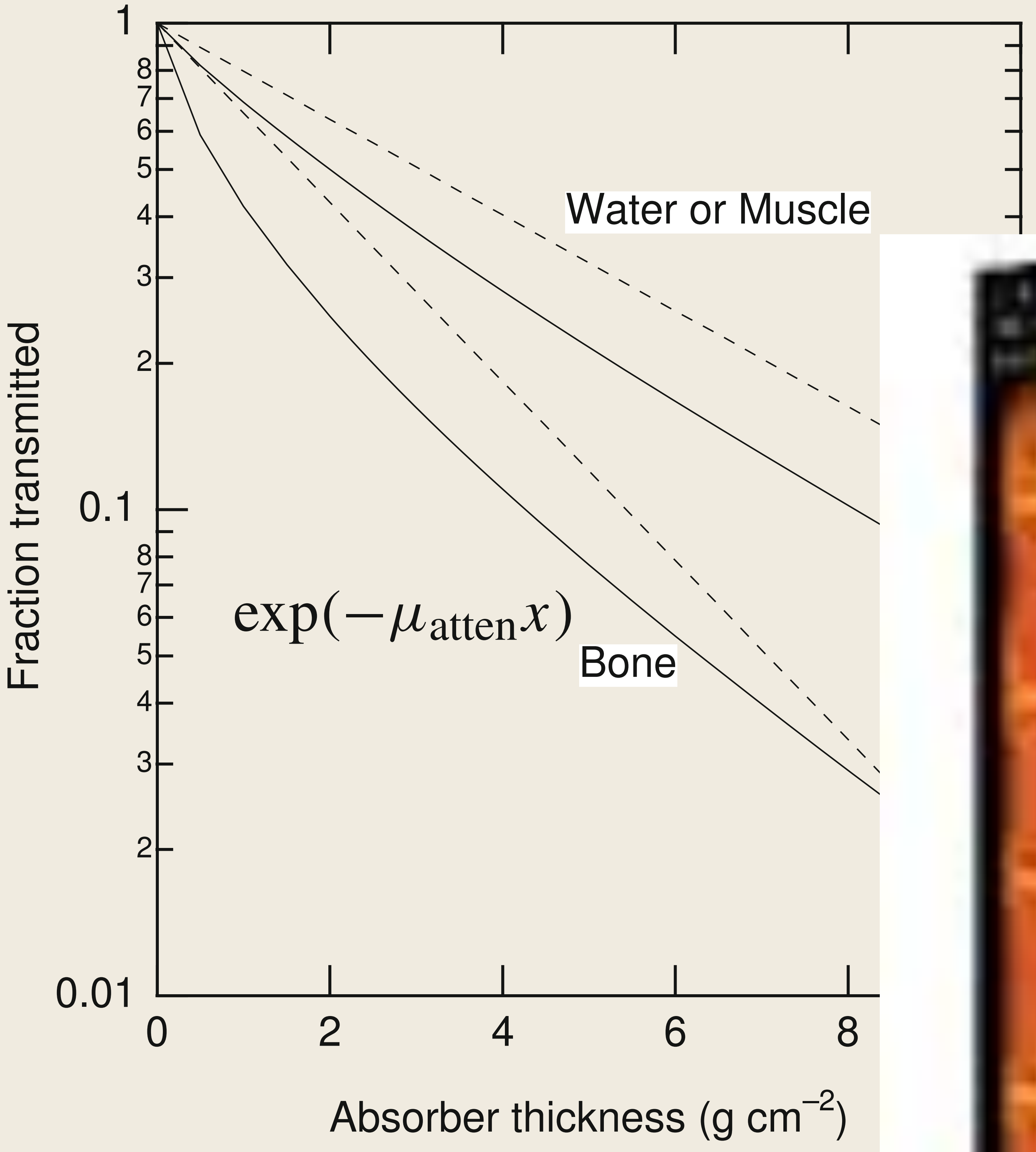
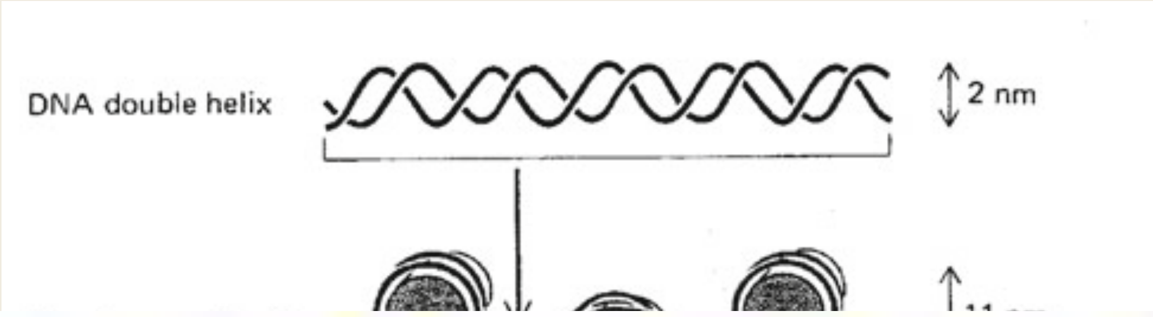
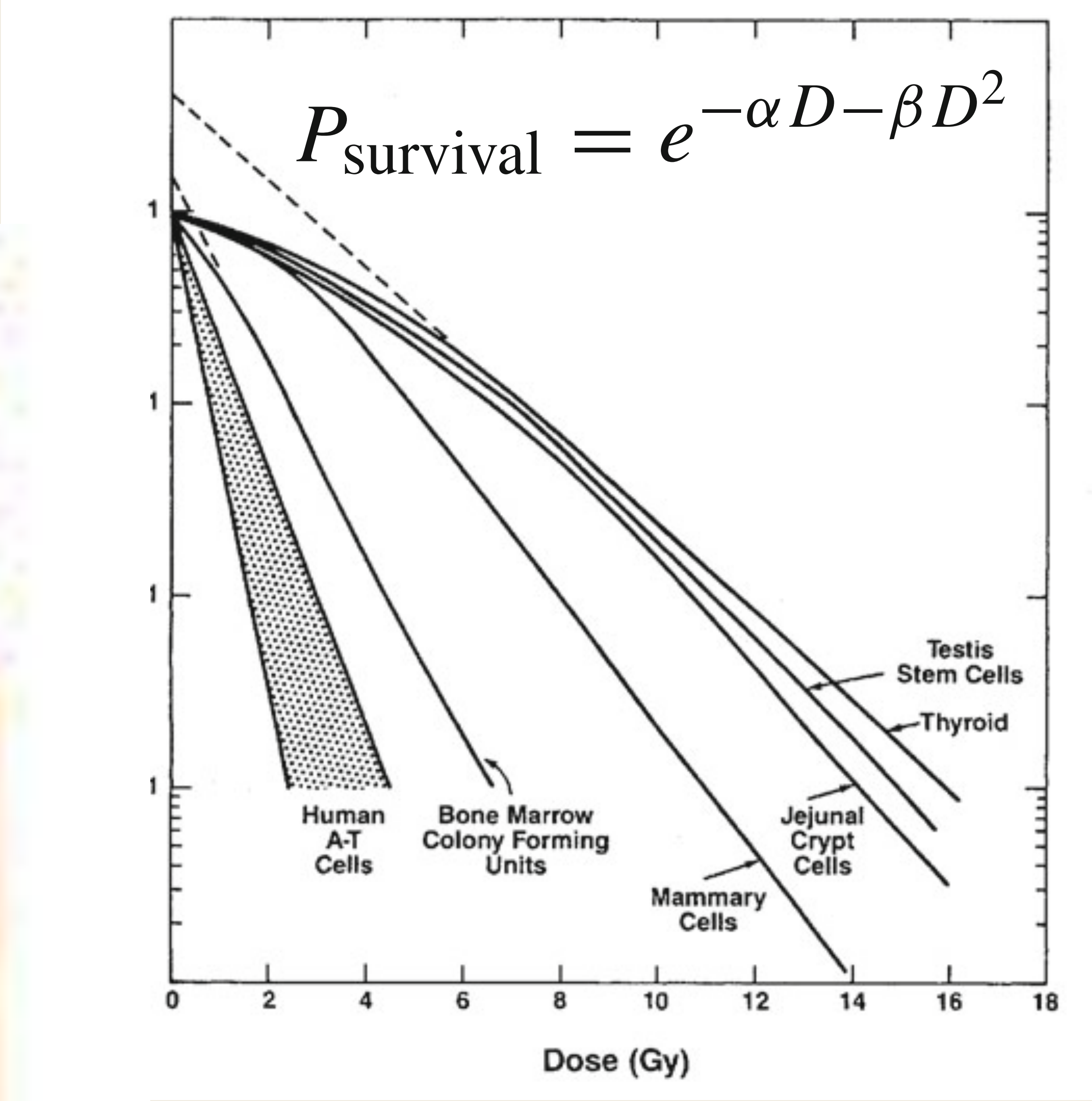


Fig. 16.34 Survival curves for assays of human cells. There is a wide range in initial sensitivity, but not too much difference in final slope. The shaded area labeled "human A-T cells" is for cells from a disease, ataxia-tangliectasia, where repair mechanisms are lacking. (Reproduced with permission from Hall 2002, p. 328)

Survive!







34 Survival curves for assays of human cells. There is a wide initial sensitivity, but not too much difference in final slope. ded area labeled "human A-T cells" is for cells from a disease, ngliectasia, where repair mechanisms are lacking. (Reproduced mission from Hall 2002, p. 328)

The Periodic Table

While dangerous, the energy harnessed in the nucleus of matter is responsible for everything we see today.

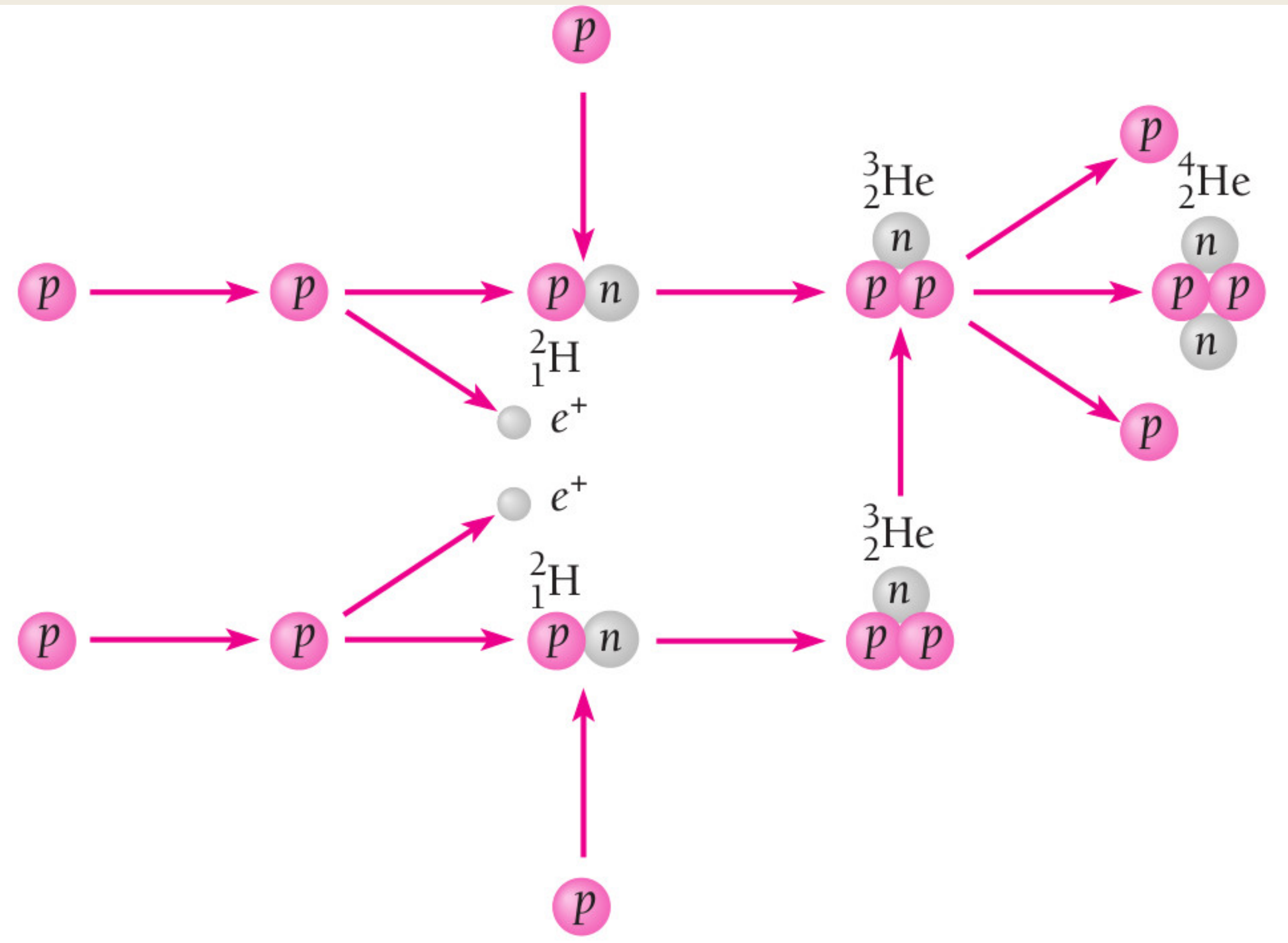


Figure 12.26 The proton-proton cycle. This is the chief nuclear reaction sequence that takes place in stars like the sun and cooler stars. Energy is given off at each step. The net result is the combination of four hydrogen nuclei to form a helium nucleus and two positrons. The neutrinos also produced are not shown.

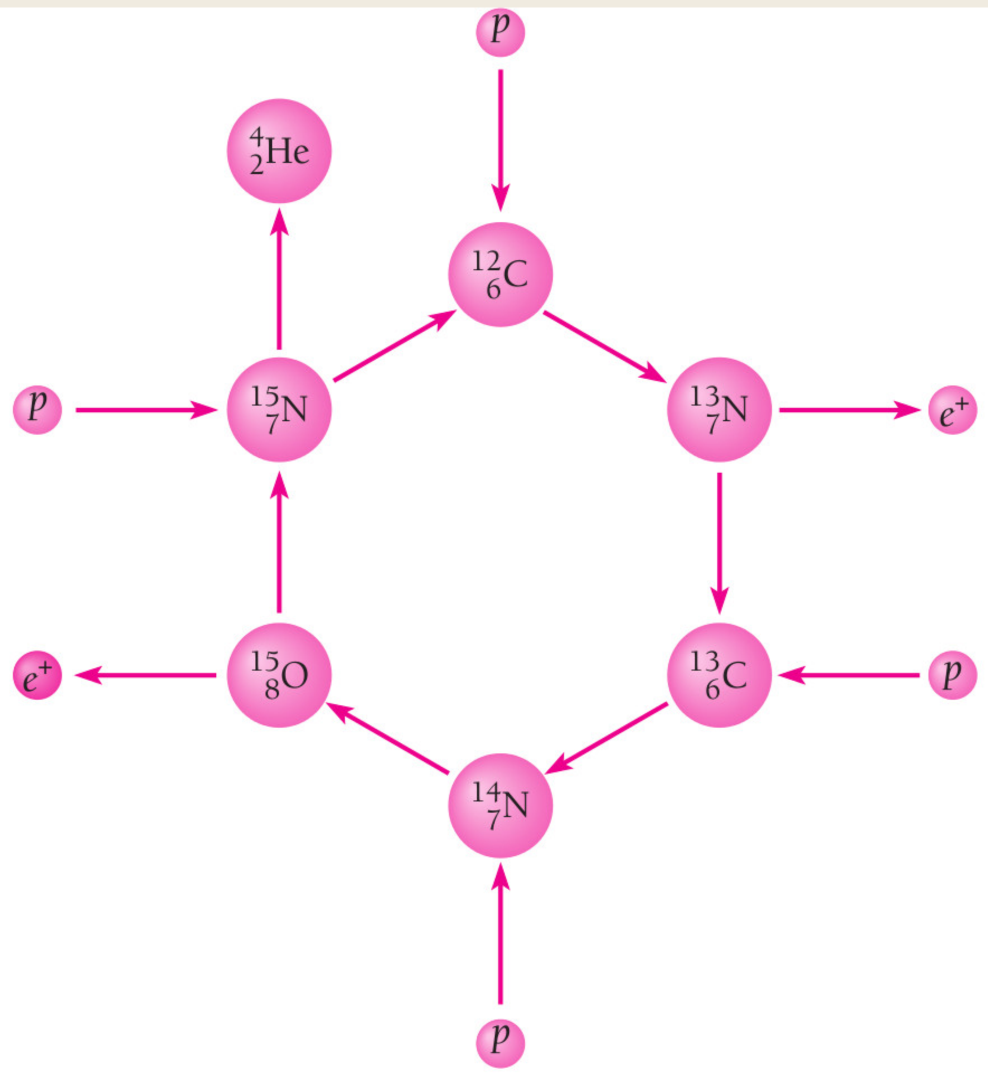


Figure 12.27 The carbon cycle also involves the combination of four hydrogen nuclei to form a helium nucleus with the evolution of energy. The $^{12}_6$C nucleus is unchanged by the series of reactions. This cycle occurs in stars hotter than the sun.