MEDICAL UNIVERSITY – PLEVEN
FACULTY OF MEDICINE

DIVISION OF PHYSICS AND BIOPHYSICS

LECTURE 15

# NUCLEAR RADIATION

A scale model of the atom. The nature of the nucleus. The three basic types of radioactivity. Radioactive decay and half-life. Medical radioisotopes. The detection of radiation. Effects of ionizing radiation on biologic material. Radiation therapy. Nuclear energy

Nuclear radiation refers to those particles or waves which emanate from the atomic nucleus.

The energy associated with such radiation is often classified with x-rays as "ionizing radiation" because the energies are large enough to strip electrons from atoms or alter the structures of atoms and molecules.

A major development in physics occurred in 1911 when Sir Ernest Rutherford bombarded thin metal foils with alpha particles, which are helium atoms stripped of their two electrons.

From the scattering of these charged particles by the metal atoms Rutherford was able to establish that the mass and positive charge were not evenly distributed but concentrated in a volume which was very small compared to the volume of the atom. This was the beginning of the nuclear model of the atom.

## THE NATURE OF THE NUCLEUS

Nuclear physics is a comparatively young field, with much of our present understanding of the nucleus having been developed since 1930.

The nucleus contains about 99.97% of the mass of the atom, while occupying an extremely tiny part of the volume of the atom.

The standard nomenclature for an isotope of a chemical element is:

$$^{A}_{Z}X$$

where X represents the chemical symbol for the element; Z(atomic number)=number of protons; N - neutron number; A(mass number) = Z + N.

For example, the isotopes of carbon may be represented as follows:

$$^{12}_{6}C,\ ^{13}_{6}C,\ ^{14}_{6}C$$

For each number of protons in the nucleus (i.e. for each chemical element) there is an optimum number of neutrons for maximum stability of the nucleus.

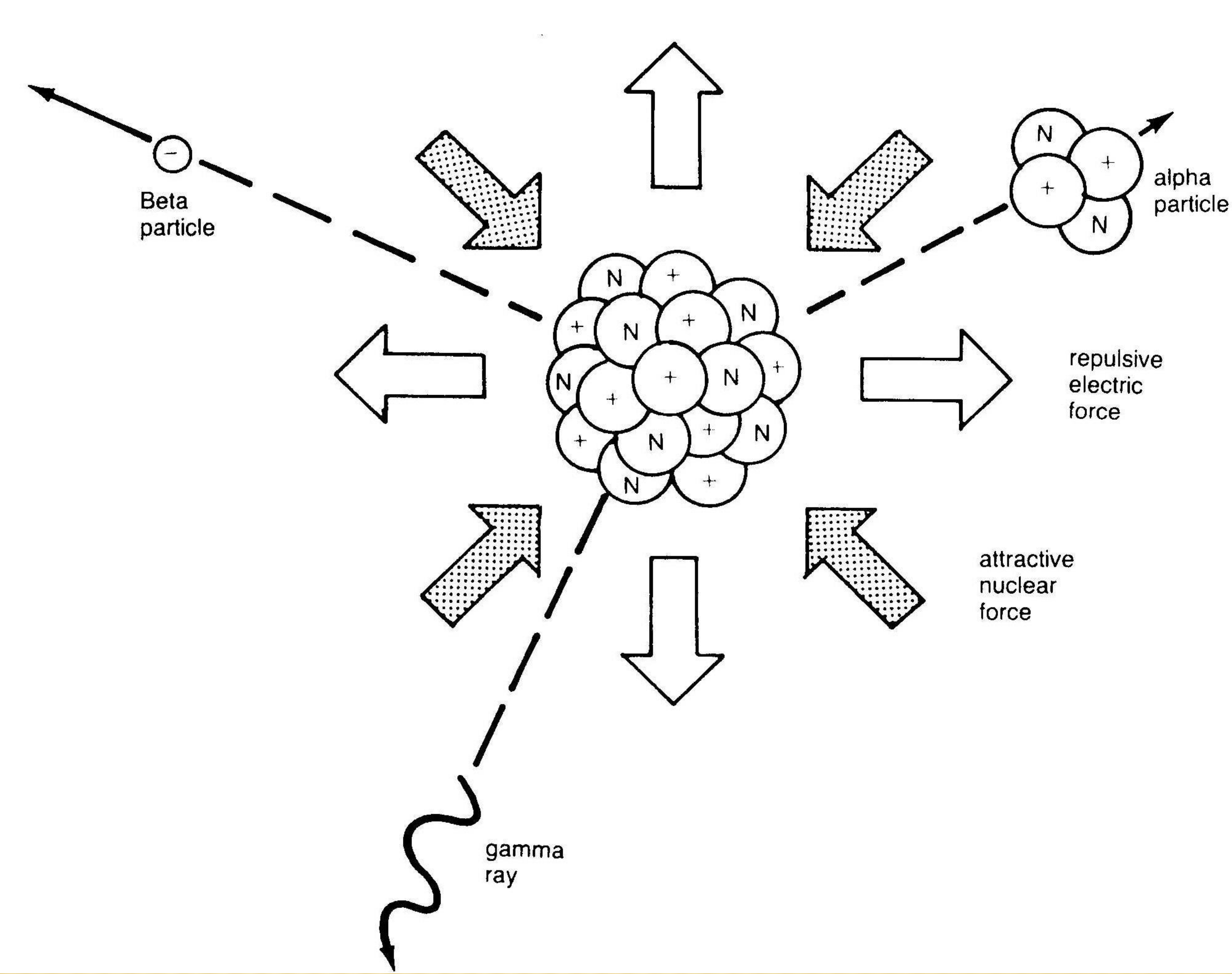
If the neutron number is too small or too large, particles or EW are emitted from the nucleus until it reaches a stable configuration. This emission process is often referred to as radioactivity or radioactive decay.

The term "radioactive" comes from "active like radium," radium being the first such substance to be extensively studied.

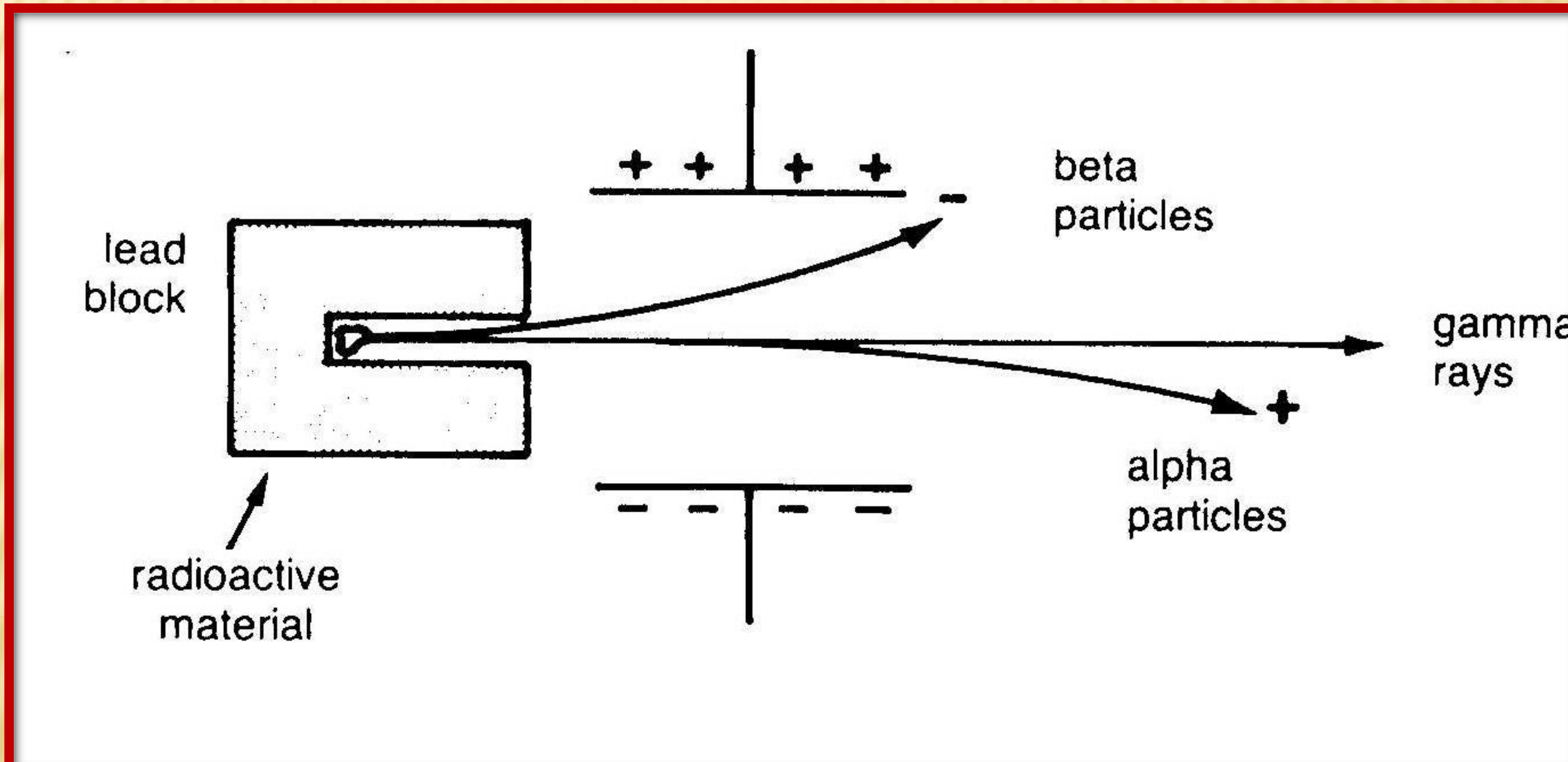
Radioactivity is the result of nuclear instability. The collection of protons and neutrons which makes up the nucleus is extremely dense. The positively charged protons repel each other with enormous forces (100 million times as strong as the attractive force, which keeps the electrons in orbit).

The stability of many nuclei demonstrates the existence of a third force, a powerful attractive nuclear force which holds the protons and neutrons together despite the electric repulsion forces.

This nuclear force is capable of maintaining stability only if the appropriate number of neutrons is present to moderate the repulsive forces; if there are too many or too few neutrons the nucleus becomes unstable (radioactive).


Beta
particle
alpha
particle
N
+
repulsive
electric
force
attractive
nuclear
force
gamma
ray

The three common types of nuclear radiation is produced from a mixture of different radioactive materials.



**Alpha radiation** Composed of two protons and two neutrons, it is a nucleus of helium.

Because of its very large mass ($m_{He}$>7000 $m_e$), it has a very short range r<0.1 mm inside the body.

Not suitable for radiation therapy. Its main radiation hazard comes when it is ingested into the body; it has great destructive power within its short range.

**Beta radiation** An electron. It has a greater range of penetration, but is much less penetrating than gamma rays. Its radiation hazard is greatest if it is ingested.

**Gamma radiation** Electromagnetic ray.

Distinguished from x-rays only by the fact that it comes from the nucleus.

Very penetrating. It is the **most useful type of radiation for therapy**, but the most hazardous because of its ability to penetrate large thicknesses of material.

A nucleus which emits a particle is transformed into a nucleus of a different chemical element in the process.

$$^{238}_{92}\mathrm{U} \rightarrow {}^{4}_{2}\alpha + {}^{234}_{90}\mathrm{Th}$$

"How can a nucleus suddenly throw out a particle or ray with such enormous energy for penetration or radiation damage?"

The answer lies in the fact that a small amount of mass is converted to other forms of energy in the radiation process according to the **Einstein relation $E=mc^2$**.

The enormous energy yield from mass conversion can be seen from the fact that **c** is a very large number, and it is squared in the Einstein equation.

**Thus the conversion of 1 kg of mass yields 9 x $10^{16}$ J!**

A very small amount of mass conversion can give a very high $E_k$ to an α or β particle or a very high frequency to a γ ray (E = hf).

E.g., when radioactive $U^{238}$ is transformed, the sum of the masses of the resulting α particle and thorium atom is slightly less than the mass of the original uranium atom. The lost mass is **transformed** into **kinetic energy,** giving a very high velocity to the α particle and a smaller recoil velocity to the Th atom.

Another type of particle, the positron, is emitted from some artificially produced radioisotopes (*it is identical to the electron except that it has a positive charge*).

The nitrogen radioisotope $^{13}_{7}N$ is transmuted into carbon by the emission of a positron

$$^{13}_{7}N \rightarrow {}^{0}_{+1}\beta + {}^{13}_{6}C + \upsilon$$

where the beta symbol with a +1 subscript is used to represent the positron.

The positron is the anti-particle of the electron; when a positron encounters an electron, they annihilate with the production of two gamma ray photons (a conversion of mass to energy in other forms).

# RADIOACTIVE DECAY AND HALF – LIFE

When a nucleus emits a particle or gamma ray it is said to "decay" into

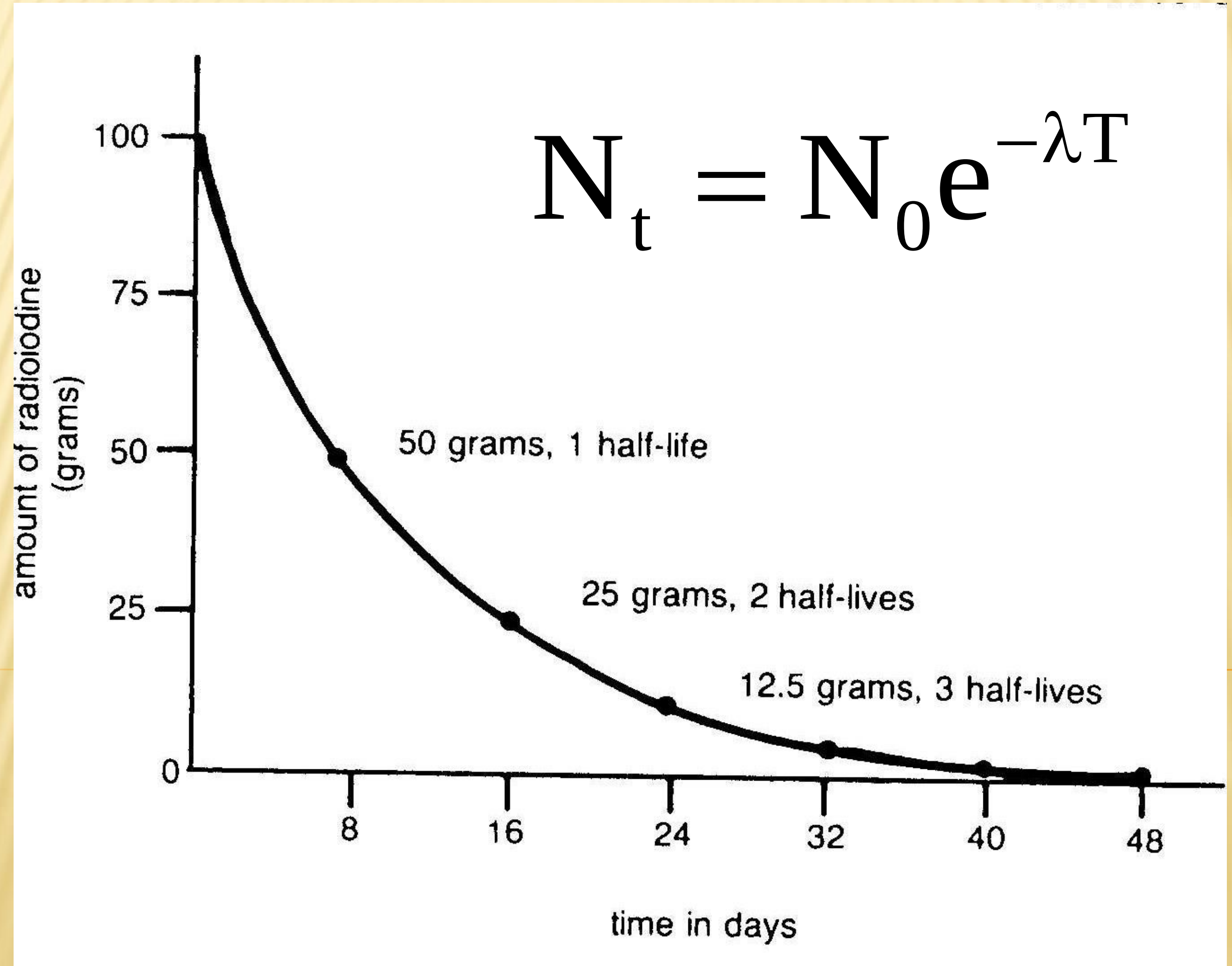
- **another species of nucleus** in the case of particle emission or
- **to a more stable configuration of the same nucleus** in the case of gamma emission.

In either case, the number of nuclei of the original radioactive species decreases with time.

A useful parameter for classification of radioactivity is the half-life, **the time for one half of the nuclei to decay,** regardless of the original number.

The radioactive decay process may be visualized as a "decay curve".

No one can predict when a given nucleus will decay, but we can statistically predict that if there are twice as many nuclei, twice as many will decay in a given time period.



A radioactive transformation process in which an alpha or beta particle emission is involved can be easily studied because the "daughter" nucleus left behind after the particle is emitted is of a different chemical element. Thus it can be separated or detected by using its different chemical properties.

E.g. Consider an element A which emits a particle and is transformed into element B in a process which has **a half-life of 10 years**.

If there is a 100 g mass of element A and none of element B at some initial time, then after 10 years there will be 50 g of A and 50 g of B, after 20 years there will be 25 g of A and 75 g of B, and so forth.

If a sample were found which contained 99 g of B and 1 g of A , it could be surmised that the sample had been there just under 70 years, if one were justified in making the assumption that the material was originally 100% A.

This kind of reasoning is the basis for radioactive dating processes.

In the case of medical radioisotopes the half-life must be known for accurate dose calculations.

Radioisotope doses are usually measured in terms of the curie, which is equivalent in activity to one gram of radium. More convenient units for medical use are mCi and µCi.

A typical dose of a radioiodine-containing compound might be 5 µC. Since the half-life of the isotope $^{131}I$ is 8 days, the radioactive quantity will be only 2.5 µC after 8 days.

The activity of radioisotopes which have been introduced into the body decreases with time as a result of natural biologic elimination processes as well as through radioactive decay.

It is convenient to define a "biologic half-life" as the time required to reduce the activity to one-half by elimination processes. For a given radioisotope dose, the maximum total radiation in the body will occur if both the physical and biologic half-lives are long.

If either the physical or biologic half-life is short, the radiation level in the body will drop rapidly. Though the physical half-life can be considered to be a precise parameter, the biologic half-life is subject to considerable variation.

With the assumption that the biologic half-life is a valid concept, an "effective half-life" may be calculated

$$\frac{1}{T_{effective}} = \frac{1}{T_P} + \frac{1}{T_B}$$

The effective half-life will always be shorter than either $T_P$ or $T_B$.

# MEDICAL RADIOISOTOPES

Medical radioisotopes which are to be administered internally are chosen on the basis of:

- the type and energy of the radiation,
- the half-life,
- the rapidity and completeness of excretion.

The medically useful is radium and its radioactive decay products. Radium decays by α-emission with a half-life of 1622 years - not useful since its range is

$\boxed{r<1\ \text{mm}}$ inside the body.

The usefulness of radium comes from the fact that the α- decay process produces the radioactive gas radon, and successive decays produce other radioisotopes with short half-lives.

Radium itself is one stage of a long radioactive series which begins with $^{238}U$ and ends with the stable lead isotope $^{206}Pb$.

Because of its long half-life, radium can be isolated from uranium ore and used as a source for its shorter-lived products.

Radium produces 8 successive "daughter" isotopes before reaching the stable lead isotope at the end of the series.

Since the second member of the series is a gas, radon, the radium must be sealed in a capsule (gold or platinum alloy containers).

Besides containing the radon, the capsule stops all the alpha particles and most of the beta particles.

The radium source is essentially a gamma emitter. The high energy gamma rays come from the isotopes of $^{214}_{82}Pb$ and $^{214}_{83}Bi$, which are the fourth and fifth members of the radium series.

After 30 days the capsule is a constant intensity gamma source, since the radioactive quantity is determined by the radium, which activity decreases only 1% in 25 years.

This constant activity is desirable for some applications, but makes it unsuitable for permanent implantation in the body. If the capsule is broken, the radon gas escapes, it is quite damaging inside the body because of the ionizing power of its high energy α emission.

Artificially produced isotopes are used in diagnostic applications because of

1. their relatively short half-lives and
2. the ease of introduction into chemical compounds which are utilized by the body.

These radioisotopes are produced by bombarding normal atoms with energetic particles.

An important feature of the artificially produced radioisotopes is the fact that they are isotopes of ordinary chemical elements - constituents of molecules found in bone and tissue.

Since the nucleus of any atom is so remote from the outer electrons, and since the outer electrons are the only ones involved in chemical processes, the radioactive decay processes of nuclei are independent of the chemical state or the chemical compound in which they are found.

The radioactive decay rates are independent of T and matter state. The radioactive nuclei can be introduced into whatever chemical compound is desired.

Radioactive isotopes are often put into human albumin (iodine$^{131}$), vitamin $B_{12}$ (cobalt$^{60}$), etc. which are assimilated by the body.

# THE DETECTION OF RADIATION

The methods for detecting x-rays and nuclear radiation are based upon the fact that the high energy radiation ionizes atoms and molecules in materials through which it passes.

- photographic film - the relative blackening of the film is proportional to the amount of radiation received (used by personnel who work with radiation sources).

At regular intervals the film is developed; any blackening of the film will be caused by ionizing radiation.

- **thermoluminescent dosimetry (TLD) crystals**

The absorption of radiation causes excitation. The amount of light emitted is proportional to the radiation dose received. The average radiation dosage is compared with the established safety standards.

- **radiation dosimeter** (electroscope principle).

Consists of a quartz fiber which deflects when charged. After the fiber is charged by a battery, ionizing radiation acts to remove charge from the fiber and alters its deflected position.

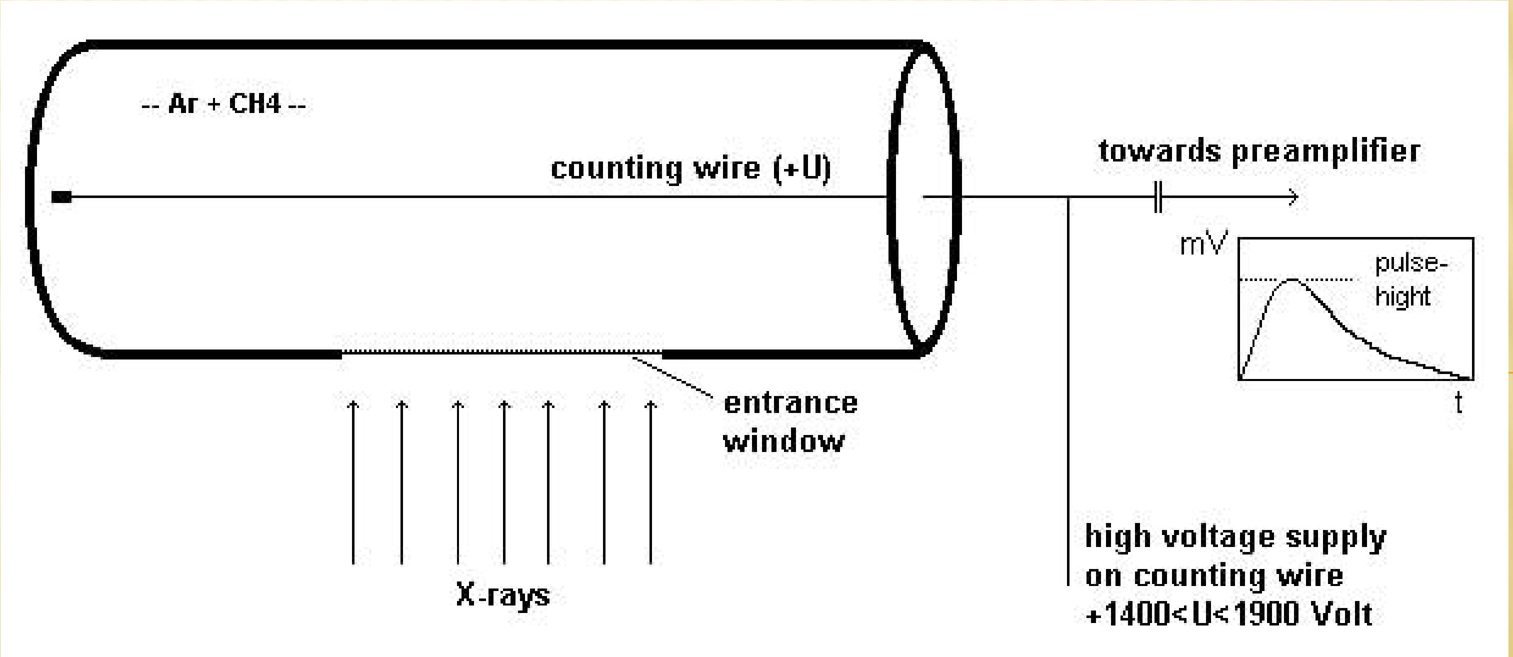
These dosimeters are about **the size of a pencil** and have a magnifying eyepiece which is marked with a radiation dose scale.

Ionization chambers, proportional and Geiger-Muller counters differ in terms of the voltage applied to the electrodes in the ionizable gas.

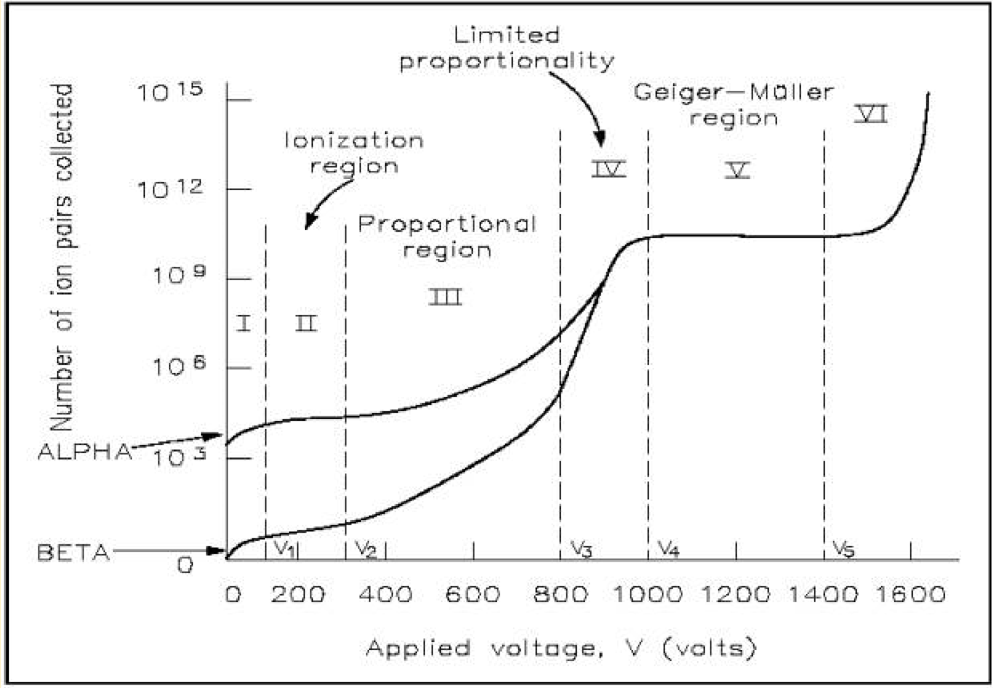
- Ionization chambers

A sealed tube containing an ionizable gas and electrodes with an applied fairly low voltage on them. The ions produced by the radiation do not themselves gain enough energy from the voltage to produce further ions by collision. Such counters can be used to identify the type of radiation (an α particle directly produces many more ions than a β particle) and radiation energy (number of ions is proportional to the energy of the radiation). Disadvantage - low sensitivity.

Proportional counters - If the electrode voltage is raised, there is a narrow voltage range in which a number of secondary ions are produced by the collisions of primary ions, but the **size of the electrical signal** is nevertheless **proportional to the energy of the original radiation.** The tube **retains the ability to discriminate** between types and energies of radiation.



If the voltage is further increased to a point near the threshold for direct electrical ionization, ions and photoelectrons may be produced in the entire chamber by a single ionizing event.




A pulse up to $10^8$ times the ionization chamber pulse can be produced.

In this type of operation it is called a Geiger-Muller tube. Disadvantage - an α particle which directly produces thousands of ions will give the same output pulse as a particle which produces only one or two direct ionizations, so all discriminating ability is lost.

- **The scintillation counter** - the primary detection instrument for medical radioactive tracer work.

It is based on the fact that the absorption of x-ray, gamma ray, or particle by some types of crystals is followed by the emission of a flash of light. These flashes of light can be counted to indicate the number of absorption events and therefore the intensity of the radiation.

In addition, the light intensity for a given event is proportional to the energy of the absorbed radiation, thus the sensitivity of such scintillation counters can be made quite high.

# BIOLOGIC EFFECTS OF IONIZING RADIATION

When X-rays or γ rays enter tissue, they may

- give all their quantum energy to an electron in ejecting it from a molecule (photoionization) or
- they give only a fraction of their energy to the electron and then "scatter" the remainder off in the form of a lower energy photon (Compton scattering).

In either case the ejected electrons have enough $E_k$ to ionize many other atoms.

The ionization resulting from any type of radiation produces very active chemical species which may disable cellular components or produce toxins.

At the cellular level, radiation damage is not so clear-cut. If an ionization event were to disrupt some of the macromolecules essential to the reproduction of the cell, then a major biologic effect is possible.

Radiation can break chromosome chains, and it appears that a small number of such violent ionization events can destroy the delicate machinery of the cell. At the same time, the probability of such an effect is extremely small.

The assessment of the biological risks must involve not only the nature of the ionization events but also their probability.

The most directly observable effects of radiation at the cellular level are:

✓the cell fails to reproduce (cellular "reproductive death“)

✓serious illness or death in case of intense radiation

✓"mutated" cells

✓ cancer

The latency of radiation effects, plus the fact that a person can be exposed to ionizing radiation without feeling anything, is responsible for the extreme caution in the use of ionizing radiation.

# MEASUREMENT OF RADIATION EXPOSURE

Radiation exposure standards are stated in terms of the measurable ionization effects and the amount of energy transferred to the tissue.

The units for exposure measurement are:

- The curie (Ci) - the unit for the "strength" or "activity" of a given radioactive sample.

A source of activity of 1 Ci is equivalent to 1 g of radium (which will produce $3.7 \times 10^{10}$ nuclear decays/s). The curie is not a satisfactory unit for radiation exposure, since the energy and type of radiation strongly affect its ionizing power.

- The Becquerel (Bq) is the unit for **source** activity in SI system, and it is defined as 1nuclear decay/s, so that 1 Ci = $3.7 \times 10^{10}$ Bq.

- The roentgen (R) is a measure of radiation exposure **for X-rays or gamma rays**.

The formal definition of 1R is the radiation intensity required to produce an ionization charge of 0.000258 C/kg of air.

It **is not applicable to α, β and other particle radiation** and **does not accurately predict** the tissue effects of **γ-rays of extremely high energies**.

The roentgen is used for the calibration of the output of X-ray machines.

- The rad is a unit of absorbed radiation dose in terms of the energy actually deposited in the tissue.

The rad is defined as an absorbed dose of 0.01 J/kg of tissue.

The rad is the basic unit for clinical applications.

A typical radiation treatment for cancer - 200 rad.

It is observed that the same doses of different types of radiation have different degrees of biological effectiveness.

This relative biological effectiveness (RBE) depends upon the amount of energy transferred to the tissues per unit length along the path of the radiation (i.e. it is range-dependent).

E.g. The linear energy transfer (LET) for α- particles is much higher than that for gamma rays.

Therefore, a smaller dose in rads of alpha particles is required to inhibit cell division in a biological specimen.

- The Gray (Gy) is the SI unit for absorbed radiation dose and is defined as 1 J of absorbed energy per kg of tissue. 1 Gy=100 rads.

- The rem is a unit designed to measure the radiation dose in terms of its biological effectiveness in man, and the unit name is an acronym for "roentgen-equivalent-man."

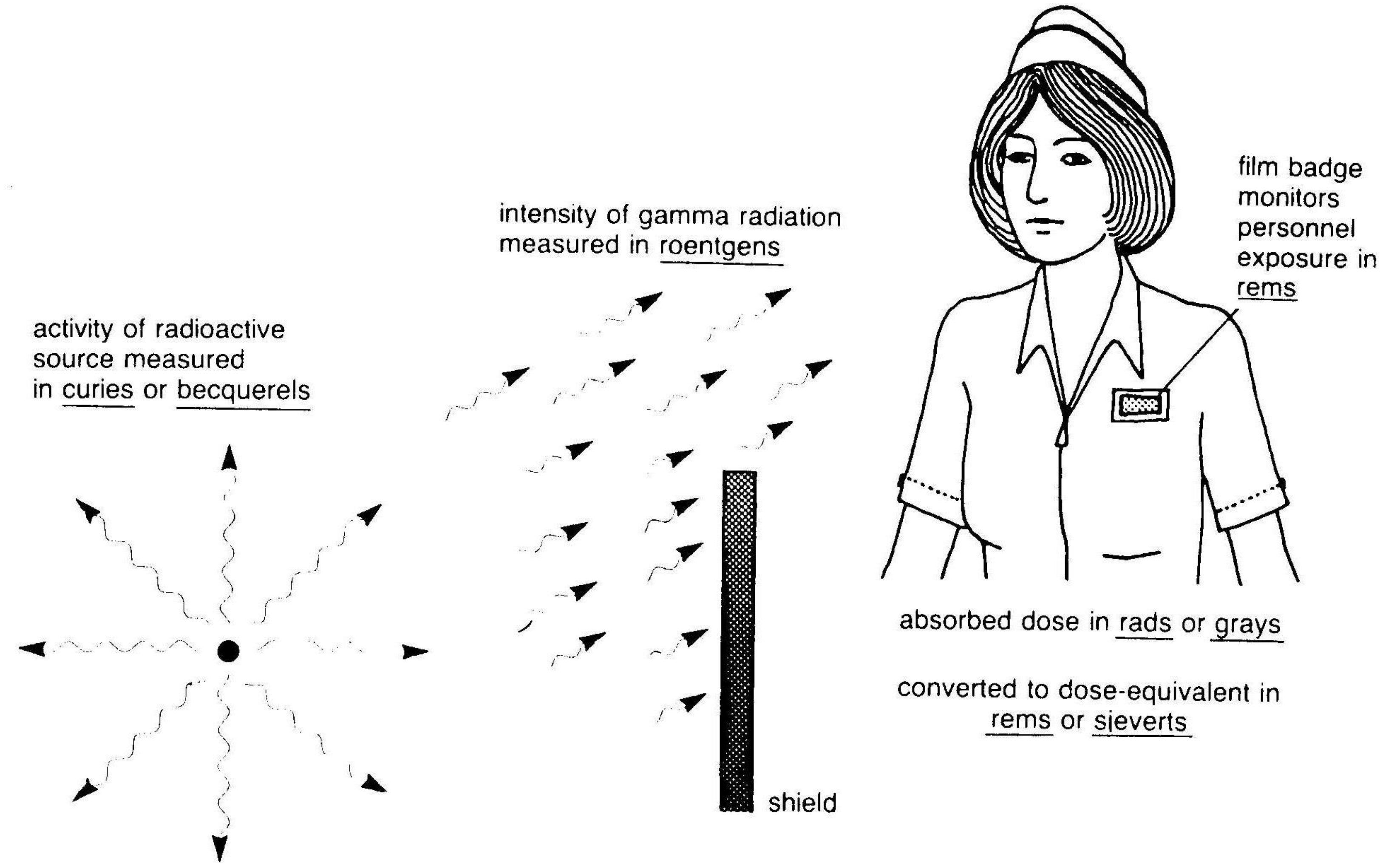
The dose in rems is defined as the dose in rads multiplied by a "quality factor," which is an assessment of the biological effectiveness of the particular type and energy of radiation.

For alpha particles, the quality factor is 20, so that

1 rad =20 rems.

It has been recommended that the radiation exposure from sources other than natural or medical radiation sources be limited to 0.17 rem/year, a much more stringent standard than that used before.

# HOW TO MINIMIZE YOUR EXPOSURE




Safety measures:

1. Maximize *distance* between you and the source.
2. Minimize the *time* you spend near the source.
3. Use *shielding* whenever possible.
4. Use a film badge or other monitoring device to record the radiation dose you have received.

# RADIATION THERAPY

X-rays and gamma rays have proved to be a useful therapeutic tool for the treatment of cancer.

Drawback - there is no way to irradiate the cancer without also damaging the normal tissue surrounding it.

The aim of radiation therapy - to find ways to damage the cancer more than the normal tissue, or at least to limit the damage to normal tissue so that there is no unacceptable loss of function.

The ratio of cancer cells killed to normal cells killed is called the "therapeutic ratio."

The effectiveness of the therapy depends upon making the therapeutic ratio as high as possible.

- Undifferentiated cells and rapidly dividing cells are more sensitive to radiation than well-differentiated and slowly reproducing cells,

- Normal tissue recovers faster and more completely from radiation effects than does cancerous tissue,

- The "oxygen effect" is a significant factor related to the radiation, sensitivity of tissue (free radical production). A number of experiments have been performed in which the oxygen supply to tumor cells was increased.

- An option for radiation therapy is the implantation of a radioactive source within a cancerous tumor (brachytherapy).

- ✓ High energy γ rays from radioisotopes such as $^{60}Co$ and high energy X-rays are commonly used for therapy (teletherapy).

- ✓ Radioiodine, $^{131}I$, is unique as a therapeutic agent because it is selectively taken up by the thyroid gland.

- ✓ Another way to increase the therapeutic ratio for particle radiation therapy is to inject boron into a tumor and irradiate with low energy neutrons. Since boron interacts with neutrons much more strongly than ordinary tissue, this results in a much higher dose to the tumor.

# DIAGNOSTIC USE OF RADIOISOTOPES

The radiation exposure in diagnostic procedures (millirems) is on the order of a million times less than in radiation therapy procedures (thousands of rems).

The tracer principle is the key to most diagnostic applications of radioisotopes.

The nucleus is very small compared to the entire atom. The events that occur in the nucleus, such as radioactivity, are removed by a factor of 10,000 or more from the outer boundaries of the atom where chemical processes take place.

Molecules having radioisotopes of calcium, sodium, phosphorous, etc. are exactly the same as those molecules containing the normal isotopes of those elements. Therefore they will follow the normal metabolic pathways and can "trace" those pathways by the fact that some of the nuclei of the radioisotopes will decay and give off radiation, which can be detected and analyzed outside the body.

The fact that the radioactive decay process is totally independent of the chemical compound in which the isotope resides makes it possible to "label" many convenient molecules with radioisotopes.

Circulation studies may be done by injecting a radioactive species into the venous system.

The plasma volume may be determined by the intravenous injection of radioiodinated ($^{131}I$) serum albumin through the measurement of the dilution of the tracer in a subsequent blood sample (albumin will not leave the circulatory system under normal conditions).

Liver scans can be made by injecting a colloidal suspension containing a tracer, since the tiny particles that make up such a suspension will quickly be deposited in the liver.

$Co^{57}$ and $Co^{58}$ are used to label vitamin $B_{12}$ for the Schilling test for pernicious anemia.

# NUCLEAR ENERGY

Changes in nuclear structure involve changes in the total mass of the particles involved.

When mass is lost, it is transformed into energy ($E= mc^2$). Consider the process of building an α particle from two *p* and two *n*. It would be expected that $m_\alpha = m(2\,p) + m(2\,n)$, but that is not the case:

Neutron masses=2 x 1839$m_e$=3678 $m_e$
Proton masses=2 x 1835.7$m_e$=3671.4 $m_e$
Total=7349.4 $m_e$
Mass of alpha particle=7294 $m_e$
Mass discrepancy=55.4 $m_e$

The mass of the α particle is less than the sum of the masses of its constituents by 55.4 $m_e$.

Mass of original particles (fuel) 7349.4 g

Mass of resulting alpha particles 7294.0g

Mass converted into energy 55.4 g

Using Einstein's equation, the energy yield would be E= (0.0554 kg) (3 x $10^8$ m/s)$^2$= 5 x $10^{15}$ J.

This energy is more than the explosive yield of one billion tons of **trinitrotoluene** (TNT), compared to about 20,000 tons of TNT energy yield for the Hiroshima and Nagasaki nuclear fission bombs.

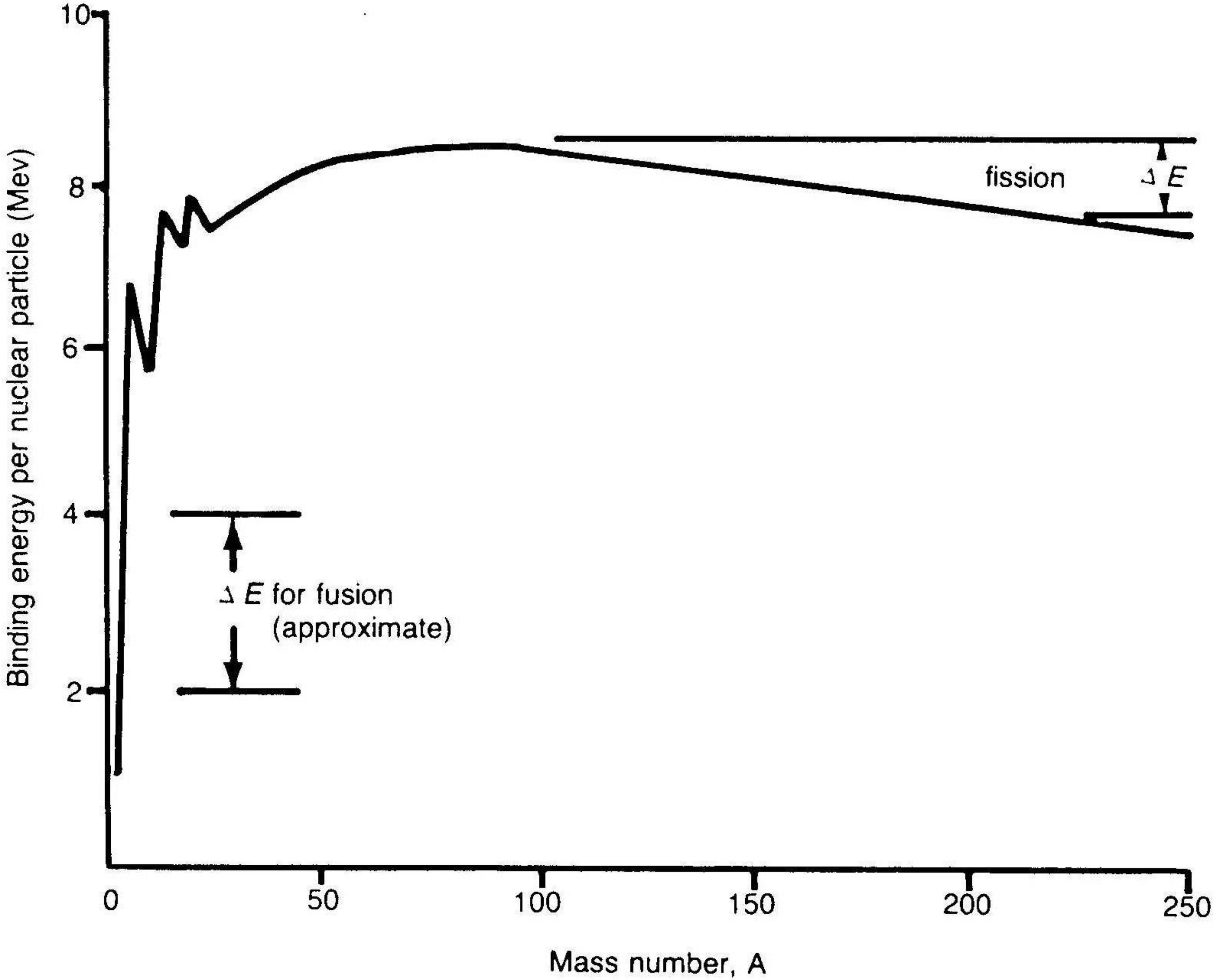
It also is possible to release energy by *nuclear fission*, the splitting of the nuclei of heavy elements such as uranium into two or more lighter nuclei.

Nuclei of intermediate masses have the greatest binding energy per nuclear particle, i.e the minimum mass per nuclear particle.

If heavy nuclei can be spitted to form two intermediate nuclei, the total mass is reduced and E is released (**nuclear fission**).

Alternatively, if light nuclei are combined to form intermediate nuclei, the total mass is reduced and E is released (**nuclear fusion**).

All present nuclear power generation is done by the nuclear fission process. The fission of $U^{235}$ produces large amounts of energy, but it is scarce and expensive and produces radioactive waste materials.



10
8
6
4
2
0
50
100
150
200
250
Binding energy per nuclear particle (Mev)
Mass number, A
fission
Δ E
Δ E for fusion
(approximate)

The nuclear fusion process produces more energy for a given mass of fuel. It also makes use of cheap and abundant fuel and produces no radioactive waste products. But it has not yet been possible to initiate and control the fusion process to the degree necessary to produce useful energy.

The main reason is that it requires T of several million degrees $^{0}$F, about the temperature of the center of the sun. Besides the problems of generating and sustaining such temperatures, no material container can withstand such T .

Laboratories around the world are working on means for controlling the nuclear fusion process.