Introduction to Nuclear Physics

(see MIT Introduction to Applied Nuclear Physics 22.02 http://ocw.mit.edu/courses/nuclear-engineering/22-101-applied-nuclear-physics-fall-2006/lecture-notes/
and Hyperphysics http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html)

Nuclear physics describes nuclear properties, structure and characteristics of nuclei and radiations, radiation sources and interaction with matter. To understand nuclear structure and radiation we study nuclei, nucleons and electrons, as well as miroscopic processes. We apply quantum echanics and special relativity.

1. Nuclear characteristics From Wikipedia

https://en.wikipedia.org/wiki/Atomic_nucleus: De la ►►► pana la ◄◄◄

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"The **nucleus** is the small, dense region consisting of protons andneutrons at the center of an atom. The atomic nucleus was discovered in 1911 by Ernest Rutherford based on the 1909 Geiger–Marsden gold foil experiment. After the discovery of the neutron in 1932, models for a nucleus composed of protons and neutrons were quickly developed by Dmitri Ivanenko[1]and Werner Heisenberg. Almost all of the mass of an atom is located in the nucleus (99.9%), with a very small contribution from the electron cloud. Protons and neutrons are bound together to form a nucleus by the nuclear force.

The **diameter of the nucleus** is in the range of **1.75 fm** (1.75×10^{-15} m) **for hydrogen** (the diameter of a single proton)[7] to about **15 fm for the heaviest atoms**, such as uranium. These dimensions are much smaller than the diameter of the atom itself (nucleus + electron cloud), by a factor of about 23,000 (uranium) to about 145,000 (hydrogen).]

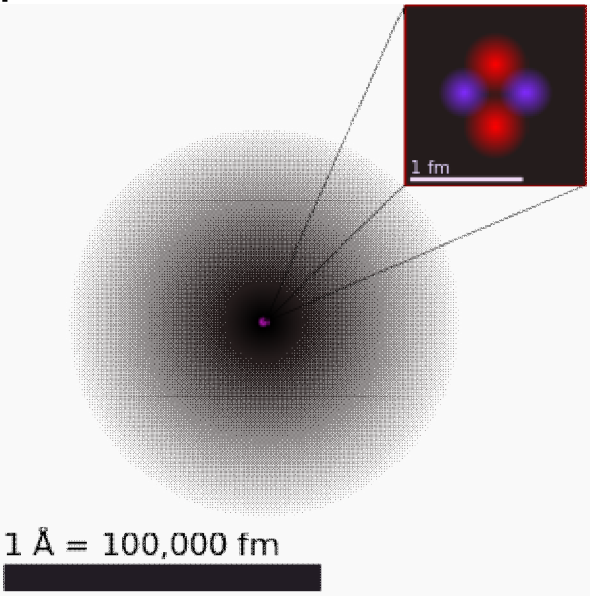
The branch of physics concerned with the study and understanding of the atomic nucleus, including its composition and the forces which bind it together, is called nuclear physics."

History

Main article: Rutherford model

The nucleus was discovered in 1911, as a result of Ernest Rutherford's efforts to test Thomson's "plum pudding model" of the atom.[8] The electron had already been discovered earlier by J.J. Thomson himself. Knowing that atoms are electrically neutral, Thomson postulated that there must be a positive charge as well. In his plum pudding model, Thomson suggested that an atom consisted of negative electrons randomly scattered within a sphere of positive charge. Ernest Rutherford later devised an experiment with his research partner Hans Geiger and with help of Ernest Marsden, that involved the deflection of alpha particles (helium nuclei) directed at a thin sheet of metal foil. He reasoned that if Thomson's model were correct, the positively charged alpha particles would easily pass through the foil with very little deviation in their paths, as the foil should act as electrically neutral if the negative and positive charges are so intimately mixed as to make it appear neutral. To his surprise, many of the particles were deflected at very large angles. Because the mass of an alpha particle is about 8000 times that of an electron, it became apparent that a very strong force must be present if it could deflect the massive and fast moving alpha particles. He realized that the plum pudding model could not be accurate and that the deflections of the alpha particles could only be explained if the positive and negative charges were separated from each other and that the mass of the atom was a concentrated point of positive charge. This justified the idea of a nuclear atom with a dense center of positive charge and mass.

Nuclear makeup



A figurative depiction of the helium-4 atom with the electron cloud in shades of gray. In the nucleus, the two protons and two neutrons are depicted in red and blue. This depiction shows the particles as separate, whereas in an actual helium atom, the protons are superimposed in space and most likely found at the very center of the nucleus, and the same is true of the two neutrons. Thus, all four particles are most likely found in exactly the same space, at the central point. Classical images of separate particles fail to model known charge distributions in very small nuclei. A more accurate image is that the spatial distribution of nucleons in a helium nucleus is much closer to the helium **electron cloud** shown here, although on a far smaller scale, than to the fanciful nucleus image.

The nucleus of an atom consists of **neutrons and protons** hat are held in association by the nuclear strong force . The nuclear strong force extends far enough so as to bind the neutrons and protons together against the repulsive electrical force between the positively charged protons. **The nuclear strong force has a very short range**, and essentially drops to zero just beyond the edge of the nucleus. The collective action of the positively charged nucleus is to hold the electrically negative charged electrons in the region around the nucleus. The collection of negatively charged electrons orbiting the nucleus display an affinity for certain configurations and numbers of electrons that make their orbits stable. **Which chemical element an atom represents is determined by the number of protons in the nucleus; the neutral atom will have an equal number of electrons** orbiting that nucleus. Individual chemical elements can create more stable electron configurations by combining to share their electrons. It is that sharing of electrons to create stable electronic orbits about the nucleus that appears to us as the chemistry of our macro world.

Protons define the entire charge of a nucleus, and hence its chemical identity. Neutrons are electrically neutral, but contribute to the mass of a nucleus to nearly the same extent as the protons. Neutrons explain the phenomenon of isotopes – varieties of the same chemical element which differ only in theiratomic mass, not their chemical action.

Protons and neutrons

Protons and neutrons are fermions, with different values of the strong isospinquantum number, so two protons and two neutrons can share the same spacewave function since they are not identical quantum entities. They are sometimes viewed as two different quantum states of the same particle, the*nucleon*.[11][12] Two fermions, such as two protons, or two neutrons, or a proton + neutron (the deuteron) can exhibit bosonic behavior when they become loosely bound in pairs, which have integral spin.

In the rare case of a hypernucleus, a third baryon called a hyperon, containing one or more strange quarks and/or other unusual quark(s), can also share the wave function. However, this type of nucleus is extremely unstable and not found on Earth except in high energy physics experiments.

The neutron has a positively charged core of radius ≈ 0.3 fm surrounded by a compensating negative charge of radius between 0.3 fm and 2 fm. The proton has an approximately exponentially decaying positive charge distribution with a mean square radius of about 0.8 fm.

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Dupa **http://www2.lbl.gov/abc/wallchart/teachersguide/pdf/Chap02.pdf**

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term nucleon is used for either a proton or a neutron. The simplest nucleus is that of hydrogen, which is just a single proton, while the largest nucleus studied has nearly 300 nucleons. A nucleus is identified by its atomic number Z (i.e., the number of protons), the neutron number, N=A-Z, and the mass number, A, where A = Z + N. The convention for designating nuclei is by atomic number, Z, and mass number, A, as well as its chemical symbol X.

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

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Proton from **https://en.wikipedia.org/wiki/Proton** De la ►►► pana la ◄◄◄

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Classification	Baryon
Composition	2 up quarks, 1 down quark
Statistics	Fermionic
Discovered	Ernest Rutherford (1917–1919)
Mass	$1.672621898(21)\times10^{-27}$ kg[1] 938.2720813(58) MeV/c^2[1] 1.007276466879(91) u[1]
Mean lifetime	$>2.1\times10^{29}$ years (stable)
Electric charge	+1 e=$1.6021766208(98)\times10^{-19}$ C[1]
Charge radius	0.8751(61) fm[1]

Neutron from https://en.wikipedia.org/wiki/Neutron

Classification	Baryon
Composition	1 up quark, 2 down quarks
Statistics	Fermionic
Interactions	Gravity, weak, strong,electromagnetic
Theorized	Ernest Rutherford[1] (1920)
Discovered	James Chadwick[2] (1932)
Mass	$1.674927471(21)\times10^{-27}$ kg[3] 939.5654133(58) MeV/c^2[3] 1.00866491588(49) u[3]
Mean lifetime	881.5(15) s =approx 15 min (free)
Electric charge	0 *e* $(-2\pm8)\times10^{-22}$ *e* (experimental limits)[4]

Free neutron decay. Neutron and proton transformations inside a nucleus

Outside the nucleus, free neutrons are unstable and have a mean lifetime of 881.5±1.5 s (about 14 minutes, 42 seconds); therefore the half-life for this process (which differs from the mean lifetime by a factor of ln(2) = 0.693) is 611.0±1.0 s (about 10 minutes, 11 seconds). Beta decay of the neutron, described above, can be denoted by the radioactive decay:[49]

$$n_0 \longrightarrow p+ + e- + v_e$$

where p+, e−, and v_e denote the proton, electron and electron antineutrino, respectively. For the free neutron the decay energy for this process (based on the masses of the neutron, proton, and electron) is 0.782343 MeV.

Inside a nucleus, a proton can transform into a neutron via inverse beta decay, if an energetically allowed quantum state is available for the neutron. This transformation occurs by emission of an antielectron (also called positron) and an electron neutrino:

$p+ \rightarrow n_0 + e+ + v_e$

The transformation of a proton to a neutron inside of a nucleus is also possible through electron capture:

$p+ + e- \rightarrow n_0 + v_e$

Positron capture by neutrons in nuclei that contain an excess of neutrons is also possible, but is hindered because positrons are repelled by the positive nucleus, and quickly annihilate when they encounter electrons.

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Nuclear binding energy from

http://hyperphysics.phy-astr.gsu.edu/hbase/nucene/nucbin.html#c2

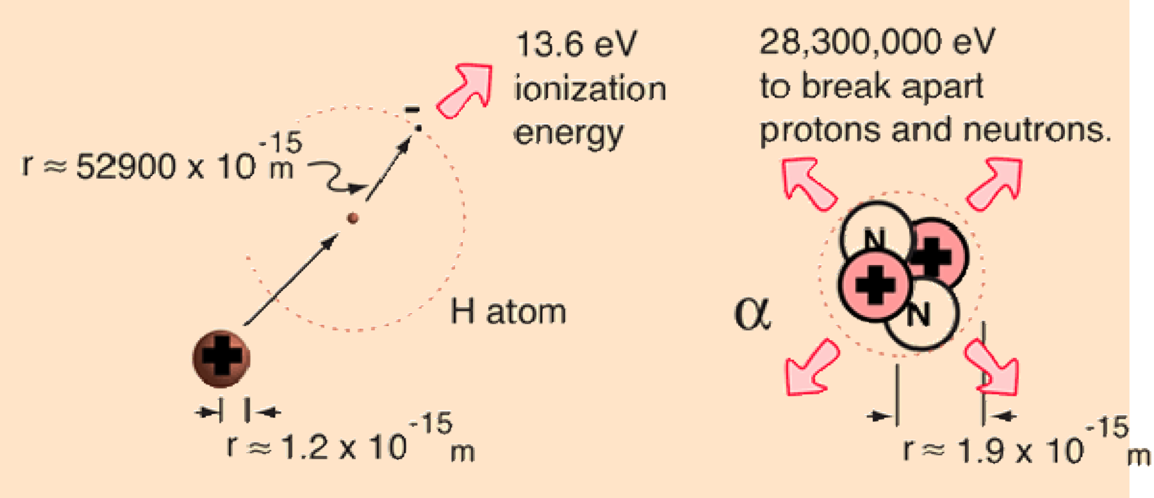
Nuclear Binding Energy

Nuclei are made up of protons and neutron, but the mass of a nucleus is always less than the sum of the individual masses of the protons and neutrons which constitute it. The difference is a measure of the nuclear binding energy which holds the nucleus together. This binding energy can be calculated from the Einstein relationship:

$$\text{Nuclear binding energy} = \Delta mc^2$$

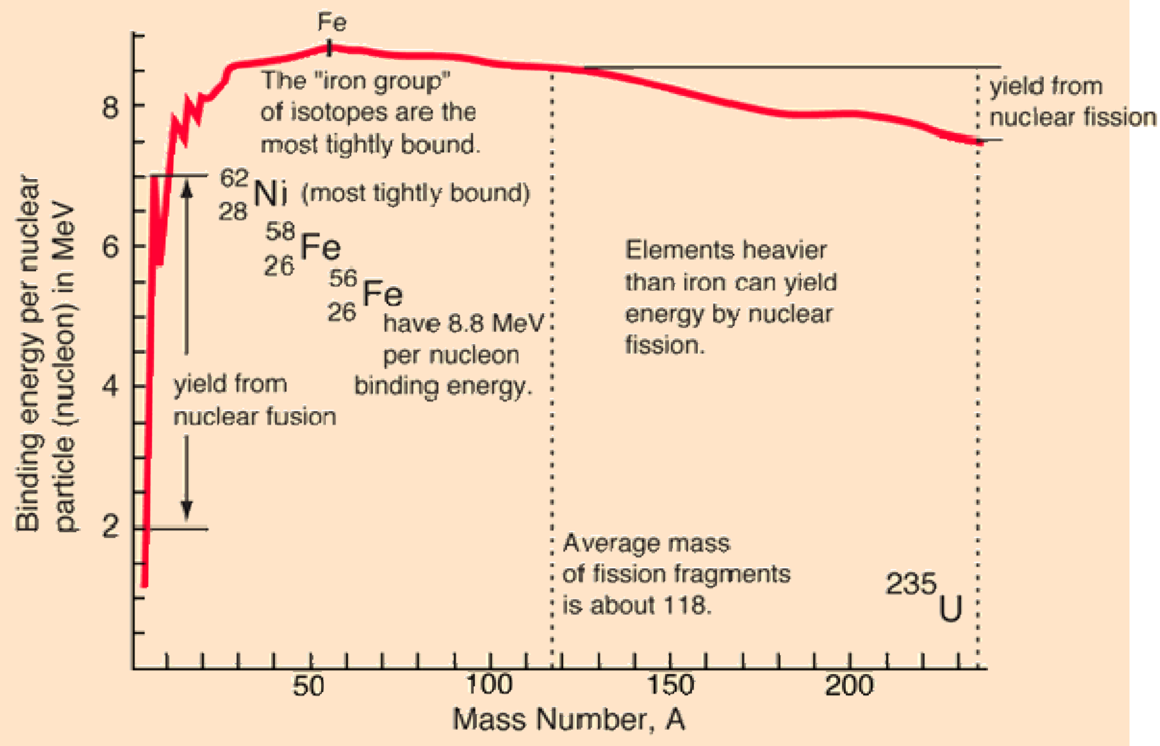
For the alpha particle $\Delta m = 0.0304$ u which gives a binding energy of 28.3 MeV.

The enormity of the nuclear binding energy can perhaps be better appreciated by comparing it to the binding energy of an electron in an atom. The comparison of the alpha particle binding energy with the binding energy of the electron in a hydrogen atom is shown below. The nuclear binding energies are on the order of a million times greater than the electron binding energies of atoms.



Comparison of atomic and nuclear scales and binding energy

Fission and fusion can yield energy



Nuclear Binding Energy Curve

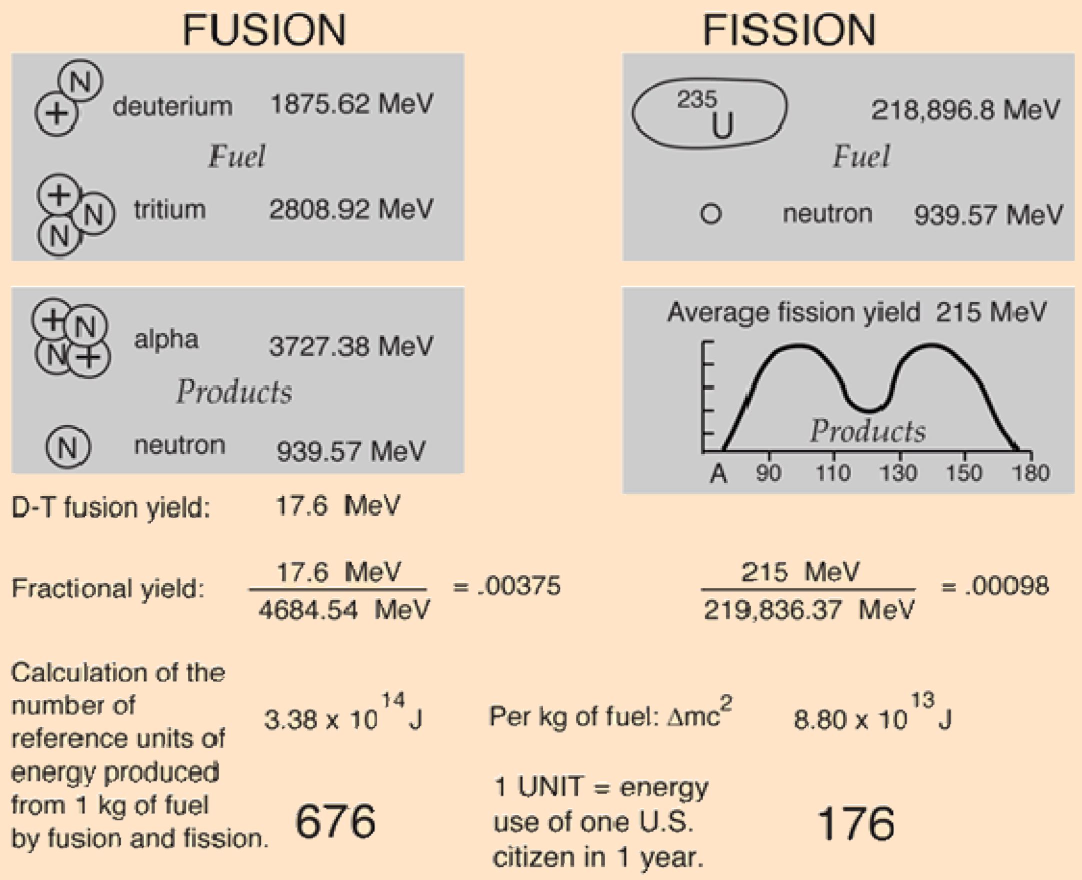
The binding energy curve is obtained by dividing the total nuclear binding energy by the number of nucleons. The fact that there is a peak in the binding energy curve in the region of stability near iron means that either the breakup of heavier nuclei (fission) or the combining of lighter nuclei (fusion) will yield nuclei which are more tightly bound (less mass per nucleon).

The binding energies of nucleons are in the range of millions of electron volts compared to tens of eV for atomic electrons. Whereas an atomic transition might emit a photon in the range of a few electron volts, perhaps in the visible light region, nuclear transitions can emit gamma-rays withquantum energies in the MeV range.

The iron limit

The buildup of heavier elements in the nuclear fusion processes in stars is limited to elements below iron, since the fusion of iron would subtract energy rather than provide it. Iron-56 is abundant in stellar processes, and with a binding energy per nucleon of 8.8 MeV, it is the third most tightly bound of the nuclides. Its average binding energy per nucleon is exceeded only by ^{58}Fe and ^{62}Ni, the nickel isotope being the most tightly bound of the nuclides.

Fission and Fusion Yields



Deuterium-tritium fusion and uranium-235 fission are compared in terms of energy yield. Both the single event energy and the energy per kilogram of fuel are compared. Then they expressed in terms of a nominal per capita U.S. energy use: 5×10^{11} joules. This figure is dated and probably high, but it gives a basis for comparison. The values above are the total energy yield, not the energy delivered to a consumer.

Illustration	Comparison unit:1 U.S. year	Further discussion

Some Nuclear Units

Nuclear energies are very high compared to atomic processes, and need larger units. The most commonly used unit is the MeV.

1 electron volt = 1eV = 1.6×10^{-19} joules
1 MeV = 10^6 eV; 1 GeV = 10^9 eV; 1 TeV = 10^{12} eV

However, the nuclear sizes are quite small and need smaller units:

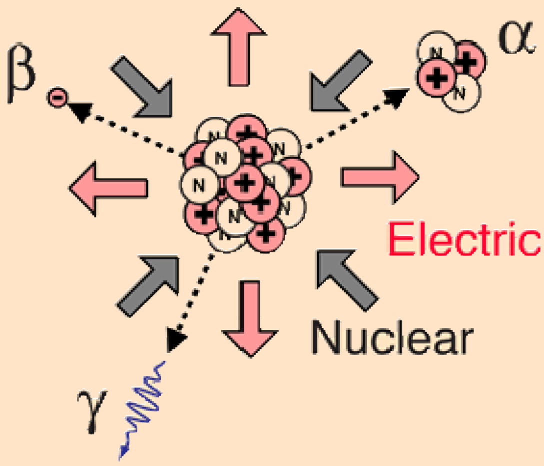
Atomic sizes are on the order of 0.1 nm = 1 Angstrom = 10^{-10} m
Nuclear sizes are on the order of femtometers which in the nuclear context are usually called fermis:

$$1 \text{ fm} = 10^{-15} \text{m}$$

Atomic masses are measured in terms of atomic mass units with the carbon-12 atom defined as having a mass of exactly 12 amu. It is also common practice to quote the rest mass energy $E=m_0c^2$ as if it were the mass. The conversion to amu is:

$$1 \text{ u} = 1.66054 \times 10^{-27} \text{ kg} = 931.494 \text{ MeV}$$

Radioactivity

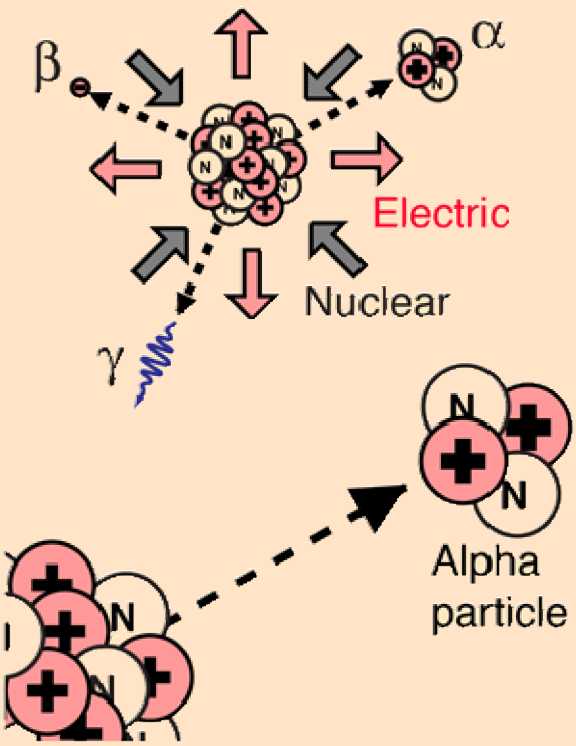


Radioactivity refers to the particles which are emitted from nuclei as a result of nuclear instability. Because the nucleus experiences the intense conflict between the two strongest forces in nature, it should not be surprising that there are many nuclear isotopes which are unstable and emit some kind of radiation. The most common types of radiation are calledalpha, beta, and gamma radiation, but there are several other varieties of radioactive decay.

Radioactive decay rates are normally stated in terms of their half-lives, and the half-life of a given nuclear species is related to its radiation risk. The different types of radioactivity lead to differentdecay paths which transmute the nuclei into other chemical elements. Examining the amounts of the decay products makes possible radioactive dating.

Radiation from nuclear sources is distributed equally in all directions, obeying the inverse square law.

Alpha Radioactivity

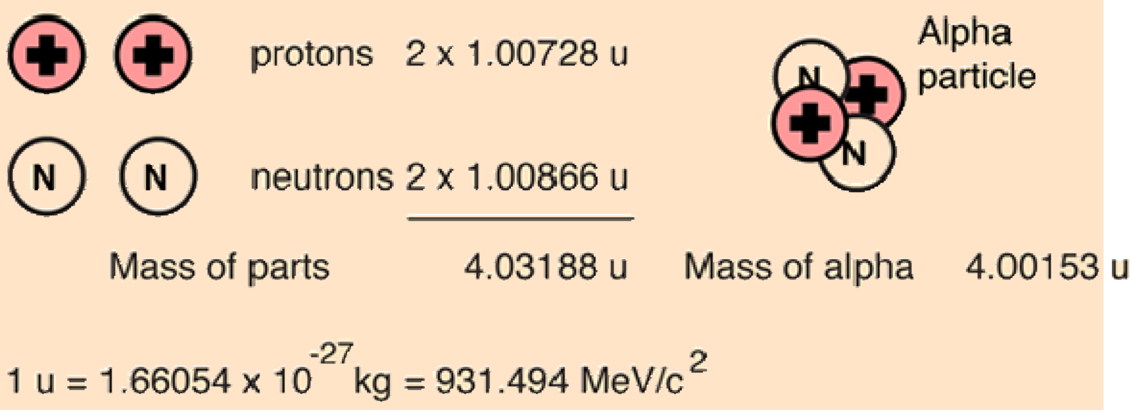


Composed of two protons and two neutrons, the alpha particle is a nucleus of the element helium. Because of its very large mass (more than 7000 times the mass of the beta particle) and its charge, it has a very short range. It is not suitable for radiation therapy since its range is less than a tenth of a millimeter inside the body. Its main radiation hazard comes when it is ingested into the body; it has great destructive power within its short range. In contact with fast-growing membranes and living cells, it is positioned for maximum damage.

Alpha particle emission is modeled as a barrier penetration process. The alpha particle is the nucleus of the helium atom and is the nucleus of highest stability.

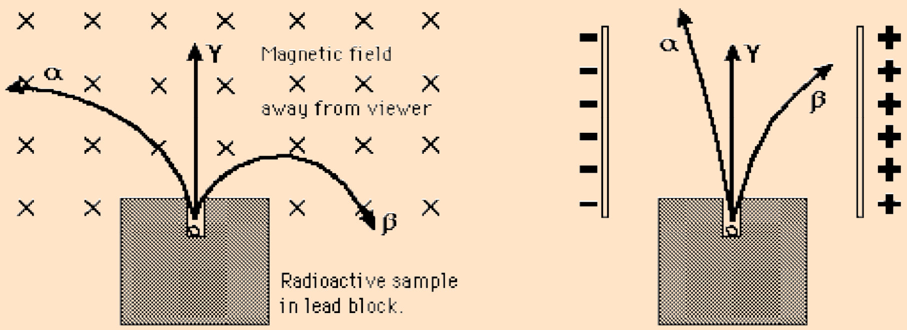
Alpha Binding Energy

The nuclear binding energy of the alpha particle is extremely high, 28.3 MeV. It is an exceptionally stable collection of nucleons, and those heavier nuclei which can be viewed as collections of alpha particles (carbon-12, oxygen-16, etc.) are also exceptionally stable. This contrasts with a binding energy of only 8 MeV for helium-3, which forms an intermediate step in the proton-proton fusion cycle.



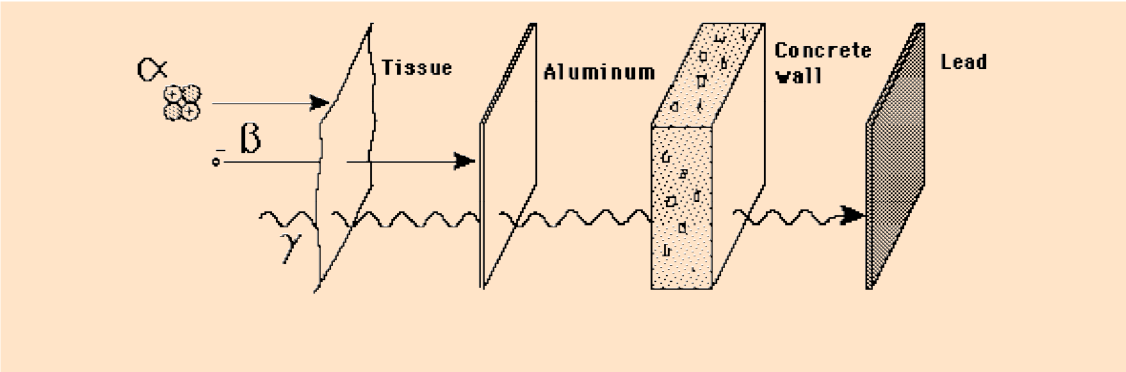
Alpha, Beta, and Gamma

Historically, the products of radioactivity were called alpha, beta, and gamma when it was found that they could be analyzed into three distinct species by either a magnetic field or an electric field.



Penetration of Matter

Though the most massive and most energetic of radioactive emissions, the alpha particle is the shortest in range because of its strong interaction with matter. The electromagnetic gamma ray is extremely penetrating, even penetrating considerable thicknesses of concrete. The electron of betaradioactivity strongly interacts with matter and has a short range.


α
β
γ
Tissue
Aluminum
Concrete
wall
Lead