

Lecture 21

Fundamentals of Physics

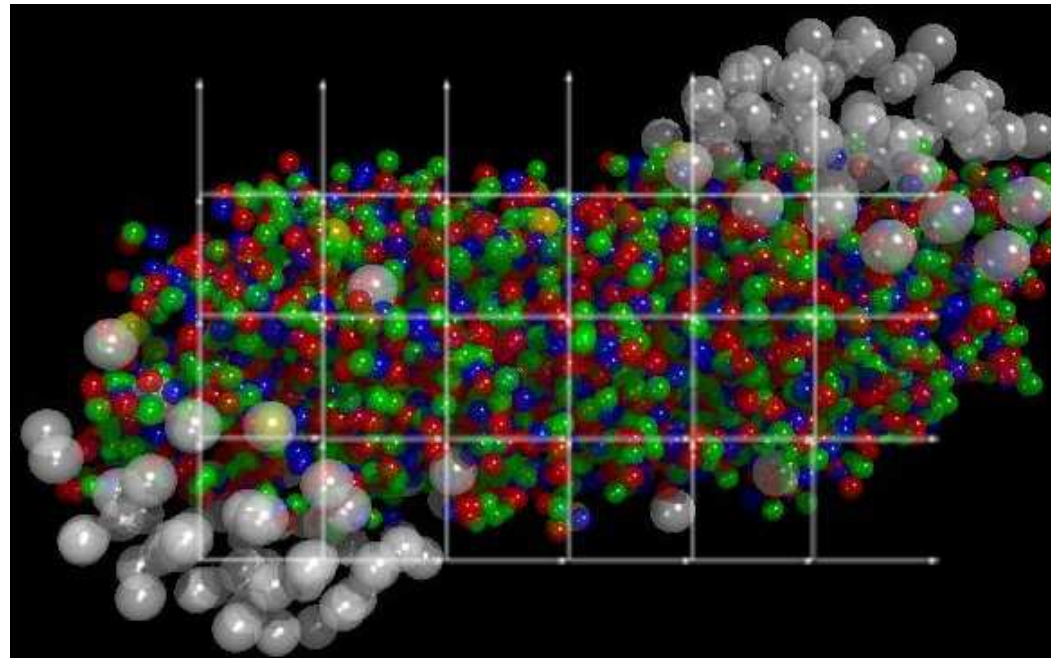
Phys 120, Fall 2015

Nuclear Physics

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Overview

- Why care about nuclei?
- How do nuclei stick together?
- Nuclear energy and nuclear structure.
- Radioactive decay
- Nucleodide table

What is a nucleus?

We saw that Rutherford found in 1911 that an atom has electrons spread out over most of its volume, but that all the mass is localized in a very small center.

The nucleus is positively charged and Rutherford postulated positively charged particles he called protons that make up the nucleus. A proton is a Hydrogen ion.

To explain the measured mass of elements it had to be postulated that there is a second neutral nuclear particle that Rutherford called the neutron*. Most atoms have roughly an equal number of protons and neutrons.

It took until 1932 when James Chadwick (1891-1974) was credited with directly showing the existence of these postulated neutrons.

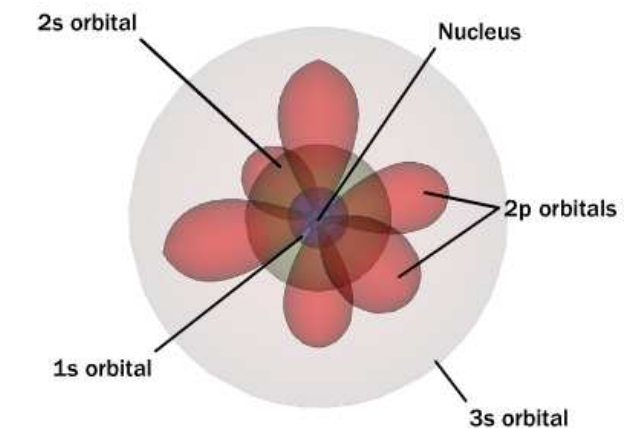
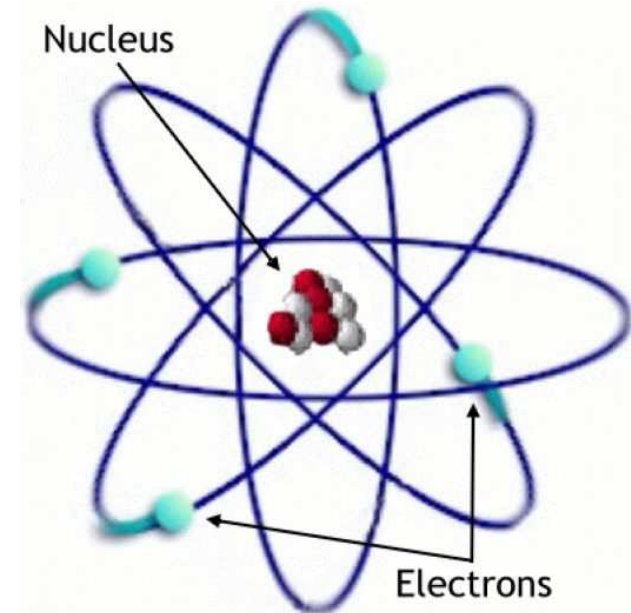
*Another possibility was that there were electrons and protons present in the nucleus as the electron mass would be small enough to be tough to detect.

Do nuclei matter?

You may imagine that the nucleus of an atom is a small inert object which would be of little relevance to humans.

We would be wrong, however. The dynamics of the nucleus is what is responsible for radioactive decay. You need to understand this to see a) where the Radon in your basement comes from and b) why it is a bad idea to breath in this Radon.

And we have seen the terrifying power of the nucleus in the use of nuclear explosives. In this and the next lecture you will learn about how nuclei work and the importance of nuclear effects for you.



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Concept Check

Which of the atomic models depicted on the previous page is more correct?

- a) The planetary model, where we can see the electrons orbit the nucleus
- b) The quantum model, where we see a representation of the electron-matter wave

Concept Check

What is the typical size of an atom?

- a) 1m
- b) 10^{-5} m
- c) 10^{-10} m
- d) 10^{-15} m

What are atomic nuclei?

The atomic nucleus is found at the center of an atom. From Rutherford's scattering experiments we know that the nucleus is much smaller than the atom.

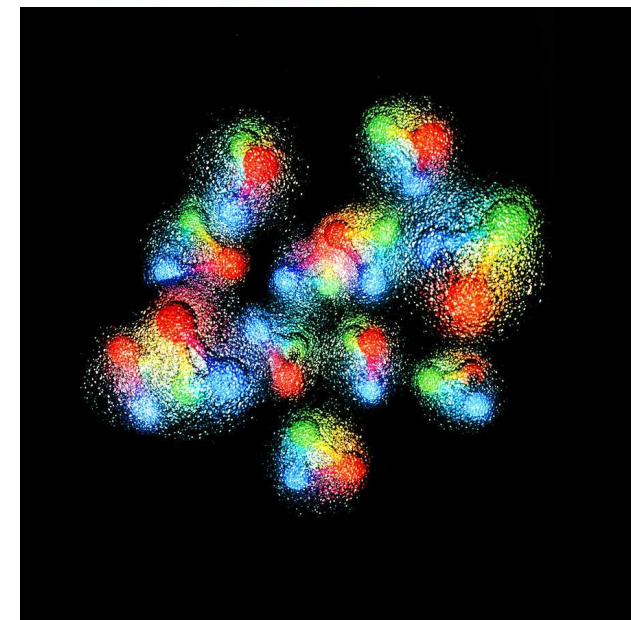
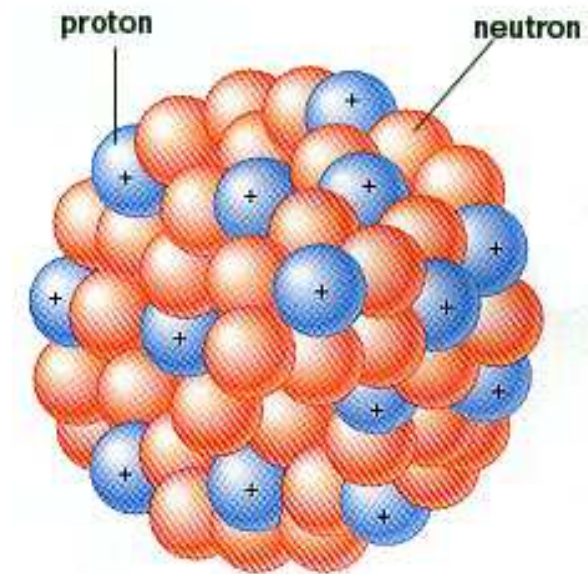
We also know that the number of **protons** must equal the number of electrons, since an atom is electrically neutral.

From knowing the mass we know that the nucleus must also contain a certain number of neutral components which we call **neutrons**.

On the right we see two artists renditions of atomic nuclei. The typical distance between the **nucleons** is about 10^{-15} m.

Neutrons and protons are not fundamental particles: they consist of three quarks, as shown in the bottom artist's rendition.^a

^aWe will discuss this in a lecture on elementary particles later.



What keeps nuclei together?

For nuclei to be stable, the constitutive parts must be held together. What forces will do this?

Electric: there is only positive charge and this should blow the nucleus apart.

Gravity: it is attractive, but the masses are so small, that electric effects would be *much* stronger.

So according to our current knowledge, atomic nuclei should not exist!

We need to postulate a new kind of force:

- keeps nuclei stable
- lets nuclei only grow to a certain size

The strong force

This new force is called the **strong force**. It only acts at short distances of 10^{-15} m. It is attractive between protons and protons, and between neutrons and protons.

There is one more fundamental force, the weak nuclear force, or simply **weak force**, needed to understand radioactive beta decay*

These four forces, electric, gravity, and weak and strong nuclear force make up the **four fundamental forces** of nature. These forces determine the structure of our universe.

*We will see that a beta decay is a neutron that becomes a proton and an electron, and the electron escapes the nucleus giving the beta radiation.

Concept Check

Suppose that the strong force had a somewhat longer range than it actually has. How would this affect the list of elements (the periodic table)?

- a) The periodic table would be much smaller than it actually is.
- b) The periodic table would be much larger than it actually is.
- c) The periodic table would be left unchanged.

Strength of the strong nuclear force

The neutrons and protons are restricted to a very small space of dimension of about 10^{-14} m. Because of Heisenberg's uncertainty principle this means that the velocity uncertainty must be large:

$$\Delta v = \frac{h}{m\Delta x} = \frac{6.6 \cdot 10^{-34}}{(1.7 \cdot 10^{-27} \text{kg})(10^{-14} \text{m})} = 0.13c$$

Protons and neutrons move with relativistic speeds, so the force holding them together must be very large!

Compare that to an electron:

$$\Delta v = \frac{h}{m\Delta x} = \frac{6.6 \cdot 10^{-34}}{(9.1 \cdot 10^{-31} \text{kg})(10^{-10} \text{m})} = 0.024c$$

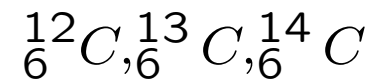
Nuclear Structure

Elements are determined by the number of electrons they have, since it is the electrons that are responsible for chemical reactions.

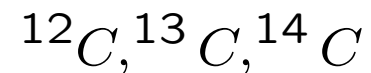
The number of protons must be identical to the number of electrons, since atoms are electrically neutral. This number is also known as the **atomic number**.

The number of neutrons, however, can vary. We identify these **isotopes** by a new quantity, the **mass number** which corresponds to the total number of protons and neutrons. Such isotopes are chemically identical but their nuclear properties are different.

Carbon has atomic number 6, so every carbon atom has 6 protons. Additionally the carbon atom can contain 6, 7, or 8 neutrons, so that these isotopes would have the mass numbers 12,13 or 14. We write this as



or, since the atomic number 6 is already contained in the symbol C,



Concept check

Which fundamental forces come into play during chemical reactions?

- a) Gravitational
- b) Electromagnetic
- c) Frictional
- d) Nuclear

Concept check

The nuclei ${}^3\text{H}$ and ${}^3\text{He}$ have

- a) identical atomic numbers but different mass numbers
- b) different atomic numbers and different mass numbers
- c) different atomic numbers and identical mass numbers
- d) identical atomic numbers and identical mass numbers

Henri Becquerel

In 1896 Henri Becquerel (1852-1908) stored a uranium compound in a drawer next to an undeveloped photographic plate. When he tried to use the plate later he realized that it had already been exposed.

Instead of just getting a new plate he began to ponder this mystery. He concluded that the uranium compound must have radiated and exposed the photographic plate. He then experimented with different uranium compounds, but discovered that the chemical composition had no effect on the photographic exposures.

So he discovered a nuclear effect before the discovery of the nucleus!



Marie Curie

Two years later Marie Curie (1867-1934) and her husband Pierre discovered radioactivity in pitchblende. It contains uranium, but the radiation was much more intense.

They then chemically extracted 0.01 grams out of 8 tonnes of pitchblende of this new, highly radioactive substance. Because of its radioactivity they called it **radium**.

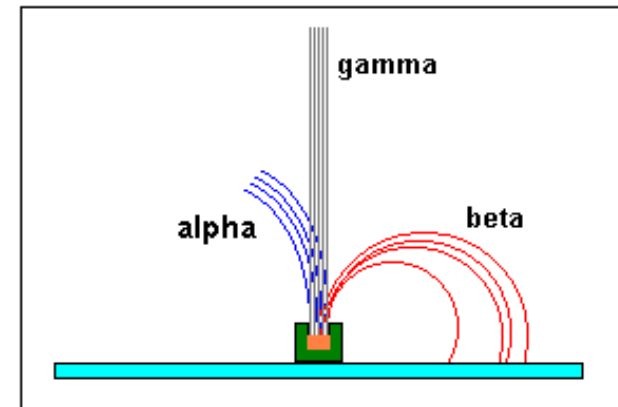


Radioactive decay

We now know that *every* isotope with atomic number higher than 83 (Bismuth) is radioactive and that there are many **radioactive isotopes** of the lighter elements. Of the three isotopes of carbon ^{14}C is radioactive, but ^{13}C and ^{12}C are not.

Experiments show that radioactive materials emit three distinct types of rays, known as **alpha**, **beta**, and **gamma** rays. The way that these rays react to electric and magnetic fields shows that alpha rays are positively charged and beta rays are negatively charged while gamma rays are uncharged.

Most nuclei are **stable**. Others are unstable or **radioactive**; they will eventually change their structure even without outside disturbance. such a spontaneous structure change is called **radioactive decay**.



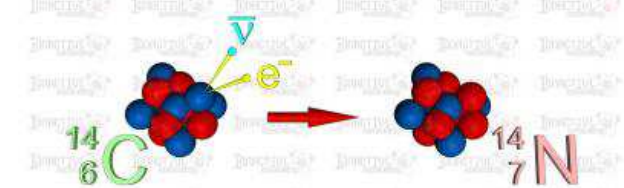
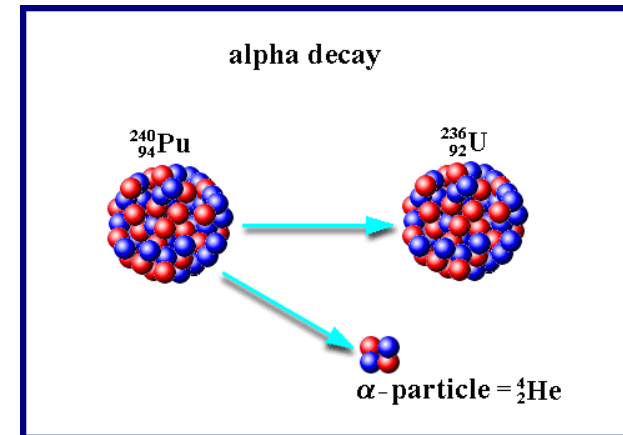
Alpha, beta and gamma radiation can be deflected by using magnetic field. Alpha and beta particles have contrary charges - they undergo deflection in opposite directions gamma rays don't transfer any charge - they don't undergo deflection.

Radioactive decay path

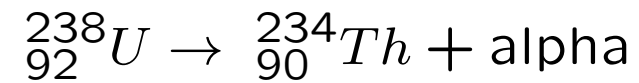
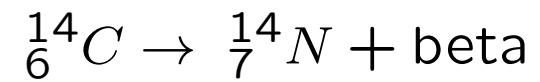
alpha decay: a nucleus emits a particle consisting of two protons and two neutrons. Such an alpha particle will collide with molecules in the air, pick up two electrons and become a Helium atom.

beta decay: here a nucleus emits an electron. This is strange, since there are no electrons in the nucleus. Instead due to the weak force a neutron is transformed into a proton and an electron.

gamma rays: both decay forms above transform a nucleus to a nucleus of lower energy. The excess energy is emitted in form of a high energy **gamma ray photon**, similar to the emission of radiation when electrons take on a different quantum state.



Examples



Energy:

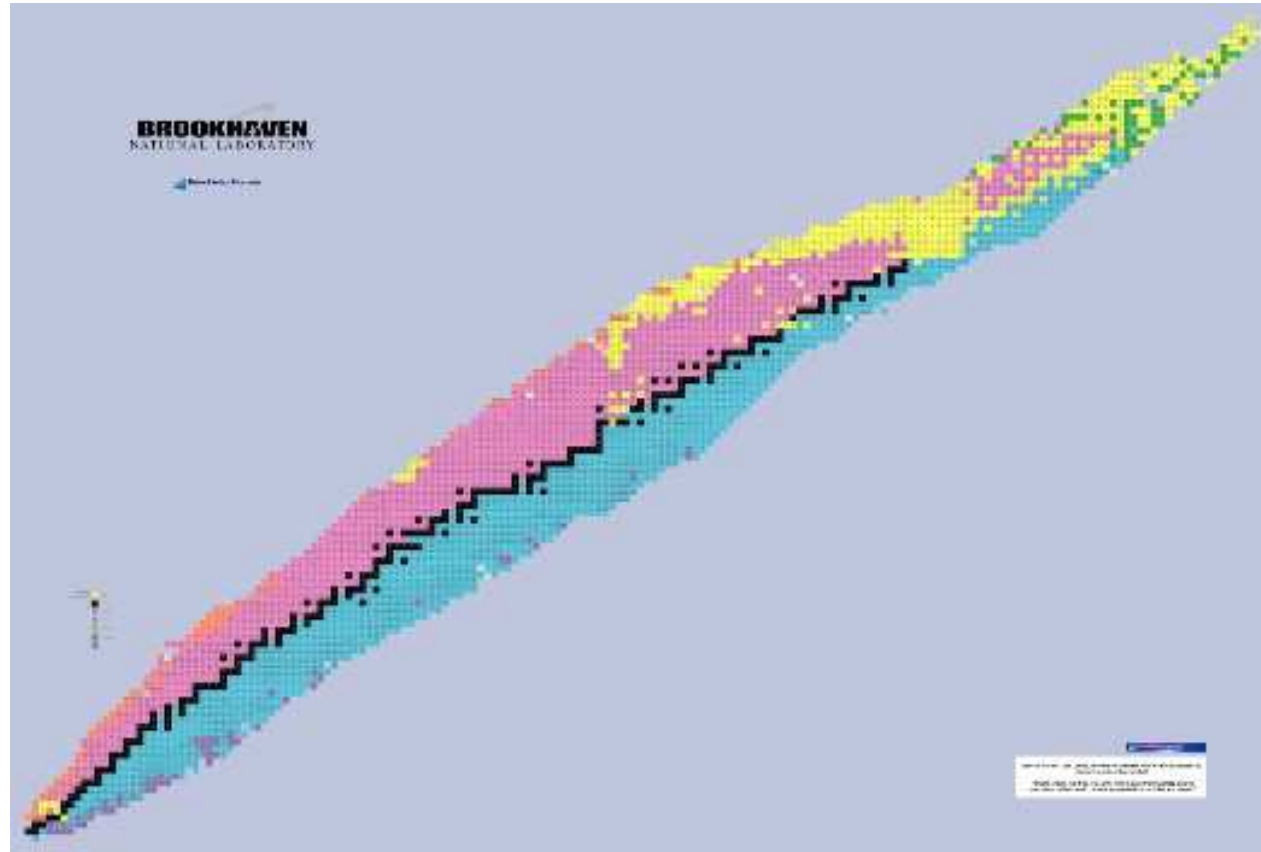
nuclear energy \rightarrow thermal energy + **radiant energy**

Concept check

Which fundamental forces come into play during nuclear reactions?

- a) gravitational
- b) electromagnetic
- c) frictional
- d) strong or weak nuclear

Nucleotide table



200Bi 36.4 M	201Bi 103 M	202Bi 1.72 H	203Bi 11.76 H	204Bi 11.22 M	205Bi 15.31 D	206Bi 6.343 D	207Bi 32.9 Y	208Bi 9.68E+5 Y	209Bi STABLE 100%	210Bi 5.012 D
← 100.00%	← 100.00%	← 100.00% α = 1.0E-5N	← 100.00%	← 100.00%	← 100.00%	← 100.00%	← 100.00%	← 100.00%	← 100.00%	β- 100.00% α = 1.3E-4N
199Pb 90 M	200Pb 21.5 H	201Pb 9.33 H	202Pb 52.5E+3 Y	203Pb 51.92 H	204Pb α = 1.4E+17 Y 1.4%	205Pb 1.73E+7 Y	206Pb STABLE 24.1%	207Pb STABLE 22.1%	208Pb STABLE 52.4%	209Pb 3.253 H
← 100.00%	← 100.00%	← 100.00%	← 100.00% α = 1.00%	← 100.00%	← 100.00%	← 100.00%	← 100.00%	← 100.00%	← 100.00%	β- 100.00%
198Tl 5.3 H	199Tl 7.42 H	200Tl 26.1 H	201Tl 3.0421 D	202Tl 12.23 D	203Tl STABLE 29.524%	204Tl 3.78 Y	205Tl STABLE 70.476%	206Tl 4.200 M	207Tl 4.77 M	208Tl 3.053 M
← 100.00%	← 100.00%	← 100.00%	← 100.00%	← 100.00%	← 100.00%	β- 97.10% α = 2.90%	← 100.00%	β- 100.00%	β- 100.00%	β- 100.00%
197Hg 64.14 H	198Hg STABLE 10.0%	199Hg STABLE 16.87%	200Hg STABLE 23.10%	201Hg STABLE 13.18%	202Hg STABLE 29.86%	203Hg 46.594 D	204Hg STABLE 6.87%	205Hg 5.14 M	206Hg 8.15 M	207Hg 2.9 M
← 100.00%	← 100.00%	← 100.00%	← 100.00%	← 100.00%	← 100.00%	β- 100.00%	β- 100.00%	β- 100.00%	β- 100.00%	β- 100.00%
196Au 6.1662 D	197Au STABLE 100%	198Au 2.6956 D	199Au 3.139 D	200Au 48.4 M	201Au 26.0 M	202Au 25.5 S	203Au 60 S	204Au 39.8 S	205Au 31 S	
← 95.00%	← 100.00%	β- 100.00%	β- 100.00%	β- 100.00%	β- 100.00%	β- 100.00%	β- 100.00%	β- 100.00%	β- 100.00%	β- 100.00%
195Pt STABLE 33.032%	196Pt STABLE 25.242%	197Pt 19.0615 H	198Pt STABLE 7.163%	199Pt STABLE 30.80 M	200Pt 12.8 H	201Pt 3.5 M	202Pt 44.3	203Pt 16.2		
← 100.00%	← 100.00%	β- 100.00%	← 100.00%	β- 100.00%	β- 100.00%	β- 100.00%	β- 100.00%	β- 100.00%		

Brief summary of decay paths

Alpha A helium nucleus of two protons and two neutrons is emitted from a nucleus. The atomic number is decreased by two. Mostly decay path for large nuclei.

Beta A neutron decays into a proton, an electron and a neutrino. The two latter particles are emitted from the nucleus. The atomic number is increased by one. This occurs mostly for nuclei which have too many neutrons.

Gamma The emitted particles can carry all or only part of the energy related released in the decay. A high energy photon is also emitted to make up for the energy difference.

In the description above an important scenario is missing. What is it?

Timeline

1850

2000



1875

1900

1925

1950

1975

2000



Becquerel



M. Curie



Chadwick



Rutherford



Schrödinger



Heisenberg

Summary

- nuclei are made up of protons and neutrons
- nuclei are held together by a new force: the strong force
- chemical properties depend on number of electrons (or protons)
- chemically identical atoms with different weights are called isotopes
- only some nuclei are stable others will decay via alpha or beta decay