Demonstration: levitating globe comparing a magnetic force with the force of gravity; Geiger counter, sources.
Text: Mod. Phys. 2.A, 2.B
Problems: 1, 5, 6, 13 from Ch. 2

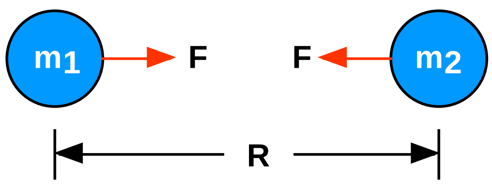
What's important:
•four fundamental forces: strong, electromagnetic, weak, gravitational
•strength and range of forces
•dependence of cross sections and lifetimes on interaction

Fundamental interactions

We summarized in Lec. 2 the sizes and masses of atoms, nuclei and their constituent elementary particles, which are properties of particles in isolation. We now turn to a discussion of how particles interact, starting with the most familiar interaction - gravity.

Gravity

As you know from high school physics, the gravitational force between two objects with masses $\mathbf{m_1}$ and $\mathbf{m_2}$ is attractive



and has the functional form

$$\mathbf{F_{grav} = G\, m_1\, m_2\, /\, R^2} \qquad \text{with} \qquad \mathbf{G} = 6.67 \times 10^{-11}\ \text{Nm}^2/\text{kg}^2.$$

The proportionality constant **G** is a universal constant applying to all objects, and the functional form is referred to as Newton's law of universal gravitation.

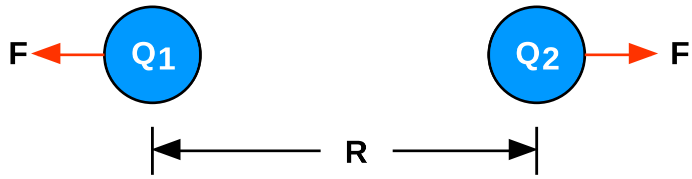
Let's calculate the force between two protons separated by a distance of 1 fm:

$$\mathbf{F_{grav}} = 6.67 \times 10^{-11} \times (1.67 \times 10^{-27})^2 / (10^{-15})^2 = 1.9 \times 10^{-34}\ \text{N}.$$

This certainly looks like a small force, as measured in Newtons. But is it actually small on the scale of elementary particle interactions? To answer this question, we turn to another force with which we are familiar - the electrostatic interaction between charges.

Electrostatic interaction

Coulomb's law describes the force between objects arising from their charge Q. If the charges have the same sign, then the force is repulsive:



and the magnitude is given by

$$F_{elec} = k\, Q_1\, Q_2 \,/\, R^2 \qquad \text{with} \qquad k = 8.99 \times 10^9\ \mathrm{Nm^2/C^2}.$$

This functional form is identical to that of Newton's law for gravity:
•the force is proportional to the product of a characteristic of the objects (charge or mass)
•the force is inversely proportional to the square of the separation between the objects.
However, gravity is always attractive, whereas the electrostatic interaction can be attractive or repulsive depending on whether the charges are different or alike in sign.

The charge **Q** on a proton is equal to 1.6×10^{-19} Coulombs (C). Hence, the electrostatic force between the two protons in the previous example is

$$F_{elec} = 8.99 \times 10^9 \times (1.6 \times 10^{-19})^2 / (10^{-15})^2 = 230\ \mathrm{N}.$$

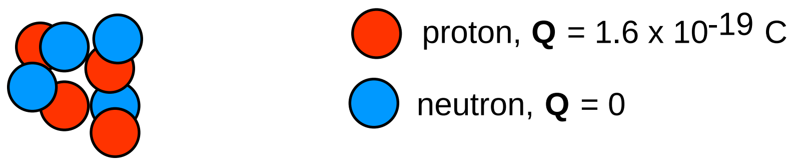
This is huge compared to the gravitational force:

$$F_{elec} / F_{grav} \sim 10^{36}.$$

The two interactions have very different **strengths**, with gravity being extremely weak compared to the electrostatic interaction. Further, F_{elec} in the example is macroscopic in magnitude: the force between the protons has the same magnitude as the gravitational attraction between the Earth and an eight-year old child.

Strong and weak forces

Are there other forces than gravity and electromagnetism? The fact that nuclei exist tells us that there must be. A nucleus consists of roughly equal numbers of protons and neutrons



As we have shown, the protons repel each other with a force 10^{36} times greater than their gravitational attraction, so there must be another interaction among the particles that allows them to bind together. Further, the interaction must be larger than the electrostatic interaction in magnitude, and hence is given the name **strong** interaction.

In addition to the strong interaction, there is a fourth interaction, smaller in magnitude than the electromagnetic interaction, that governs certain types of decay processes. For example, a free neutron decays via the sequence:

n	→	p	+	e^-	+	ν
(neutron)		(proton)		(electron)		(neutrino)

The particle called the neutrino is a massless, chargeless particle (emitted copiously in the nuclear reactions of the Sun) that cannot interact by the strong or electromagnetic interactions. This decay is said to be governed by the **weak** interaction. Of course, the weak interaction also is present in scatter processes.

How do these forces depend upon distance? The electromagnetic and gravitational forces both vary as $1/\mathbf{R}^2$, which is said to be a **long-ranged** interaction. In contrast, the strong and weak forces decrease more rapidly than $1/\mathbf{R}^2$, and therefore are said to be **short-ranged**. In summary:

Interaction name	Relative strength	Range	Effects
strong	strong	short	binds the nucleus
electromagnetic	medium	long	force between charges
weak	weak	short	governs certain decays
gravitational	very weak	long	force between masses

Interactions and cross sections

The strength of the interactions is manifested in the scattering cross sections of particles, and in their lifetimes. Consider the example of the two protons that we have used in the previous sections. We showed that the electrostatic force between protons is much larger in magnitude than their gravitational attraction. That means that, if two protons approach and scatter from each other, the contribution to the scattering probability from their electrostatic repulsion is much larger than the contribution from their gravitational attraction.

That is, particles with strong interactions are more likely to scatter than particles with weak interactions. The same applies to particle lifetimes: if a decay produces a particle having only a weak interaction with the other products of the decay, then the process will be infrequent, and the decay will be slow, on average ("slow" decay means that particles decay infrequently - it doesn't mean that the physical process is slow). Thus, strong interactions correspond to large cross sections and short lifetimes, while weak interactions correspond to small cross sections and long lifetimes.

For example, pion decay (about 1/7 the mass of a proton)

$\pi^o \rightarrow \gamma + \gamma$ is electromagnetic with lifetime of about 10^{-16} sec

$\pi^- \rightarrow \mu^- + \nu$ is weak with a lifetime of 10^{-4} sec.

Some typical examples are shown below, although each quantity covers a large range for any given process:

Interaction	Typical cross section	Typical lifetime
strong	10^{-30} m^2	10^{-24} sec
electromagnetic	10^{-36} m^2	10^{-16} sec
weak	10^{-42} m^2	10^{-8} sec

Note: cross sections are often measured in barns: 1 barn = 100 fm^2 = 10^{-28} m^2.

Why don't all measurements of a given target particle yield the same cross section? After all, isn't cross section just geometry? Not quite: cross sections can be interpreted as $\sigma = \pi R^2$ only if the interaction is strong and short-ranged. Otherwise, σ is no more than a measure of interaction probability. Thus, even though the scattering of a neutrino from a proton has a lower cross section than that of a proton hitting another proton, it doesn't mean that the target proton has a different size: it just means that the interaction is weaker.