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What is the difference between a force and an interaction?

This is a hard distinction to make. Strictly speaking, a force is the effect on a particle due to the presence of other particles. The interactions of a particle include all the forces that affect it, but also include decays and annihilations that the particle might go through. The reason this gets confusing is that most people, even most physicists, usually use "force" and "interaction" interchangeably, although "interaction" is more correct. You will usually be okay using the terms interchangeably, but you should know that they are different.

FUNDAMENTAL INTERACTIONS There are four fundamental interactions which account for all the known forces in the universe. **(i) Gravitational interaction (ii) Electromagnetic interaction**

(iii) Strong interaction (iv) Weak interaction.

- ***The range of interaction***

If a force involves the exchange of a particle, that particle has to "get back home before it is missed" in the sense that it must fit within the constraints of the uncertainty principle. A particle of mass m and rest energy $E = mc^2$ can be exchanged if it does not go outside the bounds of the uncertainty principle in the form $\Delta E \Delta t \approx mc^2 \Delta t > \frac{\hbar}{2}$

A particle which can exist only within the constraints of the uncertainty principle is called a "virtual particle", and the time in the expression above represents the maximum lifetime of the virtual exchange particle. Since this exchange particle cannot exceed the speed limit of the universe, it cannot travel further than c times that lifetime. The maximum range of the force would then be on the order of $\approx c\,\Delta t \approx \frac{\hbar}{2mc}$. Hence $\boxed{\text{Range} \approx c\,\Delta t \approx \frac{\hbar}{2mc}}$............ (i)

Range for the electromagnetic force and gravity: The rest masses of the exchange particles for the electromagnetic force and gravity, the photon and the graviton, are **taken to be zero** and those forces are presumed to be **infinite in range**. **The recent detection of gravity waves is consistent with transmission at the speed of light and therefore with a graviton mass of zero.**

Pion Range of Strong Force.

An estimate of the range of the strong force can be made by assuming that it is an exchange force involving neutral Pions. This would be considering the pion involved in the exchange to be a "virtual particle", limited in lifetime by the uncertainty principle.

When the range expression is used with a pion mass of π^0 mass $= 264\ \mathrm{m_e} = 135.0\mathrm{MeV/c^2}$

The range obtained from equation (i) is 0.73×10^{-15} m $= 0.61 \times$ classical proton radius.

This range is in the neighborhood of one fermi. When Hideki Yukawa was working on a theory of the strong force, he judged that the range of the nuclear force was about a fermi, and calculated that the exchange particle should be in the neighborhood of 100MeV in mass equivalent. This triggered the search which led to the discovery of the pion. When the nuclear particles are very close together, other heavier particles must also be included in this type of model of the strong force.

The current view is that the strong force is fundamentally an interaction between quarks, called the "color force" and that the "strong force" between nucleons which are colorless is really a residual color force.

Similarly we can calculate the range for weak interaction W Boson has a mass of $80\mathrm{GeV}/C^2$

Range of weak force is about 2×10^{-18} m.

- ***Coupling Constant for any interaction.***

A coupling constant (or an interaction constant) is a parameter in the field theory, which determines the relative strength of interaction between particles or fields. Dimensionless parameters are used as coupling constants, as well as the quantities associated with them that characterize the interaction and have dimensions.

Comparison of interactions

If we choose an object that participates in all the four fundamental interactions, the values of the dimensionless coupling constants of this object, found according to the general rule, will show the relative strength of these interactions. At the level of elementary particles, a proton is most commonly used as such an object. The basic energy for comparison of interactions is the electromagnetic energy of a photon, which equals by definition: $U_f = \frac{hc}{\lambda}$ where h is the Planck constant, c is the speed of light, λ is the photon wavelength. The choice of the photon energy is not accidental, since the basis of the modern science is the wave representation based on electromagnetic waves. All the main measurements, including length, time and energy, are made with the help of them.

Coupling constant for Gravitational interaction

The energy of gravitational interaction between two protons is given by: $U_g = -\frac{GM_p^2}{r}$

where G is the gravitational constant, M_p is the proton mass, r is the distance between the protons' centers. If we assume that the distance r and the electromagnetic photon's wavelength λ are related by the formula $\lambda = 2\pi r$, then the ratio of the absolute value of the gravitational interaction energy to the photon's energy gives the **dimensionless coupling constant:** $\boldsymbol{\alpha_g} = \frac{|U_g|}{U_f} = \frac{GM_p^2}{\hbar c} = 5.907 \times 10^{-39}$,

where ħ is the Dirac constant.

Coupling constant for Weak interaction

The energy associated with the weak interaction can be represented as: $U_W = \frac{g_F^2}{4\pi r} \exp\left(-\frac{M_W\, cr}{\hbar}\right)$

where g_F is the effective charge of weak interaction, M_W is the mass of virtual particles that are considered the carrier particles for weak interaction (W and Z Bosons). The square of the effective charge of weak interaction for the proton is expressed in terms of the Fermi constant

$G_F = 1.43 \times 10^{-62}\ \mathrm{J \cdot m^3}$ and the proton mass M_p $as: g_F^2 = \frac{4\pi G_F M_p^2 c^2}{\hbar^2}$

At sufficiently small distances the exponent in the weak interaction energy can be neglected. In this case, the dimensionless coupling follows: $\alpha_W = \frac{U_W}{U_f} = \frac{G_F M_p^2 c}{\hbar^3} = 1.0 \times 10^{-5}$.

Coupling constant for Electromagnetic interaction

The electromagnetic interaction of two fixed protons is described by the electrostatic energy:

$$U_e = \frac{e^2}{4\pi\varepsilon_0 r}$$

where e is the elementary charge, ε_0 is the electric constant.

The ratio of this energy to the photon energy U_f determines the electromagnetic coupling constant, known as the fine structure constant: $\alpha = \frac{U_e}{U_f} = \frac{e^2}{4\pi\varepsilon_0\hbar c} = 7.297 \times 10^{-3}$

Coupling constant for Strong interaction

At the level of hadrons, the strong interaction is regarded in the Standard Model of elementary particle physics as "residual" interaction of quarks that are part of hadrons. It is assumed that gluons as the carriers of strong interaction generate virtual mesons in the space between the hadrons. In the pion-nucleon model of Yukawa interaction, the nuclear forces between the nucleons are explained as a result of the virtual Pions exchange, and the interaction energy is as follows: $U_s = -\frac{g_{N\pi}^2}{4\pi r}\exp\left(-\frac{M_\pi cr}{\hbar}\right)$

where $g_{N\pi}$ is the effective charge of the pseudo scalar pion-nucleon interaction, M_π is the pion mass. The dimensionless strong interaction coupling constant is: $\alpha_s = \frac{|U_s|}{U_f} = \frac{g_{N\pi}^2}{4\pi\hbar c} \approx 14.6$

Characteristic of fundamental interaction.

	Strong	Electromagnetic	Weak	Gravitational
Carrier of the interaction and spin parity (J^π)	Gluon (1^-)	Photon (1^-)	$W^\pm, Z^0(1^-)(1^+))$	Graviton (2^+)
Coupling constant	1	$\frac{1}{137}$	10^{-5}	6×10^{-39}
Mass	0	0	80GeV, 90 GeV	0
Relative strength	1	10^{-2}	10^{-5}	10^{-38}
Cross section	10 mb	10^{-3}mb	10^{-12}mb	-
Time scale	$10^{-23}s$	$10^{-18}s$ *to* $10^{-20}s$	$\geq 10^{-13}s$	-
Range	$\leq 10^{-15}m$	∞	$10^{-15}m$	∞
Source	Colour charge	Electric charge	Weak charge	Mass

Classification of elementary Particle according to statistics. (Classification On the basis of "SPIN")

In the Standard Model, Elementary Particles are categorised in two classes i.e. **Fermions** and **Bosons.** All observed particles are either Fermion or Boson.

Fermions

- In particle physics, Fermions is particle that follows Fermi-Dirac Statistics and generally has half odd integer spin $\frac{1}{2},\frac{3}{2}$,etc.
- This particle obeys **Pauli Exclusion Principle.**
- Fermion contains all quark and leptons as well as composite particle made of an odd number of these such as all **Baryons** and many **atoms** and **nuclei**. A Fermion can be an elementary particle such as the electron or it can be an elementary particle such as proton (which is made up of two up quark and one down quark).
- Wave function of Bosons is anti-symmetric: $that\ means\ \Psi_B(x_1,x_2,\dots,x_n) = -\Psi_B(x_2,x_1,\dots,x_n)$

What Makes Fermions So Special?

Fermions are sometime called matter particle, because they are the particle that make up most of what we think of as physical matter in our world including proton, neutron and electron.

Types of Fermions:

1. Fundamental Fermions There are the total 12 Fundamental Fermions It divided into two categories:

1a) Quarks: Quarks are the particles that makes up hadron such as protons and neutrons.

Quark	Spin parity	charge	Bayron number	isospin	S	C	B	T	Mass (GeV/c^2)
Up (u)	$\frac{1}{2}^+$	$\frac{2}{3}e$	$\frac{1}{3}$	$\frac{1}{2}$	0	0	0	0	~0.3
Down (d)	$\frac{1}{2}^+$	$-\frac{1}{3}e$	$\frac{1}{3}$	$\frac{1}{2}$	0	0	0	0	~0.3
Charm (c)	$\frac{1}{2}^+$	$\frac{2}{3}e$	$\frac{1}{3}$	0	0	+1	0	0	1.6
Strange (s)	$\frac{1}{2}^+$	$-\frac{1}{3}e$	$\frac{1}{3}$	0	-1	0	0	0	0.5
Top (t)	$\frac{1}{2}^+$	$\frac{2}{3}e$	$\frac{1}{3}$	0	0	0	0	+1	174
Bottom (b)	$\frac{1}{2}^+$	$-\frac{1}{3}e$	$\frac{1}{3}$	0	0	0	+1	0	4.5

1b) Leptons: Leptons are subatomic particle that does not takes part in strong attraction. There are six-types of leptons: -

Particle	Antiparticle	Rest mass (MeV/c^2)	L (electron)	L (muon)	L (tau)	Life time (s)
Electron (e^-)	(e^+)	0.511	1	0	0	stable
Electron type neutrino (ν_e)	($\overline{\nu_e}$)	$< 7 \times 10^{-3}$	1	0	0	stable
Muon (μ^-)	(μ^+)	105.7	0	1	0	2.2×10^{-6}
Muon type neutrino(ν_μ)	($\overline{\nu_\mu}$)	< 0.27	0	1	0	Stable*
Tau (τ^-)	(τ^+)	1777	0	0	1	2.96×10^{-13}
Tau type neutrino(ν_τ)	($\overline{\nu_\tau}$)	< 31	0	0	1	Stable*

Note that: The difference between quarks and leptons is that quarks have a colour charge (and therefore interact with the strong force) and leptons do not. This means that gluons will react with quarks but not with leptons. Quarks are always accompanied by gluons, and are always in sets where their total colour charge equals zero. Quarks are what make up the composite particles like hadrons (heavy) and mesons (medium).

2) Composite Fermions: Beyond the fundamental fermions there is another class of Fermions which can be created by combining Fermions together to get a resulting particle with Integral half spin. Composite Fermions are made of an odd number of fermions as all **Baryons** (These are the particle like proton and neutron that are composed of three quarks join together).

Note that: Fermions were first predicted by the physicist Wolfgang Pauli in 1925. He was trying to figure out how to explain the atomic structure proposed in 1922 by Neils Bohr. Bohr had used experimental evidence to build an atomic modal which contained electron shell creating stable orbits for electron to move around the atomic nucleus. This matched well with evidence, there was no. of particular reason why this structure would stable and that's the explanation that Pauli was trying to reach. He realised that if you assigned quantum number (later named as quantum spin) to the electron.

Then there seemed to be some sort of principle which means that number of two of the electrons could be in exactly the same state. This rule become the Pauli Exclusion Principle.

In 1926, Enrico Fermi and Pauli Dirac Independently tried to understand other aspect of electron behaviour and in doing so, established a more complete statistical way to dealing with electron. Though Fermi developed the system first, they close enough and both did enough work that posterity has dubbed their statistical method Fermi-Dirac Statistics.

The fact that fermions cannot collapse into the same state, that's the ultimate meaning of Pauli Exclusion Principle.

Bosons:

In particle physics Boson is the type of particle that obeys the rule of Bose-Einstein statistics. These Bosons have quantum spin having integral value 0, +1, -1, +2, -2, etc.

- Boson are fundamental particle such as **gluons, $W^{\pm}, Z^0$ Boson**, recently discovered **Higgs Boson aka God particle** and also **Graviton**.
- Bosons are mainly the fundamental force carrying particles. When Bosons are exchanged between two matter particle then there exist a force between them. They include all forces of nature (electromagnetism, gravity, weak nuclear force and strong nuclear force).
- Boson may be **elementary** like Photon or **Composite** i.e. made with two or more elementary particles.
- We can have arbitrary number of Bosons in given state
- Wave function of Bosons is symmetric: *that means* $\Psi_B(x_1, x_2, x_3, \dots, x_n) = \Psi_B(x_2, x_1, x_3, \dots, x_n)$

Note that: The name Boson comes from the surname of Indian physicist Satyendra Nath Bose and physicist Albert Einstein. They develop a method of analysis called Bose-Einstein Statistics. In an effort to understand the Plank's law, Bose proposed a method to analyse the behaviour of photon in 1924. He sent paper to Einstein. One of the most dramatic effect of Bose- Einstein Statistics is the prediction that **boson can overlap and coexist with other bosons**. Because of this it is possible to become a photon to laser. The name Boson First coined by scientists Paul Dirac in the honour of famous scientists Satyendra Nath Bose and Albert Einstein.

Elementary bosons

1. Gauge Boson: Gauge Boson are the particle that Carries the interaction of fundamental forces between particles. All known Gauge Boson have **spin 1** and therefore all Gauge Boson are vector. Gauge boson is characterized into categories. **Gluons (g):** That carries strong nuclear forces between matter particle. There are eight different types of Gluons **Photon (γ):** The particle of light that carries electromagnetic forces, which holds the electron in an atom. **W&Z Boson:** It carries the week nuclear force, which involved in some form of radioactivity and also plays the role in the How Sun Burn. $W^{\pm}$ are Charged weak bosons And Z^0 neutral weak Boson.	**2. Scaler boson:** The only scaler boson **(spin=0)** which has been discovered is Higgs Boson. **Higgs Boson:** It is an elementary particle in standard modal of particle physics. It is produced by quantum excitation of Higgs field (field in particle physics theory). It is the interaction with Higgs field which gives mass to the particle. The **key difference** between **Gauge boson** and **Higgs boson** is that **gauge bosons have a spin of 1, whereas Higgs bosons have a zero spin.**
Graviton (G): There may be a sixth tensor boson **(spin=2)**, the graviton (G). The only **hypothetical Gauge boson** that carries the gravitational force because how gravity work in quantum world is not very well understood.	

Composite Bosons A composite Boson is a bound state of fermions such that the combination gives a boson. a particle containing an **even number of fermions** is a boson, since it has integer spin.

Examples include the following:

i) Any **Meson,** since mesons contain one quark and one antiquark.

ii) The nucleus of a carbon-12 atom, which contains 6 protons and 6 neutrons.

iii) The helium-4 atom, consisting of 2 protons, 2 neutrons and 2 electrons; Also the tritium atom, consisting of 1 proton, 2 neutrons and 1 electron.

iv) The nucleus of deuterium, known as a deuteron, and its anti-particle.