

Summary of Elementary Particle Physics

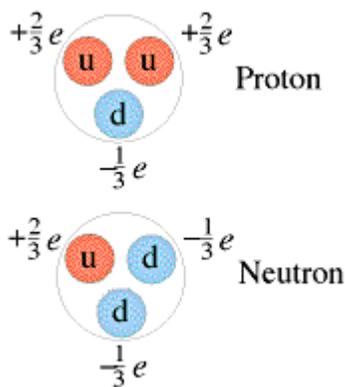
Physicists believe that the Universe contains 24 elementary particles which interact with each other via four fundamental forces. Each of the four forces is transmitted by quantum carriers which are themselves elementary particles. The characteristics of the four forces are:

<u>Force</u>	<u>Range</u>	<u>Strength</u> ¹	<u>Things Affected</u>	<u>Carrier Particle</u> ²
gravity	infinite	10^{-38}	everything, including energy	graviton ³
electromagnetic	infinite	10^{-2}	charged particles and photons	photon
strong force	$\approx 10^{-14}$ m	1	quarks and gluons	gluon ⁴
weak force	$\approx 10^{-15}$ m	10^{-8}	quarks, leptons, vector bosons	vector bosons ⁵

Footnotes

- 1) Strength relative to the strong force is given. Also, the relative strengths of the forces change as particles are brought closer together. It is thought that the strengths of the forces become equal at separations of about 10^{-43} meter. (The numbers given are for a separation of about 10^{-15} meter.)
- 2) The graviton and photon have zero rest mass (thus they move at lightspeed), whereas vector bosons have rest masses. This is why gravity and E&M have infinite ranges, but the weak force is very short-ranged. All carrier particles are virtual particles – they violate conservation of energy and simply materialize under the Heisenberg rule $\Delta E \Delta t \geq \hbar/2\pi$. Δt must be very short for a massive particle, but may be infinite for a massless particle.
- 3) The graviton is a hypothetical particle. It has never been observed, and in fact, no useful theory of quantum gravity exists.
- 4) A gluon is a very complicated thing. It has no rest mass, and so moves at the speed of light, yet the strong force is still very short-ranged. The reason is, the gluon itself carries strong charge, and thus it can interact with itself! This would be equivalent to the photon carrying electric charge instead of being neutral (except that the strong force is always attractive, never repulsive). Rather than just streaming away from a light source, electrically charged photons would tend to electrostatically pull themselves back together. So the gluon has a very limited range, despite being massless.
- 5) There are three vector bosons: the W^\pm , which can be either positively or negatively charged, and the Z^0 , which has a different mass from the W^\pm and no charge.

The 24 elementary particles can be organized into six families of four particles each. The properties of the most important set – the one of which we are made – are on the next page. Quarks are sub-nuclear particles which form protons and neutrons, among many other things. Quarks come in six types, with the haphazardly chosen names of up, down, strange, charm, top, and bottom. However, up and down are the only types that exist in ordinary matter. Quarks always exist as triplets, or as quark / antiquark pairs. For example, a proton



consists of a (up, up, down) triplet, and a neutron is a (up, down, down) triplet. Free quarks do not exist, because the energy needed to separate a quark from a triplet is so large that it exceeds the rest mass of the quark. Thus, instead of separating the quark triplet, the input energy simply turns into additional quarks. Trying to get a free quark by disrupting a proton is about like trying to get a magnetic monopole by cutting a bar magnet in two. There is no doubt that quarks and north magnetic poles exist, but they find comfort in company and do not exist as separate entities.

Up and down quarks, plus the electron, constitute all ordinary matter. The fourth elementary particle in our set is an elusive thing called the neutrino. Neutrinos have no electric charge (hence their name) and like the electron they do not feel the strong force.

This means that they only interact with other particles via gravity or the weak force, which means they scarcely interact with anything at all. In addition, neutrinos have rest masses so slight (about 10^{-36} kg) that even a 9-volt battery has enough energy to accelerate them to 99.7% of lightspeed. It is small wonder that neutrinos can pass through an object the size of the Earth as though it isn't there. Billions pass through your body every second (generated by nuclear reactions in the Sun), and it is doubtful that more than a few hundred will interact with you in your lifetime.

Properties of the First Family of Elementary Particles

	<u>electron</u>	<u>neutrino</u>	<u>down quark</u>	<u>up quark</u>
charge	-1	0	$-\frac{1}{3}$	$+\frac{2}{3}$
baryon number	0	0	$\frac{1}{3}$	$\frac{1}{3}$
lepton number	1	1	0	0
rest mass	511 keV	≈ 1 eV	heavy	heavy

The rest mass of an individual quark is not a well-defined thing, given that individual quarks don't exist. The proton and neutron have masses ≈ 1836 times that of the electron – but this doesn't mean that up and down quarks have masses of roughly one-third the proton. The strong force is so powerful inside a triplet that the energy which binds them together (think of it as “strong-force potential energy”, analogous to gravitational potential energy) is by far the largest contributor to the mass of the proton! That is, the quarks' potential energy far exceeds the energy $E = mc^2$ that their masses represent, so the mass of a proton consists of maybe 5% – 20% quark mass (it's hard to tell), and the rest is a terrific amount of nuclear binding energy.

Baryon number and lepton number are more-or-less the strong and weak force equivalents of electric charge. They are always conserved in any reaction. Particles which feel the strong force are called baryons (in other words, baryons are always some combination of quarks), and particles which do not feel the strong force are called leptons. Massless things such as the photon have zero baryon and lepton number.

There are two more families of particles beyond the one we are made of. As far as we know, they are identical to the first family except that their members are more massive. (Family 3 is more massive than Family 2, and Family 2 is more massive than Family 1.) For example, the strange quark in the 2nd family is exactly identical to a down quark in the 1st family – except that it always forms a much more massive quark triplet than the down. The table below shows how the twelve fundamental particles in the three families correspond to each other.

	Leptons		Quarks	
1 st family	electron	neutrino	down quark	up quark
2 nd family	muon	μ neutrino	strange quark	charmed quark
3 rd family	τ lepton	τ neutrino	bottom quark	top quark

Each of these twelve particles has a corresponding antiparticle. An antiparticle is exactly like a particle, except that its charge, baryon number, and lepton number have the opposite sign. If a particle and its antiparticle are brought together, they annihilate each other in a flash of energy and become photons. However, gravity works exactly the same on both matter and antimatter.

(4 members per family) X (3 families) X (2 for antiparticles) = 24, the number of elementary particles in the Universe. However, of these, only the neutrinos, the electron, and the up and down quarks (plus the antiparticles for all six) are stable. This is a subtle statement, so let me explain.

In the world of elementary particle physics, it's important to understand that the four fundamental "forces" do much more than "push or pull", which is what we normally think of forces doing. Instead, we must think of the forces more as "interactions". Among other things, both the strong and weak forces can cause quarks to change identity. Thus a quark triplet of (*bottom*, top, top) can simply become a triplet of (*down*, top, top), because the strong force interacting between the quarks can change their identity. It is not correct to think of the bottom quark as "made of" a down quark, because the bottom quark could just as easily have changed into a strange or charmed quark. This is basic quantum mechanics. There is a certain probability that quarks can be transformed into other quarks (consistent with the conservation laws), and so eventually they always do. In quantum mechanics, if it is not forbidden, then it is mandatory.

This is why only particles in the first family are stable. If I take a massive particle in an upper family, there is always the possibility that it will transform into a lower-mass particle in the 1st family and thereby release most of its mass-energy. A typical reaction might be something like this:

muon → electron (to preserve charge) + 2 neutrinos (don't ask) + excess energy.

And what about the reverse reaction? Can an electron turn into a muon? Yes – **if** it is carrying a tremendous amount of kinetic energy, and slams into another particle such that some of that energy can be converted into a muon. Otherwise, no. Conservation of mass-energy allows quantum mechanics to spontaneously transform heavier particles into lighter ones, but not the other way around. Thus, the particles in the first family are stable only because they are the lightest ones, and have nothing else they can change into. The proton is the lightest possible combination of all quarks, and that is why it is the only combination of quarks with an infinite lifetime. The neutron is a distant second at 10.6 minutes, and after that the lifetimes of quark combinations (that is, baryons) plummet to 10^{-9} down to 10^{-24} sec.