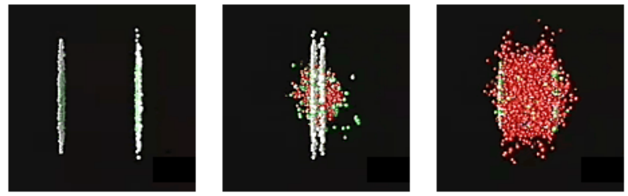
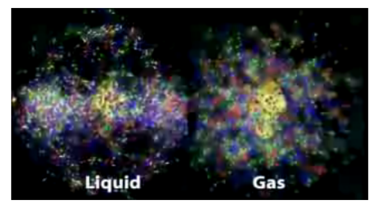
Structure of matter, 5

The quark-gluon plasma



At the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory on Long Island in New York (the only major research accelerator functioning in the US) and the Large Hadron Collider (LHC) at CERN in Switzerland, heavy atoms, stripped of most or all of their electrons, are collided with energies approaching 100-1000 GeV per nucleon. Traveling at nearly the speed of light, these heavy ions are Lorentz contracted into pancake shapes in the laboratory frame of reference and, consequently, have very large quark and gluon densities within the constituent protons and neutrons. The energy density in the collision is sufficiently high that for a brief period the nucleons "explode" into a fireball of quarks and gluons—a kind of "quark-gluon plasma" (QGP).



Recent experiments colliding Au^{+79} (RHIC) and Pb^{+82} (LHC) ions have produced a number of interesting and unexpected results. Analysis of the energy spectrum of photons emitted in the collision indicates that the effective temperature of the QGP must be the order of 10^{12} K. Comparison of this value with the putative radiation temperature in the early universe suggests that the QGP at RHIC corresponds to the state of color-charged matter at about 10^{-6} s after the Big Bang, that is, at a time before nucleons could have (stably) formed. Analyses of the angular distribution of the emitted photons at RHIC and LHC indicate that the shape of the QGP is an elongated blob rather than a spherical ball. The inference is that the QGP is much more like a liquid than a gas. In other words, the components of the QGP continue to strongly interact producing a collective state of matter rather than one consisting of autonomous particles. Moreover, the shape of the elongated blob appears to imply that the QGP liquid might have very little viscosity: it might be a "perfect liquid!"

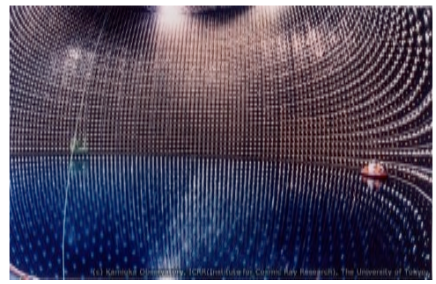
The gluons in the short-lived QGP are able create additional quark-antiquark pairs. As the QGP cools, quarks coalesce into mesons and baryons and even nuclei. Analysis of the particle tracks of the decay products at RHIC indicates that weird nuclei, such as anti-helium-3—an antineutron and two antiprotons—can form from the cooling QGP rubble. Indeed, there is even evidence for "hypertriton" and "antihypertriton." A hypertriton is akin to the nucleus of the tritium, ^3H, but instead of one proton and two neutrons, hypertriton consists of a proton, a neutron, and a neutral Λ baryon—a bound state of *u*, *d*, and *s* quarks.

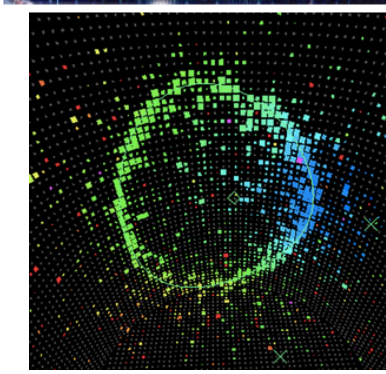
Ongoing research at these accelerator labs will surely reveal even more bizarre aspects of the state of matter in the early universe.

The weak interaction: neutrinos

The prototype "weak" process is *beta decay*: $n \rightarrow p^+ + e^- + \bar{\nu}_e$. The average half-life for this decay is about 10 minutes. Longish decay times are a signature of the weak interaction. Typical decay times for processes originating from the strong interaction are 10^{-24} s or so, and 10^{-16} s for electromagnetic decays. Weak decay times are order of 10^{-6} s or longer. Beta decay is integral to fusion processes in stars, so without it we wouldn't exist. The (anti-)neutrino on the right hand side of the reaction is devilishly hard to detect because it is electrically neutral and hardly interacts with anything else—that's where the term "weak" comes from. It is estimated that there is only a 10% chance that even one neutrino from the Sun (where lots of beta decay happens continuously) will interact with any particle in your body in your lifetime **despite the fact that something like** 10^{15} **pass through you every second**! One method for *detecting neutrinos* employs a slight variation of beta decay, in this case, the reaction $\nu_e + n \rightarrow p^+ + e^-$ (moving the anti-neutrino to the left side "converts" it into a real neutrino). Thus, in a heavy nucleus if a neutron absorbs an electron neutrino it can be converted to a proton and an electron, producing a nucleus of one higher *Z*. Practical examples include:

$$\nu_e + {}^{37}_{17}Cl \rightarrow {}^{37}_{18}Ar + e^-, \quad \nu_e + {}^{98}_{42}Mo \rightarrow {}^{98}_{43}Tc + e^-, \quad \nu_e + {}^{71}_{31}Ga \rightarrow {}^{71}_{32}Tc + e^-$$

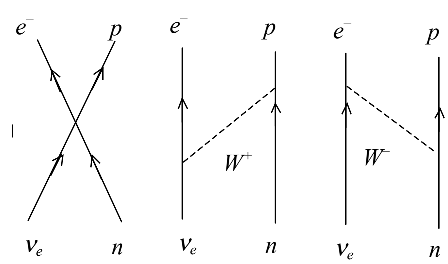




In a different method, neutrinos passing through matter interact (rarely) with electrons whose subsequent high-speed recoils produce tiny blips of light (Cherenkov radiation) that can be detected if the target is otherwise exceedingly dark. The latter is accomplished at the Super-Kamiokande (Japan) and Sudbury (Canada) neutrino observatories, both deep underground for shielding from cosmic rays. These observatories use tanks containing thousands of tons of water and thousands of sensitive photo-detectors. The figures to the right are from Kamiokande. The top figure gives a sense of the scale of the observatory. Notice the two workers aboard a raft performing maintenance on photo-detectors! During maintenance most of the water is let out of the detection chamber. the bottom figure is a reconstruction of a cone of Cherenkov light falling on a ring of photodetectors on a wall of the observatory produced by a single (rare) neutrino-electron interaction.

The even-larger IceCube observatory at the South Pole is a cubic kilometer of ice instrumented with over 5000 photodetectors capable of detecting extremely high-energy (over 10^{15} eV) neutrinos (produced by cosmic rays, not Sun). In any case, despite the rarity of the interaction of neutrinos with matter, their existence and many of their properties are now well established.

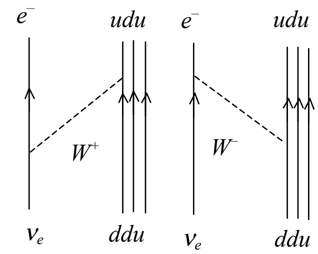
The weak interaction: W bosons and flavor switching



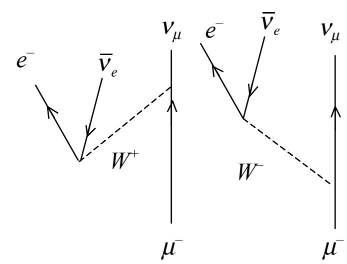
A Feynman diagram of the process $\nu_e + n \rightarrow p^+ + e^-$ might look like the first figure to the right. Such a diagram is different from the QED diagrams in that the vertices in those only had three prongs each—reflecting the idea of "minimal coupling." A weak interaction theory based on such diagrams is not renormalizable, rendering its validity uncertain. It is natural to wonder whether weak interactions might be mediated by spin-1 exchange particles similar to the photon (for electromagnetic interactions) and gluon (for color interactions). Two scenarios for this are depicted in the second and third figures to the right. Clearly, to conserve electric charge in the process $\nu_e + n \rightarrow p^+ + e^-$, the putative *W* particles—

unlike the photon and gluons—will have to be electrically charged.

If we magnify the *n* and *p* world lines in the middle and right-most diagrams above to show the respective constituent quarks, we find that *W* exchange switches quark flavor: $d + W^+ \to u$, $d \to u + W^-$. This is something new. Neither photons nor gluons can perform such a trick. Because the right-hand side of the figures involve change of flavor between two quarks it is interesting to speculate that the left-hand side similarly involves such an *electronic* flavor change (electron neutrino to electron).



Another well-known weak process is the decay of the muon: $\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$. (Muons are produced when cosmic ray particles collide with atmospheric molecules, for example.) This is a weak process because the muon lifetime is on the order of 10^{-6} s, much longer than lifetimes for other processes. The electron produced in muon decay almost never emerges with a kinetic energy equal to the rest energy difference of the muon and electron. This situation is similar to the decay of the neutron, whose "non-conservation of energy" problem was solved by introducing the neutrino. The neutrino has spin-1/2, as do the muon and electron. Thus, in order to conserve both energy and angular momentum it must be that muon decay produces an electron plus *two* neutrinos. In fact, it is now clear from various experiments that the two neutrinos are actually different. The one that is produced in beta decay (the decay of the neutron) interacts differently with matter from the second one produced in muon decay. For that reason, the first is called "electron neutrino" (ν_e) and the second "mu neutrino" (ν_μ). Decay of the muon mediated by *W* emission or absorption is depicted to the right. In it, it appears that there is a *muonic flavor change* (muon to muon neutrino).



During the period 1974-77, Marty Perl using the Stanford Linear Accelerator identified a new particle, the *tau* lepton (τ) and a companion neutrino (ν_τ). Taus decay into muons and/or electrons, plus the requisite number and types of neutrinos. For this reason, all of these particles are clumped together as kindred particles. As they never participate in strong interactions, they are assumed to *not* carry color or be made of quarks and antiquarks. Like quarks, these particles are thought to be elementary. Together, they are generically called "leptons." A "periodic table" of the six leptons is found in SM1.