SCIENCE CHINA
Physics, Mechanics & Astronomy

• News & Views •

November 2020 Vol. 63 No. 11: 119531
https://doi.org/10.1007/s11433-020-1551-0

Three flavors in a triangle

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Received March 13, 2020; accepted March 25, 2020; published online May 15, 2020

Citation: R. X. Xu, Three flavors in a triangle, Sci. China-Phys. Mech. Astron. **63**, 119531 (2020), https://doi.org/10.1007/s11433-020-1551-0

The coupling between elementary units, either weak or strong, determines the nature of matter controlled by different forces. As for three fundamental interactions (gravitational, electromagnetic, and strong), all the gauge bosons to mediate the forces are massless, and we may simply approximate the interaction energy at short distances with a Coulomb-like form of $V = -\alpha_i/r$, with r the separation between units, and α_i the coupling strength ($i = \{\mathrm{g, e, s}\}$ for gravitational, electromagnetic and strong interactions, respectively).

For the gravity, the mass of a building unit, m, should be large, otherwise the interaction would be negligible. The angular momentum of a unit inside a gravity-controlled system (e.g., the solar system) is then always much larger than the Planck constant, $\hbar$, and it is thus safe to neglect quantum effects in celestial mechanics (including galactic dynamics). Meanwhile, these massive units move non-relativistically, except for compact star binary merger.

For the electromagnetism, however, quantum effects can not be negligible anymore, because the angular momentum could be so small that it is comparable to Planck-$\hbar$, in view of a higher α_e and thus of a smaller length ℓ_sys. The kinematic energy of a non-relativistic unit is $E_\mathrm{k} \simeq \hbar^2/(m\ell_\mathrm{sys}^2)$, which is approximately the binding-energy, $\alpha_i/\ell_\mathrm{sys}$, one has then [1] $\ell_\mathrm{sys} \simeq \hbar^2/(\alpha_i m) \propto \alpha_i^{-1}$. This tells us that gravity-controlled objects (e.g., galaxies) should be much larger than the typical electric (condensed) matter.

For the strong interaction, in addition to quantum effects, particle-antiparticle pairs would also play an essential role for hadrons, in view of a much higher α_s and a small ℓ_sys. Quarks would be extremely relativistic so that gluons, coupled with quarks, can split into a number of quark-antiquark pairs, named sea quarks. In fact, a baryon contains 3 valence quarks, sea quarks as well as gluons. It is worth noting that the strange flavor of sea quarks ($s\bar{s}$) plays also a fundamental role in the structure of the nucleon though the proton and neutron are certainly non-strange [2]. This is simply due to the fact that the energy scale of strong matter at pressure free is of the order of $E_\mathrm{scale} \sim 0.5$ GeV $> m_\mathrm{s} > m_\mathrm{u,d}$, where m_s is the current mass of a strange quark and $m_\mathrm{u,d}$ of up or down quarks [1]. A perturbative calculation of quantum chromodynamics (QCD) may predict a nucleon sea with light-flavor symmetry, but the observed flavor asymmetry in the light-quark sea would be the result of the non-perturbative nature.

We would emphasize that, because of the asymmetry of e^- and e^+, virtual strange quarks in the nucleon sea could materialize as valence ones when normal baryonic matter in the core of an evolved massive star is squeezed so great that nuclei come in close contact. For lepton-related weak interactions of $u + e^- \to s + \nu_e$ and $\bar{u} + e^+ \to \bar{s} + \bar{\nu}_e$, the former should be more effective than the latter, producing eventually valence strange quarks as many as the up and down quarks. An alternative way is for two flavors only ($u + e^- \to d + \nu_e$ and $\bar{u} + e^+ \to \bar{d} + \bar{\nu}_e$), resulting in an extremely asymmetric state of isospin. In the light that nature might love symmetry, we would focus on three flavors (u, d, s) in this essay, taking advantage of a triangle diagram as explained below.

The triangle. Due to baryon conservation, it is convenient to discuss the quark numbers of the three flavors in a regular triangle (Figure 1), for a given baryon density, $n_\mathrm{b} = (n_\mathrm{u} + n_\mathrm{d} +$

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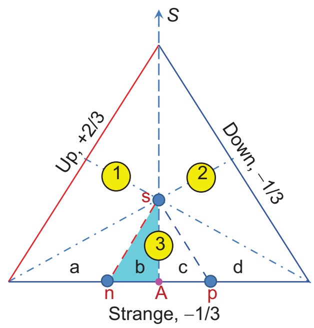

Figure 1 (Color online) Triangle of light-quark flavors. The point inside the triangle defines a state with certain quark numbers of three flavors ($\{n_u, n_d, n_s\}$ for up, down and strange quarks), which are measured by the heights of the point to one of the triangle edges. Point "s" is the center of the triangle, at which one has $n_u = n_d = n_s$. Line "sn" is parallel to the up edge, while line "sp" to the down edge. Axis S is for strangeness, where the isospin symmetry is also perfect. The triangle is divided into three regions (①, ②, ③), and furthermore the region ③ into a, b, c and d.

$n_s)/3$. It is evident that the bottom strange edge is divided into three equal parts by points "n" and "p" because the triangle "△snp" is left-right symmetrical to the "S"-axis but shrinks by two-thirds. The up-quark accounts for one-third at the states in the line of "sn" ($2n_u = n_d + n_s$), so that no electrons are necessary to keep neutrality. The triangle is divided into three regions: ① ($n_u < n_d$ and $n_u < n_s$), ② ($n_d < n_u$ and $n_d < n_s$) and ③ ($n_s < n_u$ and $n_s < n_d$). Valence s-quark density, n_s, should be the smallest in the region ③. We note that point "n" for $2n_u = n_d$ but $n_s = 0$ (e.g., pure neutron matter), and that point "s" for $n_u = n_d = n_s$ (e.g., strange quark matter). If nature loves the isospin symmetry, with symmetry broken slightly, both regions of "a" and "d" could be unlikely, and a realistic state could thus be in either "b" or "c".

Where are the stable states of strong matter in the triangle? We know that a normal nucleus takes a seat around point "A", but what about compressed baryonic matter? For the infinite strong matter, a bag-linked model, or the bag crystal model (e.g., ref. [3]), would be adaptable for both cases of two and three quark-flavors, since non-local quarks in separated bags would introduce effective interactions so as to model the condensed strong-matter. In the regime of 3-flavors of quarks, we simply apply the thermodynamic potentials of the conventional bag model (e.g., ref. [4]) for both strange quark matter (quarks free, e.g., ref. [5]) and strangeon matter (quarks localized almost in bag-like strangeon, ref. [6]). The calculations show that the 3-flavor asymmetry (represented by the ratio of electron-to-baryon numbers, $\delta_e = n_e/n_b$) and the isospin asymmetry (by $\delta_{du} = (n_d - n_u)/n_b$) become slight at high strong coupling. The ratio δ_e is from 10^{-7} to 10^{-5}, and δ_{du} is at a level of 1%-9% for $n_b = 0.3/\mathrm{fm}^3$. Therefore, the bulk strong matter could be in region "b" of Figure 1, close to point "s".

Cosmic manifestations of bulk strong matter. Given the difficulty and uncertainty of QCD's calculations including rich non-perturbative effects, it is then indispensable to trace evidence from cosmic manifestations. Compact stars provide a testbed. It is still worth noting that heavy nuclei (e.g., iron) in an active polar cap could be disintegrated into nucleons by the bombardment of energetic $e^{\pm}$ pairs (> TeV), and this electron-disintegration reaction may not favor a bare neutron star surface even with a strong magnetic field, resulting in a proton-rich magnetosphere. We may expect Chinese FAST, the biggest single-dish radio telescope [7], to affirm or negate the existence of proton there as well as to know the global structure of pulsar magnetosphere (e.g., via single pulses [8]).

Can strong nuggets pass through the Earth? Certainly, the neutron nugget at point "n" cannot exist at pressure free, but the strangeon nugget can. A strangeon nugget would be magnetized because of ferromagnetism of electrons [9], resulting in a larger cross-section. Only a tiny fraction of electrons, of the order of $3(3\pi^2)^{-1/3}\alpha_{em} \simeq 0.7\%$, contribute to the spin-alignment so that the system becomes more stable due to a lower energy of the Coulomb interaction between electrons [9], and the magnetic moment of nuggets with baryon number N_b could be $\mu_{nugget}{\sim}7{\times}10^{-3}\mu_B\delta_e N_b$ for a single magnetic domain, where $\mu_B{=}9\times10^{-21}$ Gauss cm^3. We can then estimate the magnetic field on the surface, $B \sim 7\times10^{-3}\mu_B\delta_e n_b \sim 2\times10^{11}$ G, for $\delta_e{=}10^{-5}$ and $n_b \simeq 0.3$ fm^{-3}. This field would take dynamical action inside an atom when $B > B_0{=}\alpha_{em}^2 B_Q{=}2.4\times10^9$ G, where B_Q is the critical QED field strength, and the cross section is then of the order of $\sigma \sim 2\times10^{-25}N_b^{2/3}$ cm^2. For a strangeon nugget traveling a distance L in the medium with mass density ρ_m, its momentum would be lost notably when $\sigma\cdot L\cdot\rho_m \simeq N_b m_p$, i.e., $L \simeq 8\times10^4(N_b/10^{12})^{1/3}$ cm $\cdot$ (1 g cm$^{-3}/\rho_m$). Strangeon nuggets may slow down significantly in solid earth if $N_b < 10^{24}$, but could easily go across the atmosphere as $N_b > 10^9$ for stable nuggets. Both electromagnetic and hadronic cascades occur in an air shower for relativistic strangeon nuggets, the energy loss of which determines whether a small nugget could stop inside the Earth.

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