Article ID: 1007-4627(2024) 03-0001-11

Rutherford's Atomic Nucleus versus Landau's Gigantic Nucleus: *Does Nature favor flavor symmetry?*

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Abstract: It is hypothesized that, at low temperature, though atomic nuclei are made of nucleons (i.e., nucleon matter as nuclear droplet), strongly interacting matter with baryon number from $A \simeq 10^{3-9}$ to $\sim 10^{57}$ would be composed of strangeons if Nature favors always the flavor symmetry of quarks. According to that logic, strangeon matter with $A \sim 10^{57}$ could manifest in the form of pulsar-like compact stars, and multi-messenger observations with advanced facilities (e.g., China's FAST) could eventually provide a disproof/proof. It is worth emphasizing that this point of view, based on established "old physics", may have particular consequences for understanding our material world, for both normal luminous matter and even the dark sector.

Key words: dense matter; elementary particles; symmetry energy; neutron star; pulsar

CLC number: O571.6 **Document code:** A **DOI:** 10.11804/NuclPhysRev.37.01.01

Human civilization began when humans started using tools made of materials, that is, a condensation of basic units. Besides normal atomic matter condensed by the electromagnetic (or simply electric) force, another option is to be condensed by the fundamental strong interaction which was first noted when Ernest Rutherford, in 1911,[1] recognized that nearly all the mass of an atom is concentrated in a nucleus which was necessary to account for experiments that showed the scattering of alpha particles off gold foil. By convention, we call the former *electric* matter and the latter *strong* matter. Could atomic nuclei be the only form of strong matter? The answer is "*no*" if we consider massive star evolution, i.e., resulting in the formation of possible "gigantic nucleus" in Lev Landau's words presented in 1932.[2]

What is the essential difference between a microscopic atomic nucleus and a macroscopic gigantic one? The mass spectrum of strong matter might be continuous, as in the case of electric matter from dust to white dwarfs up to the Chandrasekhar limit,[3] if there is not any conceptual difference. However, the baryon numbers A of atomic nuclei are usually $\lesssim 10^2$, even for the speculated stable island of super heavy elements, while we expect $A \sim 10^{57}$ if neutron stars are actually gigantic nuclei. Therefore, it seems then there could be a huge mass-gap, from $A \sim 10^3$ to $\sim 10^{57}$, for strong matter.

In this paper, we argue that the mass-gap would narrower considerably if Nature favors flavor symmetry. In this sense, both electric and strong matter seem to share an approximate continuous mass spectrum, from almost zero-mass to either the Chandrasekhar or the Oppenheimer mass-limit.[1] It is worth adding that the physics of strong matter at zero pressure[2] is in the regime of nonperturbative quantum-chromodynamics (QCD), so that the basic units of an atomic or a gigantic nucleus should be quark-clusters rather than free quarks, nucleons for the former and strangeons for the latter. This will be explained in the following sections.

1 Introduction

Astrophysics is that in which gravity cannot be neglected. In Einstein's theory of general relativity, gravity re-

Received date: 29 May 2024; **Revised date:** 29 May 2024

Foundation item: National SKA Program of China (2020SKA0120100) and Strategic Priority Research Program of the Chinese Academy of Sciences (XDB0550300)

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[1] The mass spectrum of black holes, to some extent, is similar, but without a mass-limit.

[2] The approximation of pressure free is certainly good on the surface of strong matter. Nonetheless, it might still be fine even in the center of a star not approaching the mass limit because of very stiff equation of state indicated by the discovery of massive pulsars. Certainly, perturbative QCD might work in the center of a compact object near the mass limit, forming a hybrid star.[4]

sults from distorted space-time, and the formation of a singularity inside an event horizon seems inevitable.[5] Nevertheless, there are three types of realistic outward pressure that could prevent a massive object dominated by radial self-gravity from collapsing to a black hole:

a) *Thermal pressure*, originating from Maxwell-Boltzmann statistics, which works at non-zero temperature. One of the typical examples is a main sequence star with nuclear fusion as source providing the thermal pressure;

b) *Degeneracy pressure*, originating from the Fermi–Dirac statistics, which works even at zero temperature. It is well known that white dwarfs are supported by the degeneracy pressure of an electron gas;

c) *Interaction pressure* of a solid, the result of residual force (see footnote 3) from neighbouring units in condensed matter, which can even be present in the limit of zero temperature. Certainly, this pressure works also for liquids which, "in some ways, has no right to exist",[6] at finite temperature.

The difference between pressures *b* and *c* could be of arbitrary choice rather than of principle, though both kinds of pressures would be responsible for stable astronomical objects without persistent energy output, from asteroid, planets to white dwarfs. Let us, hence, go back to the glorious era when quantum mechanics was being developed and talk about "wave-particle duality", which we will use to explain further.

The concepts of *waves* and *particles* are clearly distinguishable in classical physics until de Broglie's discovery of duality, which initiated the quantum era. At an operational level, the viewpoint of different particles in classical physics works if the wavelet size ($\lambda \sim h/p$, with h the Planck constant and p the momentum) is much smaller than the separation between particles (ℓ), while it becomes a quantum gas of identical particles if $\lambda \gtrsim \ell$. In the case of high temperature and low density, we have always $\lambda \ll \ell$ and thus we face classical Maxwell-Boltzmann systems. On the other hand, quantum statistics applies for materials without stable energy production. To facilitate the analysis, we categorize these materials into 4 types, {*p*F, *p*B, *c*F, *c*B}, as listed in Table 1.

Firstly, let us turn off the interactions between units. Matter made up of Boson units, "*p*B" and "*c*B", should be in a Bose-Einstein condensate (BEC) state. However, quantum degenerate pressure would be significant for Fermion units, with white dwarfs being the archetype of "*p*F" and normal neutron stars of "*c*F". Although the electromagnetic force could be negligible due to a relatively weak coupling quantified by $\alpha_{\rm em} \equiv e^2/(\hbar c) \simeq 1/137$ (with e the electron charge), the fundamental color interaction should play an important role especially at low-energy scale where the coupling is closer to $\alpha_{\rm c} \sim 1$. This is why we can model white dwarfs ("*p*F") to a high precision, while we are in an awkward situation when one tries great efforts to understand neutron stars ("*c*F").

	Fermion	Boson
point-unit	*p*F	*p*B
composite-unit	*c*F	*c*B

Table 1 The quantum statistics of cold matter without stable energy production. The building blocks could be either point-like (*p*) or composite (*c*).

Secondly, let us then turn on the interactions. In cases of "*p*F" and "*p*B", the interactions are fundamental, which is well defined in the standard model of particle physics, so a description of a particle system in full quantum field theory should be valid. On the other hand, for "*c*F" and "*c*B", the interactions could be regarded as the residual of fundamental ones,[3] which have to be quantified in phenomenological models. It is not an easy task to model the residual interactions, even for normal atomic matter: it is well known that strongly correlated electrons should be responsible for high-temperature superconductivity, which is still one of the most challenging topics in condensed matter physics. Strictly speaking, for atomic matter, the difference between materials with free electrons (e.g., white dwarfs) and with bound electrons (e.g, rocky planets) could be quantitative rather qualitative, since electrons inside both are essentially wandering, but electrons are just traveling with a higher probability in the former than in the latter. In this sense, the difference between pressures *b* and *c* is not essential.

Interactions do matter for the states of different types of particle systems listed in Table 1. It may change '*p*F" into "*p*B" if two Fermions are pairing to behave as a boson. The Bardeen-Cooper-Schrieffer (BCS) theory devel-

[3]In fact, point-like particles (electron and quarks) cannot be confined inside a composite unit because of the duality-caused quantum tunneling between neighbor units, resulting thus in the residual forces. The Lennard-Jones-like form could be an example of characterizing such forces quantitatively, which could be effective in modeling insulators and also condensed matter made of noble-gas atoms. That form, without surprise, might also be valid to model even strong matter, i.e., the interaction between either nucleons or strangeons.

oped in 1957 is successful in explaining the behavior of low-temperature superconductivity, involving Cooper pairs formed on the Fermi surface of electrons in metal. Similarly, quarks could also pair in cold quark matter, resulting in states of color superconductivity (CSC), either 2SC (2-flavor superconductivity) or CLF (color flavor locked). Certainly, a completely different state of matter, rather than superconductivity, emerges if the interaction is high enough to group point-units into composite ones. This is the reason why CSC occurs in the regime of perturbative quantum chromodynamics (QCD), but the nonperturbative QCD force can bind quarks together into hadrons, especially nucleons in a nucleus at pressure free.

One may also change the statistics of "*c*F" and "*c*B" into the classical Maxwell-Boltzmann statistics if composite-units are trapped in the potential shaped by the residual interactions. Quantum statistics would, indeed, apply to "*c*F" and "*c*B" if the interactions between units can be negligible, and even BCS-like states appear too (e.g., the superfluid neutrons in normal neutron stars). However, for instance, the quantum zero-energy of a non-relativistic baryon-like unit trapped in δx is $\sim \hbar^2/(m\,\delta x^2)$, with m its rest mass. It is then evident that classical statistics would be suitable if the potential depth is much deeper than ~ 40 MeV $(1\ \mathrm{GeV}/m)\,(1\ \mathrm{fm}/\delta x)^2$. We will explain, in the next section, that this requirement could be satisfied for strangeon matter. In a sense, strangeon matter is more akin to usual atomic matter, with both: obeying classical Maxwell-Boltzmann statistics (except for free electrons), existing at zero pressure and having a broad mass spectrum.

2 Strong matter: microscopic and macroscopic

After the establishment of Rutherford's model to describe the structure of atoms in 1911 but before the discovery of neutron in 1932, it was commonly thought that a nucleus of mass number A and atomic number Z contains A protons and $(A-Z)$ electrons. By 1910, experiments (e.g., scattering of X-rays by atoms, photoelectric effect, etc.) showed that atoms seem to have roughly $A/2$ electrons outside, except for hydrogen nuclei ($A = Z = 1$), and therefore the electrons ($\sim A/2$) inside nuclei should be tightly combined with protons there.[4] In 1920, with a title of "The Internal Constitution of the Stars", Eddington[7] wrote in a paper: "The nucleus of the helium atom, for example, consists of four hydrogen atoms bound with two electrons. ... If 5 per cent. of a star's mass consists initially of hydrogen atoms, which are gradually being combined to form more complex elements, the total heat liberated will more than suffice for our demands, and we need look no further for the source of a star's energy".[5] As his first "postulate", Harkins stated[9] "The positive charge on the nucleus of an atom is equal in magnitude to the sum of the negative charges on all of the non-nuclear or planetary electrons".

The key to solve all of these dilemma problems is related to the novel statistics proposed independently by Pascual Jordan in 1925 and Fermi and Dirac in 1926. It is then not surprising that, before the discovery of neutron, Landau speculated[2] "all stars heavier than 1.5 $\odot$ certainly possess regions in which the laws of quantum mechanics (and therefore of quantum statistics) are violated. ... this must occur when the density of matter becomes so great that atomic nuclei come in close contact, forming one gigantic nucleus" when realizing the mass limit of white dwarfs.[10-11] The quantum theory, accurately, applies to both Rutherford's microscopic nucleus and Landau's macroscopic one, and the latter, in modern words, involves the weak interaction of converting protons to neutrons by $p+e^- \rightarrow n+\nu_e$, otherwise electrons would be too energetic to be stable (see footnote 3). For simplicity, we may call the former microscopic strong matter, while the latter macroscopic one. Landau, in a word, tried to neutralize via neutronization in order to have stable macroscopic strong matter, resulting in a concept of neutron stars even in today's mainstream society.

Now is the era of the standard model of particle physics, with 12 flavors of fundamental fermions,[6] interacting with each other by the exchange of gauge bosons. Compared with non-relativistic atoms (i.e., electrons and atomic nuclei move non-relativistically or quasi-relativistically at most), nucleons are relativistic systems due to the strong force binding; the stronger the force is, the smaller the scale, and thus more energetic the building blocks are. One could have a typical energy scale, $E_{\rm scale} \sim \hbar c/\ell \sim 0.5$ GeV, with $\ell \sim 0.5$ fm being the separation between quarks, from Heisenberg's

[4] This is, in terms of quantum physics, certainly wrong because of the unrealistically high zero-point energy (~ 200 MeV) if electrons are bound in a nucleus.

[5] Eddington summarized in his major monograph published in 1926,[8] with the same title, and dedicated a large discussion to puzzling white dwarfs. He discussed seriously and argued that a white dwarf, in an awkward predicament, must expand and do work against gravity when it regains the normal matter, concluding "The star will need energy in order to cool".

[6] Half are quarks listed in Figure 1, and the other half leptons. The strong force takes effect for quarks, but not for leptons.

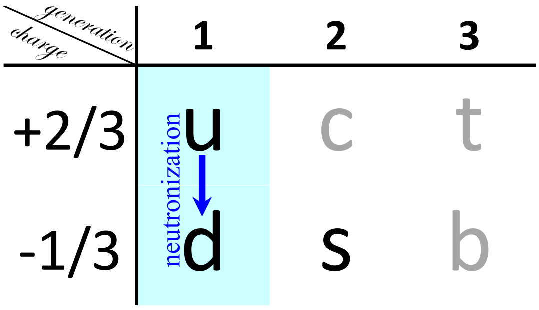

Fig. 1 (Color online) Six flavors of quarks in the standard model, which could further be divided into three generations. The bare masses of {u,d,s}-quarks are lower than 100 MeV, while that of {c,t,b}-quarks are higher than 1 GeV. We thus call the former light flavors and the latter heavy ones. Note that quarks are not charged anti-symmetrically, i.e., the electric charge of {d,s,b}-quarks is not simply the negative of {u,c,t}-quarks.

relation,[12] implying (*a*) non-perturbative coupling between quarks and (*b*) the existence of a sea of light-flavored quarks besides valence ones, in view of

$$\Delta m_{\rm uds} < E_{\rm scale} < \Lambda_\chi, \qquad (1)$$

where perturbative QCD works only if the energy scale is higher than $\Lambda_\chi > 1$ GeV, and $\Delta m_{\rm uds} \sim 0.1$ GeV is the difference among the bare masses of light quarks. Heavy quarks contribute negligibly to strong matter at zero pressure because their bare masses are much larger than $E_{\rm scale}$. Only valence quarks are usually noted in the structures of protons and neutrons, which are then {uud} and {udd}, respectively. It is, therefore, evident that Landau's neutronization is basically converting u-quarks to d-quarks by $u + e^- \to d + \nu_e$,[7] as indicated in Figure 1.

An important property, unfortunately unknown during Landau's time, lurks in the option of neutronization: the nuclear symmetry energy! Stable atomic nuclei have approximately equal numbers of protons and neutrons (i.e., the isospin symmetry), and the symmetry energy is introduced to characterize the mass-energy growth when deviating from the equality. At the quark-scale, in fact, the symmetry energy measures the deviation from the balance of u-/d-quark numbers, that is, the flavor symmetry between up and down quarks. Certainly, this symmetry has to be broken significantly due to Landau's neutronization which kills energetic electrons, and a relatively dense electron gas would then be necessary to suppress the β-decay of neutrons, educing a stellar crust to meet the requirement of such a high electron density in the standard neutron star model.

Can we find a way both to neutralize and to keep flavor symmetry? The answer is yes even in the standard model of particle physics, using "old physics"! As shown in Fig. 1 and Equ. (1), three flavors of quarks, {u,d,s}, participate in constructing the structure of strong matter at zero pressure. It is then intuitive to take advantage of a triangle diagram[13] because of the conservation of baryon number. Clearly,

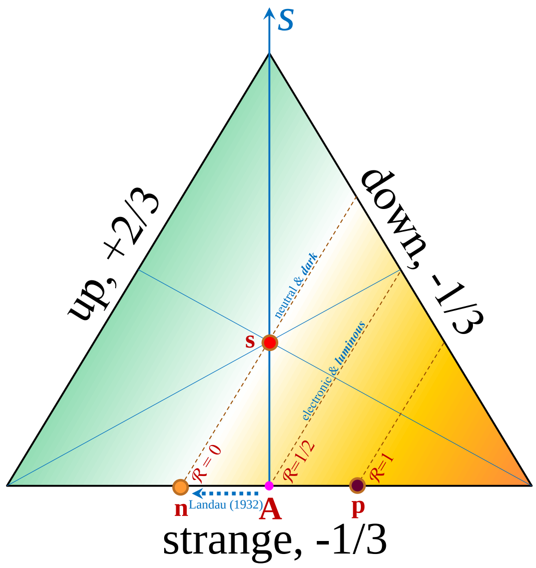

Fig. 2 (Color online) Three flavors in a triangle. A point inside the triangle defines a state with certain quark numbers of three flavors of up, down and strange quarks, which are measured by the heights of the point from their respective edges. At point "s" in the center of the triangle, we have equal numbers of the light quarks, but atomic nuclei are near at "A". Points in lines parallel to the up-side have equal charge-mass-ratio, $\mathcal{R}$, to be 1/2 at "A". In 1932, Landau superficially anticipated to go from "A" to "n" when creating a "gigantic nucleus" with huge numbers of atomic nuclei, that is, the idea of a neutron star.

as seen in Fig. 2, both neutralization and flavor symmetry are satisfied if one goes from "A" to "s" after compressing huge numbers of atomic nuclei to a "gigantic nucleus". Even at point "s", the building units could be either dissocia-

[7]If quark sea is included, this neutronization should be a consequence of the asymmetry of e and e^+. In a quantum vacuum with fermions and anti-fermoins (e.g., $\{e, e^+\}$, $\{u, \bar{u}\}$, $\{d, \bar{d}\}$, $\{s, \bar{s}\}$), lepton-related weak interactions could convert u-quarks to d-quarks ($u + e^- \to d + \nu_e$) as well as anti-ups to anti-downs ($\bar{u} + e^+ \to \bar{d} + \bar{\nu}_e$), so that the numbers of protons and neutrons inside atomic nuclei maintain approximate equality. However, in a dense electron gas, the former should be more effective than the latter, producing eventually more valence d-quarks, i.e., more neutrons. Similarly, if considering three flavors of light quarks, one has (1) in a vacuum: nucleons inside atomic nuclei keeps without strangeness, and (2) in a dense electron gas: strangeness becomes non-zero via the interaction of $u+e^- \to s+\nu_e$, to be more effective than that of $\bar{u}+e^+ \to \bar{s}+\bar{\nu}_e$.

tive quarks [14] or strangeons with (6,9,12,15,18)-number of valance quarks, [15-16] the latter being analogous to nucleons which are the constituents of atomic nuclei due to nonperturbative QCD interaction at pressure free.

Strangeon matter could be in a classical solid state [15] because of (1) a small quantum wave packet $\lambda_{\rm c} \simeq \hbar/(mc)$ since the mass of a strangeon is much higher than that of a nucleon, and (2) a significant interaction energy between strangeons ($\sim$ a few tens of MeVs) which is much higher than their temperature which is typically $\lesssim$ 1 keV. These two aspects may explain our preference of solid strangeon (rather nucleon) matter, though solid nucleon matter (i.e., solid atomic nuclei) has already been suggested in 1974, [17] motivated by the fact that the giant resonance (i.e., collective excitation of atomic nuclei) might resemble the vibration of an elastic solid. In fact, this also works for electric matter: elements including the inert ones could condense into a solid state, but helium is the only exception that cannot be solidified by sufficient cooling at almost zero pressure. Helium becomes a quantum superfluid at extremely low temperature, but nevertheless, an idea of a "supersolid" has alternatively been proposed, [18] and evidence for a supersolid candidate has recently been announced. [19] Similarly, supersolid quark matter had also been speculated, the so called phase of crystalline color superconductivity. [20-21] Finally, classical solids are common to us, the rupture of which could naturally result in starquakes, but the solid evidence for supersolids has still not been seen, let alone the fault structure necessary for a starquake.

3 Bulk strong matter in reality

As explained in §2, electrons show up for 2-flavored strong matter, but not necessarily for a 3-flavored one. For microscopic strong matter (i.e., atomic nuclei), 2-flavored matter should be the most stable because the rest mass of an electron is much lower than that of a strange quark since the less bound electrons (with negligible kinematic energy) exist outside a nucleus. However, there is a serious *competition* for macroscopic strong matter because of an electron's non-negligible kinetic energy which is subjected to Fermi–Dirac statistics: the nuclear symmetry energy in the 2-flavored case *versus* the cost of converting u/d- to s-quarks in the 3-flavored case. We conjecture that macroscopic strong matter should be made of strangeons if Nature favors the flavor symmetry, and strangeon matter could exist normally in a classical solid state.

Pulsars, an archetype of macroscopic strong matter, provide realistic testbeds for understanding the non-perturbative nature of the fundamental strong interaction. The first pulsar, CP 1919, was discovered through radio waves, [22] and the current total number of this kind of compact object is more than 3000. They are also visible in X-rays and γ-rays, and are sources of neutrinos and gravitational waves. Overall, radio astronomy provides most important information about the physics of bulk strong matter.

In addition to the puzzling state of dense matter inside a pulsar, the peculiar coherent mechanism of radio emission from the magnetosphere remains poorly understood even after more than half a century. To combat this, one needs a new approach to reveal the real nature of pulsars, one of which can be to study the surface of the pulsar. Formally, the surface separates the magnetospheric plasma from the constituent matter of the pulsar. We suggest that the strangeon idea merits careful consideration because of its good conduct in explaining the following.

(*a*) *Charged particles* with bounding energy high enough for "sparking" on the polar cap. In 1975, Ruderman & Sutherland (RS) proposed a user-friendly model, the inner vacuum gap model, [23] to understand pulsar radio emission on different timescales, from single-pulse fluctuation to sub-pulse drifting/modulation, and even to micro-structures. However, this foundational model is seriously challenged by two of its basic assumptions: (1) the binding energy of ions is usually much lower than what is required to maintain the RS-type vacuum gap, (2) it works only for antiparallel rotators but not for parallel ones (i.e., "antipulsars"). A bare strange star, [8] without these two issues, does not preclude but embraces the RS model. [24-26]

(*b*) *Polar sparking-hills* necessary for understating both integrated and individual pulses. In view of the complexity and stability of integrated pulse profiles, Vivekanand & Radhakrishnan [27] offered an explanation of mean pulse structure arising from surface relief at the polar cap. The mode-switches of PSR 0329+54 and PSR 1237+25 have also been interpreted as a change of the pulsar surface followed by an alteration of the electrostatic conditions in the polar caps,

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[8] Compact objects in point "s" of Fig. 2 are called strange stars, which could be either strange quark stars or strangeon stars. The basic units of the former are quarks, while of the latter strangeons. Strange matter could be covered by normal matter (i.e., crusted strange star), but can also not (bare strange star).

which leads to a different distribution of particles in the magnetosphere.[28] It is worth noting that a fan-shaped pattern of pulsar's radio emission could be a natural result of polar relief/hill,[29] with radiation power fading as pair-plasma, created above a hill, moves along flux tubes.

Small hills (or "zits") could be a natural consequence of strangeon stars with rigidity. Pulsar radio emission is emit-

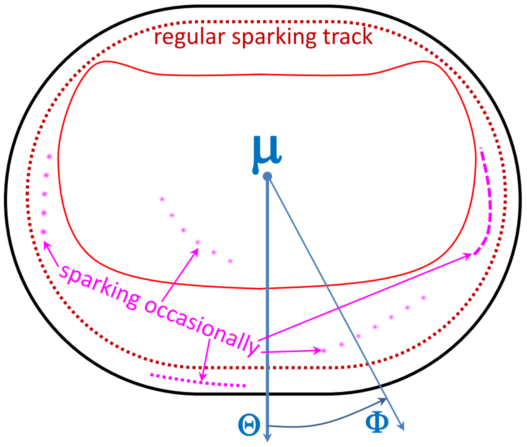

Fig. 3 (Color online) The magnetic pole of a pulsar in spherical coordinates, where μ symbolizes the magnetic pole. Regular sparking occurs along the "regular track". However, if intercepted by a small hill, occasionally, there may be preferential point discharge, observed as a different type of sparking, and this could suppress regular sparks.

ted from open magnetic field lines whose footprints concentrate in the polar cap on the pulsar surface, with a boundary given by the solid black line drawn in Fig. 3. Polar cap sparking prefers to occur at positions where the local electric field parallel to magnetic field, $E_{||}$, is higher and the curvature of the local magnetic field line is smaller. It is, therefore, expected that sparks happen in the "regular track" unless around a small hill, where there may be preferential point discharge. Once in a while rare sparks may suppress regular ones, and a pulsar could then radiate in different modes. Observational consequences of sparking around small hills inside the polar cap may include the strong and weak individual pulses of pulsar B2111+46[30] and the unusual arc-like structure of the bright pulsar PSR B0329+54,[31] or the distinct core-weak patterns.[32] Recently, with FAST (Five- hundred-meter Aperture Spherical Telescope) and Parkes-64m observations, the non-symmetrical sparking of PSR B0950+08[33-34] and the mode switches of PSR B0943+10[35] and PSR J0614+2229[36] may hint at zits existing on a pulsar's surface. The unusual pulse shape change event detected in PSR J1713+0747[37] could be the result of jumping to an occasional sparking hill but recovering gradually to the regular track. Certainly, further studies of radio single pulses are encouraged to find solid evidence for zits on the pulsar surface.

Pulsar's zits could also help in producing a large bunch of particles for coherent curvature radiation of repeating fast radio bursts (FRBs),[38-40] but this differs from conventional pulsars in two aspects. (*a*) Energy release: gradually spin-powered *v.s.* sudden quake-powered. Strain energy, rather than the magnetic energy in magnetar models, accumulates in strangeon stars, which becomes a potential candidate for building-up a quake-like situation, and this stored stress-energy could be high enough for repeating FRBs in either Newtonian gravity[41] or general relativity.[42] A starquake-induced model of repeating FRBs is proposed, based on the similarity between the FRB burst distribution and the earthquakes (i.e., the Gutenberg–Richter law and the Omori law),[43] suggesting that repeating FRBs trigger aftershocks resembling earthquakes but not solar flares.[44] Certainly, a large timing irregularity happens after an enhanced spin-down caused by high radiation power during a quake-induced activity. (*b*) Emission region: open *v.s.* closed magnetic field lines. The central engines of repeating FRBs could be slow rotators with a small open-field-line region, but a huge amount of dense plasma ejected from a hill could flow out even in closed field lines where multipole B-fields would be significant. This can cause low-altitude radiation with a high degree of coherence and thus much higher luminosities, as well as a large window of emission. These two aspects could be the reason why it could be extremely difficult to measure the spin periods.

We speculate that repeating FRBs are from monopole-negatively charged pulsars with $\Omega \cdot \mathbf{B} < 0$. It is proposed that, for closing its global current flow, an anti-parallel pulsar could be negatively charged if the potential of the critical field lines is the same as that of the surrounding interstellar medium.[45] An electron "volcano" may erupt after a quake when enough negative charge accumulates through a zone constrained by the last-open and critical field lines in a relatively clean magnetosphere, followed by the radiation of extremely strong coherent radio emission.

(*c*) *Strangeon magnetars* created during core-collapses or binary-mergers. It is natural to speculate that effective dynamo action works during the formation of compact star, via either core-collapse supernova or binary star merging, in both models of conventional neutron star[47] and strange star[48] because of large-scale convection and differential rotation. Both strange quark star and strangeon star are located in the center of the triangle, point "s" in Fig. 2, and we may expect similar dynamo action takes place in newborn strangeon star. However, besides the initial short period $P_0 \lesssim 3$ ms,[47] a high mass approaching to the mass-limit (even higher than $M_{\rm TOV}$) could be another key factor to determine the formation of a magnetar. It worth noting that the two essential factors may not be independent: a relic object could spin faster if it has a higher mass. The equation of state of strangeon matter is so stiff that its mass-limit would even be around $3M_\odot$, and it was suggested that anomalous X-ray pulsars and soft gamma-ray repeaters are very massive strangeon stars,[49-50] where starquakes could occur frequently.

Let us provide an order-of-magnitude quantification for the formation of strangeon magnetars. We approximate, as followings, newborn strangeon star with uniform density because of (1) very stiff equation of state and (2) strong centrifugal force due to rapidly rotating, $M \propto R^3$, with mass M and radius R. Assuming that the efficiency of converting gravitational energy $\sim GM^2/R$ to total magnetic energy, $\Omega_{\rm m} \sim B^2R^3$, is relevant to the dimensionless magnetic Reynolds number, $R_{\rm m}^\alpha$, with $R_{\rm m} \sim R^\alpha$ (for same typical velocity and magnetic diffusivity), where α measures the degree of the efficiency, one comes to

$$\Omega_{\rm m} \sim M^{(\alpha+5)/3}. \qquad (2)$$

The magnetic energy of $3M_\odot$-star could be 10^2 times that of $1.5M_\odot$-star if $\alpha = 15$. This may hints that dynamo action becomes extremely effective for very massive stars, which would be tested by future numerical relativity.

A rapidly rotating and massive strangeon star solidifies when it cools down to the melting temperature ~ 0.1 MeV via neutrino emission. The residual energy of either spin or gravitation could power later activities, which would be necessary to understand the central engines of gamma-ray bursts (GRBs) or repeating fast radio bursts (FRBs). Starquakes occurred in solid strangeon stars may trigger the bursts of repeating FRBs,[51] and changing the composition at the center may provokes a release of huge free energy. Note that a nucleon-strangeon membrane separates the 3-flavoured strong matter to the normal electric matter, which would be beneficial for making a clean fireball.

4 A coincidence problem and the anthropic principle

From the perspective of the standard model of particle physics, as also indicated in Equ. (1), three flavors (i.e., the light ones) of quarks would mainly participate in constructing strong matter at zero pressure, but two flavors (up and down) may behave as valence quarks of microscopic strong matter because of (i) the electromagnetic interaction being much weaker than the strong force (electrons could then be non-relativistic) and (ii) the mass difference between strange and up/down quarks (one could cut down ~ 100 MeV via converting strange to up/down quarks). Note that the charges of up/down quarks in the first generation are not exactly anti-symmetric, and therefore, microscopic strong matter has to be positively charged if it is to keep flavor symmetry. Consequently, we have a nice picture of "electrons moving around an atomic nucleus", and then, fortunately, the beautiful material world.

What happens if the charges of the first generation quarks are anti-symmetric (say, an up-quark has charge of "+1/3")? That should be a horrible and dead world if Nature favors the flavor symmetry! In the early Universe, primordial nucleosynthesis without a Coulomb barrier would be very effective in creating large volumes of strong matter. This is a case controlled almost by the pure strong interaction, with negligible contribution from the electromagnetic and weak interactions. No atoms and stars, and thus no life. In a sense, we are pretty lucky to exist in a world where quarks are not charged anti-symmetrically.

Nevertheless, we are coincidentally in a world without charge anti-symmetry, but the quantized charge of quarks can also make things interesting! It is true that a Coulomb barrier plays an important role in preventing microscopic nuclei from fusion in the early Universe, and only a few types of atomic nuclei would then be left over due to the nuclear shell effect (no stable atomic nuclei with baryon numbers of $A = 5, 8$). However, because the temperature of the QCD phase transition is higher than the rest mass of a strange quark, we may also expect three light flavor symmetry during cosmic hadronization. Macroscopic strong matter, called strangeon nuggets, could probably form, with $A > A_{\rm c}$, via primordial nucleosynthesis without a Coulomb barrier.[9] Admittedly,

[9] It is well known that nuclear fusion of atomic nuclei is not easy because of two factors: the Coulomb barrier tunneling (electromagnetic interaction) and the

this critical baryon number, A_c, should be determined by both the strong and weak interactions, $A_c \simeq (10^3 \sim 10^9)$ just a rough guess. The idea of strangeon dark matter is based on “old physics” (i.e., in the framework of the standard model of particle physics), with which the comparable proportion of dark/normal matter might be reasonable.[46,52]

5 Summary and outlook

We guess that Nature/God created the World within the standard model of particle physics. Because the electric charges in each of quark generations are not anti-symmetric, 2-flavored microscopic strong matter (i.e., atomic nuclei made of nucleons, with baryon number $A \lesssim 10^2$) could be synthesized during the early Universe when Nature favors quark-flavor symmetry. Atoms, the basic unit of normal condensed matter, are then lucky to survive, and stars and galaxies form by their self gravity as the Universe evolves. A compact object with $A \sim 10^{57}$, initially named a “gigantic nucleus”, may form as the remnant of a massive star left after the exhaustion of their nuclear energy, which could be made of strangeons if Nature also favors quark-flavor symmetry this time. It is even conjectured that strange matter with baryon number larger than a critical one, $A_c \simeq 10^{3-9}$, could be produced either during the early Universe or via astrophysical events (e.g., supernova and strangeon star merger). The application of these concepts to the material world is

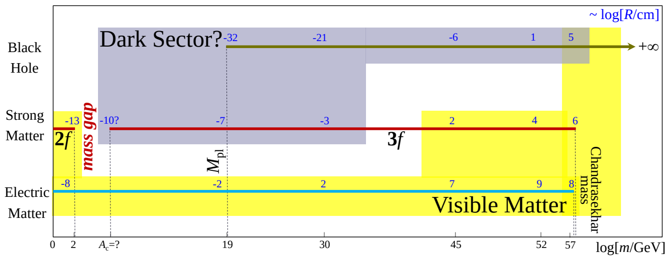

Fig. 4 (Color online) The material world deduced in the standard model of particle physics. All the mass spectra of normal baryon-matter, strangeon matter and black hole are continuous, but differ on mass distribution. Besides baryon number as the horizontal ordinate, the length scale, R, of different types of matter is also labelled (log[R/cm]). For strong matter, atomic nucleus is two-flavored ($\mathbf{2}f$), while strangeon matter is three-flavored ($\mathbf{3}f$). It is evident that $\mathbf{2}f$ Rutherford’s atomic nucleus and $\mathbf{3}f$ Landau’s gigantic nucleus are separated by a mass gap.

summarized in Fig. 4, in which strangeon nugget (e.g., with $A \sim 10^{30}$, about 10μm but one ton) works to be apparently invisible.

As shown in Fig. 2, Landau’s neutron star is actually a “neutral” star, anticipated superficially even before the discovery of the neutron. However, we wish the strangeon conjecture is too simple to be ruled out in the future, otherwise, we should feel embarrassed with a sigh, “*The more knowledge we have, the more mistakes we make*”, if pulsars are really made of neutrons because the concept of neutron stars was proposed when physicists were under the delusion that neutrons are fundamental particles. Certainly, Nature would not mind our dignity, and we have to understand the nature of pulsars by observations with better telescopes though the lake of neutron star models is really dirty.

A pulsar-like compact object forms after nuclear free energy stops providing thermal pressure against gravity in a massive star, but more free energy could still be stored inside, besides spin-kinematics, if pulsars are indeed strangeon stars. This huge free energy could be necessary for us to understand extreme events with diversity, including γ-ray bursts[41,53-54] and repeating FRBs.[38-40,55] Meanwhile, single pulse studies of radio pulsars may reveal more about the pulsar’s surface, which could be linked to the rigidity of strangeon matter (e.g., zits on pulsar surface), and China’s FAST with extremely high sensitivity could play an essential role here. A recent review on bulk strong matter has just been published.[56]

Let us go back to the magnificent era more than one hundred years ago, from Rutherford atomic model (1911) to the establishment of quantum theory: Bohr model (1913), particle nature of light (Planck in 1900, Einstein in 1905 and Compton in 1923), wave-particle duality (de Broglie in 1924), and eventually the quantum mechanics (Heisenberg in 1925 and Schrödinger in 1926). We acknowledge that, with some sorts of fundamental symmetry, the combination of quantum theory and special relativity is successful in building-up of the “standard model of particle physics”. Nonetheless, it becomes more and more attractive to explore the physics in strong gravity, that is, a couple of the standard model and the general relativity, in multi-messenger astronomy. The Einstein’s gravity, we must admit, is still non-quantized, but it could work always well in large scale if pulsars are strangeon stars,[12] with an additional assumption of nonzero/positive cosmological constant. In this sense, modifying gravity might not be worth the effort.[57] Certainly, we

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flavor changes (weak interaction), but these two difficulties would be alleviated effectively in case of strangeon nugget fusion.

are expecting more experimental tests by future advanced facilities.[10]

Acknowledgments

The author thanks those involved in the continuous discussions in the pulsar group at Peking University, and acknowledges especially Dr. Erbil Gugercinoglu and Dr. Garvin Yim for their comments and suggestions after carefully reading the manuscript, as well as Dr. Chengjun Xia for technical assistance.

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[10] We submitted this contribution to arXiv on Feb. 18 (submit/5415244), 2024, but were told that arXiv's moderators had determined that our submission will not be accepted and made public on March 19. We received a message of "Due to the high volume of submissions arXiv receives, we cannot offer more detailed feedback" on March 22, in response to our appeal (1, How does arXiv define a submission to meet standards or not? 2, Why does it take more than a month to judge? Can it be understood as arXiv peer-reviewed? by moderator(s)?) on March 19. However, we think that the strangeon idea could still be offered as an option to solve big questions.

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从 Rutherford 的原子核到 Landau 的巨核: 大自然偏好味对称吗?

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摘要: 原子核的对称能本质上体现了两味价夸克的对称性，其组成单元为核子。本文试图阐述如下概念: 若自然总喜欢味对称，重子数 A 在 $10^{3\sim9}$ 和 $\sim 10^{57}$ 之间的巨核应该由三味对称的奇子构成。根据这一逻辑，脉冲星其实是 $A \sim 10^{57}$ 的大块奇子物质；若干多信使天文观测或有望澄清该论断的合理性。值得强调是，在“旧物理”框架内提出的奇子物质看法有助于深刻地认识我们所处的物质世界，甚至包括暗物质。

关键词: 致密物质; 基本粒子; 对称能; 中子星; 脉冲星

收稿日期: 2024-05-29； **修改日期:** 2024-05-29
基金项目: 科技部 SKA 专项 (2020SKA0120100), 科学院先导项目 (XDB0550300)
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