Electron Pairs and the QCD $u\tilde{d}d\tilde{u}$ Tetrahedrons

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Abstract: We propose that the exotic meson tetraquark $u\tilde{d}d\tilde{u}$, introduced in previous papers, may be a condensed pseudo-Goldstone boson in a compact bound state having a tetrahedron geometry. The transition from two free mesons, $d\tilde{d}$ and $u\tilde{u}$, to the tetrahedron state may be seen as the Goldstone theory symmetry breaking. We note that the QFT quantum harmonic oscillator zero-level does not describe the non-empty QCD ground state and that the QCD tetrahedrons may be a better description of the QCD ground state. We assume that electrons and positrons are composite particle charged mesons, $d\tilde{u}$ for the electrons and $u\tilde{d}$ for the positrons that spin around their center of mass. We propose that the QCD tetrahedrons play a central role in the electron pairing mechanism in both molecules and superconductors. We suggest that the cosmological redshift may be alternatively, or in addition to, due to the QCD tetrahedron density variations in space and particularly due to its density reduction in the cosmic web great voids.

Keywords: QCD vacuum, Tetrahedrons, Cooper Pairs, Isotope Effect, Superconductor, Dirac Equation, Klein paradox, Cosmic Web Voids, Doppler Redshift, Black Holes, AGNs.

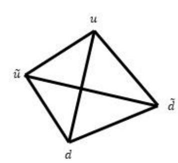
1. Electrons, Positrons and the QCD Tetrahedrons

Inspired by the Loop Quantum Gravity (LQG) tetrahedrons[1] we propose that the QCD exotic meson tetraquarks $u\tilde{d}d\tilde{u}$ introduced in previous papers[2,3,4,5] may have tetrahedron geometry as illustrated below. We note that pion π^0 comprised of $d\tilde{d}$ and $u\tilde{u}$ which are the same four quarks and antiquarks of the proposed exotic meson $u\tilde{d}d\tilde{u}$ and that a transition of the two free mesons to a tetrahedron bound state may be a Goldstone theory pseudo symmetry breaking[6] -

$$d\tilde{d} + u\tilde{u} \rightarrow u\tilde{d}d\tilde{u}\,(tetrahedron) \qquad (1)$$

The pion tetrahedrons pseudo-Goldstone bosons are assumed to have about two order of magnitudes smaller volume comparing to protons and to fill space with high density. The pion tetrahedrons may be deformed into two orthogonal planes where the polarized tetraquarks are positioned in the XY or the YZ planes.

$The\ QCD\ ground\ state\ tetrahedrons$



$$u\tilde{d} + d\tilde{u} \rightarrow u\tilde{d}d\tilde{u}\,(tetrahedron)$$

Figure 1 illustrates the proposed QCD tetrahedron pseudo-Goldstone boson and two planar orthogonal polarizations where all four quarks and antiquarks collapse to the XY or the YZ planes.

In a previous paper we suggested that the compact exotic meson tetraquarks may be peculiar positroniums (see Crater and Wong TBDE solution)[7,8]. We further propose here that the $u\tilde{d}$ meson plays the positron role and the $d\tilde{u}$ meson plays the electron role in the condensed peculiar positronium. Accordingly, we assume that electrons and positrons are composite particles that spin around their center of mass and polarize their surrounding QCD tetrahedrons. Another hint for the leptons and quarks relations is Weinberg's electroweak theory[9], where the electron mass is found to be proportional to the non-vanishing QCD vacuum quark condensate expectation value $m_e \sim \langle 0|\varphi^0|0\rangle$.

Dirac's Hamiltonian spin-orbit operator couples the momentum of the electron and the positron spinor, hence, matter and antimatter components are mixed by the Dirac Hamiltonian and cannot be separated[10]. The exchange of an electron with a virtual electron-positron pair described by a Feynman diagram[11] mix matter and antimatter components, however, it also adds an interaction with the QCD ground state, exchanging a charged meson with the QCD tetrahedron as described by the following exchange reaction -

$$d\tilde{u}_{\,(e^1)} + \left[u\tilde{d}_{(p)}\, d\tilde{u}_{\,(e^2)}\right]_{tetrahedron} \rightarrow \left[\, d\tilde{u}_{\,(e^1)} u\tilde{d}_{(p)}\right]_{tetrahedron} + \; d\tilde{u}_{\,(e^2)} \quad (2)$$

According to equation 2 electrons are not created nor destroyed from the vacuum state like assumed by QFT, electrons exchange their positron partners interacting with the QCD tetrahedrons. The quarks exchange reactions of equation 2 above, and 8-9 below for the weak and strong nuclear force transfer, may be the reactions underlying the QFT vector potential gauge transformations.

Studying the Dirac equation, Klein found that electrons can cross a potential barrier without the exponential damping expected from non-relativistic quantum tunneling[12]. Brito wrote that the creation of particle–antiparticle pairs at the potential barrier explains the undamped transmitted part solving the Klein paradox[13]. The solution of Klein paradox suggests that nucleus take part in electron pairing dynamics by exciting electron-positron pairs.

The fine and hyperfine structure of the hydrogen atom energy levels can be derived from Dirac equation[14]. The magnetic hyperfine spin-spin interaction is attractive and singular at short distances-

$$W_{hyperfine} \quad = -\frac{8\pi}{3}\ \mu_e . \mu_p\ \delta(R) \qquad (3)$$

The positron magnetic moment is about 2000 times bigger than the proton magnetic moment $\mu_p$and hence the hydrogen atom fine and hyperfine perturbative solution is not justified for the positronium system. Crater and Wong solved the Two Body Dirac Equation (TBDE) system with the constraint dynamics approximation and found a new ground state significantly more strongly binding than the more familiar positronium solution of about 6.8 eV. The condensed peculiar positronium binding energy is about 300 KeV and its bond length is three orders of magnitude shorter than the hydrogen atom bond length. The main attraction term in Crater and Wong TBDE approximate solution is the magnetic spin-spin attraction term of equation 3. The peculiar positronium existence and its expected decay via 4 photons were not experimentally verified yet and a non-radiative decay channel to the QCD ground state may exist.

In the next section we propose that the QCD tetraquarks take part in electron pairing in molecule chemical bonds.

2. Electron Pairing in Molecules and the QCD Tetrahedrons

Herzberg studied the dissociation energies of the hydrogen molecule (H_2) and its isotopes HD and deuterium (D_2) molecules[15]. The dissociation energies in the ground electronic state of the three molecule isotopes are 36,118.3 cm^{-1}, 36,406.2 cm^{-1} and 36,748.9 cm^{-1}. The heavier isotopes HD and D_2 have bigger dissociation energy than the hydrogen molecule. The nonadiabatic corrections to rovibrational levels of the hydrogen molecule was studied by Puchalski and Komasa that concluded that the non-adiabatic corrections adds to the moving ions an electron coat that changes the effective mass carried by the ions[16]. Puchalski et al studied the relativistic corrections for the ground electronic state of molecular hydrogen and concluded that the ions relativistic recoil corrections might be larger than previously anticipated[17]. The outcome of the isotope effect in molecules is different from the isotope effect in superconductors but their source is similar. In both cases the isotope effect couples the ions to the electrons motion affecting the electron pairing mechanism.

The polarized QCD tetraquarks, $u\tilde{d}d\tilde{u}$, may create an effective attractive force between electrons for example in the hydrogen molecule. The QCD tetraquarks polarization created by two electrons with opposite spins is parallel in the center between the two ions creating an effective attraction between the electron pair and the two hydrogen ions.

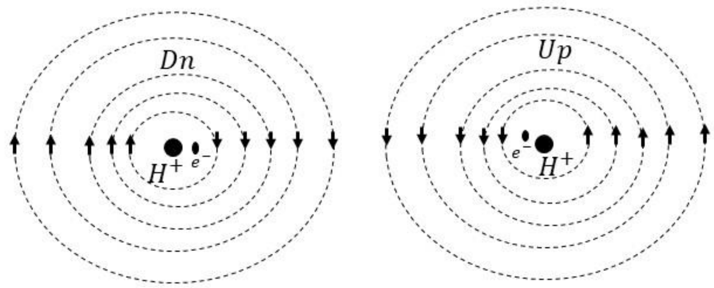


Figure 2 illustrates the QCD tetrahedrons polarization due to pair of electrons with opposite spins in a Hydrogen molecule.

A coherent double exchange reactions with two electron-positron pairs as described in equation 2 above may occur for example at the elliptic turning point as shown below. A first electron-positron pair may pop up on the right-side hydrogen ion, the positron creates a peculiar positronium tetraquark tetrahedron with the first electron in the ion center and the second electron is released at the elliptic turning point. Same sequence of events may occur coherently at the left-hand side hydrogen ion. The double exchange reactions may occur coherently and the electrons of the two ions exchange of ions form a chemical bond between the two ions.

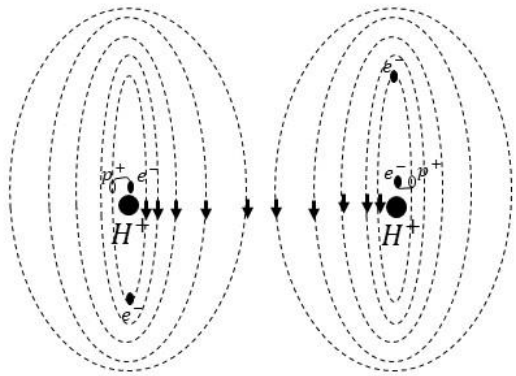


Figure 3 illustrates the QCD tetrahedron elliptic polarization creating an effective attraction between the electron pairs and a chemical bond between the two ions.

The Feynman diagram below illustrates the coherent double exchange reactions of two electrons with two electron-positron pairs excited by the two ions forming a chemical bond. The double exchange reactions lower the repulsive Coulomb interaction between the two electrons and the overall result is a force created between the two ions that forms the chemical bond.

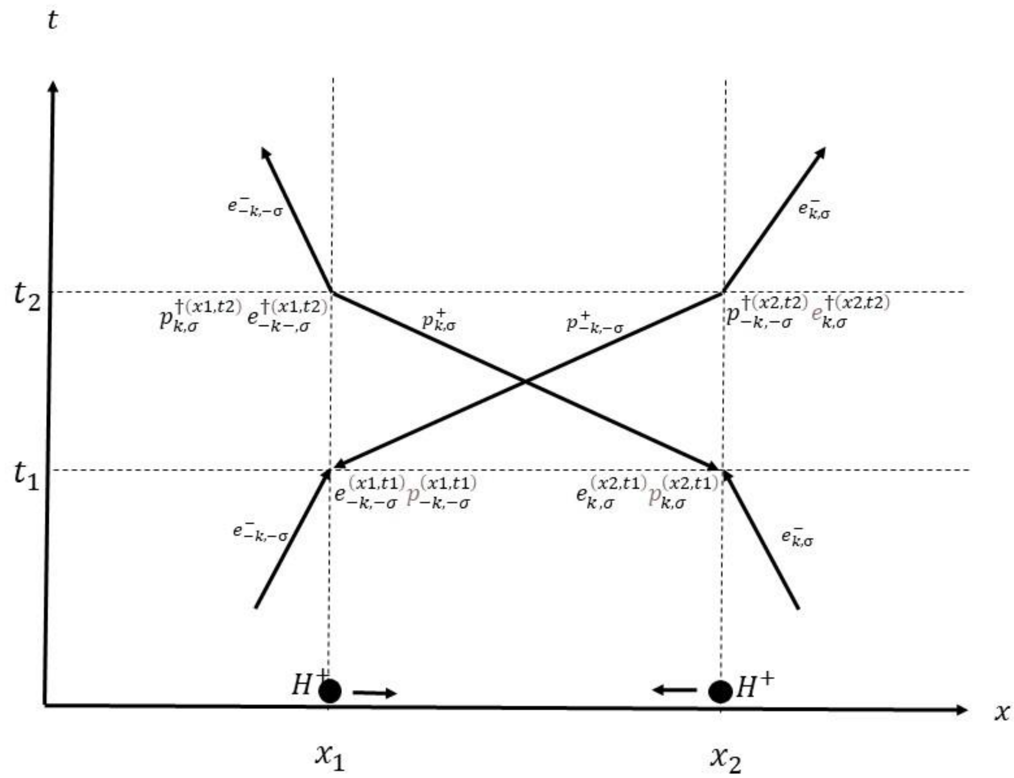


Figure 4 illustrates with a Feynman diagram the coherent double exchange reactions of two electrons with opposite spins with two electron-positron pairs tetrahedrons excited by the two hydrogen ions.

The spin polarization effect described above by the double exchange reaction of two electrons may be analogous to the Casimir force between two neutral plates in the vacuum. If a quantum system is confined between walls (here by the two ions) the ground state energy reduction will lead to a net force between the walls[18].

The isotope effect in the dissociation energy of the hydrogen, HD and deuterium molecules may be similar to the superconductor isotope effect described below[19] hinting that the electron pairing mechanism in both cases has a similar source.

In the next section we show that the QCD tetraquarks may create a cosmological redshift alternative or in addition to the Doppler redshift.

3. Redshift and the QCD Tetrahedrons

Gray and Dunning-Davies reviewed the interpretation of redshift in cosmology and astrophysics, discussed the history and origin of the traditional accepted idea of Doppler redshift and described other possible mechanisms for the redshift[20]. For example, the tired light theory was first proposed in 1929 by Fritz Zwicky, who suggested that photons lose energy over time via interaction with matter or by some other novel physical mechanism[21]. Gray and Dunning-Davies noted that the Doppler and/or space-expansion effects will yield similar photon and neutrino redshifts, whereas a non-Doppler mechanism arising from an energy-loss interaction with intervening matter will result in different redshifts for the two cases[22].

In previous paper we assumed that the QCD tetraquarks density vary in space according to the gravitational field like earth's atmospheric density[2]. The cosmic web is built from filaments of galactic walls and great voids. We suggest that the light that travels from far away galaxies and reach for example the Webb telescope pass some of these great voids where the QCD gas density is low causing the redshift. Light that comes from galaxies that are farther away cross more great voids on their path and accumulate more redshift proportional to their distance. The combination of the QCD tetraquarks density variations in space and the cosmic web great voids may be an alternative mechanism for the cosmological redshift that depends on the distance between galaxies.

4. Electron Pairing in Superconductors and the QCD Tetrahedrons

The Superconductor electron pairing mechanism forming Cooper pairs[23], especially in the high temperature superconductors (HTSC) is not fully understood. The Bardeen-Cooper-Schrieffer (BCS) theory[24] assumes that the interaction between electrons becomes attractive and dominates the repulsive Coulomb interaction in the vicinity of the Femi energy level. The ground state of a superconductor, formed by electrons virtually excited in pairs of opposite spin and momentum, is assumed to be lower in energy than the normal ground state. BCS noted that the discovery of the isotope effect[25,26] was a breakthrough that indicated that electron-phonon interactions are primarily responsible for superconductivity. According to BCS theory due to the isotope effect, $T_c \sqrt{M}$ is expected to be a constant, where T_c is the superconductor phase transition temperature and M is the lattice ions mass. The superconductor isotope effect proves that the lattice ions motion plays dynamic part in the electron pairing mechanism. Eliashberg included time-dependent phonons dynamics to the electron pairing mechanism[27].

In previous papers, we suggested that quark and antiquark pair exchange reactions between particles and the QCD tetraquarks similar to equation 2 above may accelerate or decelerate particles and that the quarks and antiquarks numbers are strictly conserved. We suggested that antimatter plays a principal role in the universe and is inseparable from both matter, via Dirac' spinors, and space, via the quarks and antiquarks pair exchange reactions with the QCD tetraquarks[2,3,4,5]. In this paper we propose that the QCD gas plays a role in the electron pairing mechanism in both molecules and superconductors. We suggest that the electron spins polarize the QCD tetrahedrons and that ions motion in both molecules and superconductors create coherent electron-positron excitations and double electron exchange reaction with the QCD tetrahedrons according to equation 2 and figure 4 above (with heavier ions of superconductors replacing the hydrogen ions) that reduce the system energy in the vicinity of the Fermi energy and create the collapse to the lower energy superconducting ground state[23,24]. The effects of the electron pairing in molecules and superconductors are different, in molecules electron pairs with opposite spins create chemical bonds and in superconductors the electron pairs enable the collapse to the lower energy superconducting state, however, the underlying electron pairing mechanism may be similar involving ions motion that creates electron-positron pair excitations from the QCD tetrahedrons in the non-empty ground state.

5. Quantum Field Theory (QFT) and the Non-Empty QCD Ground State

QFT solved the long-standing problem of Dirac negative energy states. QFT creation and destruction operators create and destroy both particles and antiparticles and both have positive energies[28]. QFT introduces extremely elegant mathematics, however, it seems not to describe well the non-empty physical ground state, the quantum vacuum, using the free fields operators of the quantum harmonic oscillator[29].

The quantum harmonic oscillator model assumes that a harmonic potential in space exists of the general form $V(q) = \frac{1}{2} m\, w^2 q^2$ and the result is the harmonic oscillator bound state spectrum $H|\, n\rangle = \left(n + \frac{1}{2}\right) \hbar\omega \mid n\rangle$. Accordingly, the zero-level empty state of the harmonic oscillator is $E_0 = \frac{1}{2}\hbar\omega$, however, free electrons and protons (comprised of quarks) are stable and do not decay to a lower zero-level empty ground state. There is no physical process that takes stable particles and destroy them to an empty lower energy ground state.

The creation and destruction operator of the quantum harmonic oscillator model raises or reduces the Hamiltonian energy as follows:

$$H\, a^{\dagger} \mid n\rangle = (E + \omega)\,|\, n\rangle \quad \text{(4a)}$$

$$H\, a \mid n\rangle = (E - \omega)\,| n\rangle \quad \text{(4b)}$$

$$H\, a \mid 0\rangle = 0 \quad \text{(5)}$$

However, equations 4a-b and particularly 5 do not describe complete physical processes. The physical processes described by Feynman diagrams destroy for example an electron and a positron in a vertex, but a high energy photon is created. Particles may be transformed to other particles in QFT but an empty physical state cannot be produced by any physical process that must conserve total momentum, energy, charge, spin, QCD color etc.

Rugh and Zinkernagel noted in their review on the quantum vacuum and the cosmological constant problem that the pion π^0 mass is proportional to its expectation value in the QCD ground state condensate, which does non-vanish[30]

$$\langle 0|\pi^0|0\rangle = \left\langle 0\middle|d\tilde{d} + u\tilde{u}\middle|0\right\rangle \qquad (6)$$

The QCD tetrahedrons compact exotic tetraquark bound state may be a better description of the underlying QCD ground state condensate. QCD bound states are reviewed by Hoyer[31] and by Fariada-Veiga and O'Carroll that reviewed meson-meson bound state using a Lattice QCD model[32]. A meson-meson bound state was found below the two-particle threshold and two sources of the meson-meson attraction were pointed out. A quark-antiquark exchange referred to as a quasi-meson exchange and a gauge field correlation of four overlapping bonds, two positively oriented and two of opposite orientation. Fariada-Veiga and O'Carroll noted that the main mechanism for the formation of the meson-meson bound state comes from the gauge contribution. QCD at finite temperature and chemical potential has a rich phase structure[33]. Dense QCD has both chiral and diquark condensates with a cross over between the broken chiral symmetry and color superconducting phase[34]. Since we assume that the QCD tetrahedrons have a small non-vanishing mass and a non-vanishing density in the QCD ground state, they may be pseudo-Goldstone bosons and the transition from two free mesons, $d\tilde{d}$ and $u\tilde{u}$, to the tetrahedron bound state may be seen as a pseudo-Goldstone symmetry breaking since the light quarks have mass[6].

Cheung et al studied tetraquark operators with lattice QCD and constructed compact tetraquark interpolating operators by combining a diquark operator with an anti-diquark operator[35]. The diquark operator is built from two quark fields coupled together to obtain appropriate color, flavor, and spin quantum numbers and, analogously, the anti-diquark operator is built from two antiquarks. The diquark and anti-diquark operators are then combined to form a color singlet with the desired flavor and spin. Bicudo recent review of tetraquarks and pentaquarks in lattice QCD with light and heavy quarks denominates three types of tetraquark systems: molecular tetraquarks, diquark tetraquarks and s-pole tetraquarks. Bicudo notes that the three mechanisms may act conjointly to produce tetraquarks[36]. Okiharu et al studied the tetraquark 4Q potential, i.e., the interaction between quarks in the 4Q system directly from QCD and investigated the hypothetical fluxtube picture and flip-flop for the multi-quark system[37]. Okiharu et al noted that the inter-quark force in the exotic multi-quark system such as tetraquark mesons (f0(980), a0(980) and X(3872)), pentaquark baryons (ϴ+(1540) and ϴc(3099)), and dibaryons is not known, however, their lattice QCD simulations showed that the compact twisted tetraquark tetrahedral structure was more stable and energetically favorable.

We propose here that the compact tetraquark tetrahedron illustrated in figure 1 may be obtained in lattice QCD by initially constructing the tetraquark interpolating operators with mixed diquark and antiquark charged meson operators, e.g. the two charged pions $u\widetilde{d}$ and $d\widetilde{u}$, that will be strongly attracted by both electromagnetic QED and nuclear QCD forces.

$$u\widetilde{d} + d\widetilde{u} \;\rightarrow\; u\tilde{d}d\widetilde{u}\,(tetrahedron) \qquad (7)$$

The QFT Lagrangian and action may be modified such that they will not describe free leptons, quarks and boson creation and annihilation operators that are assumed to be empty in their ground states like in quantum harmonic oscillator model. The QFT action and QCD ground state should describe the QCD tetrahedrons having equal number of up and down quarks and antiquarks with the tetrahedron geometry. Furthermore, the lepton field operators may be constructed from the quark and antiquark field operators.

The Yukawa meson particle that transfers the attractive nuclear force results from elementary excitation of the physical QCD vacuum[38]. The QCD tetrahedron may be the Yukawa particle transferring the short-range nuclear force. For example, the β decay may be triggered by the QCD tetrahedron. The QCD tetrahedron exchanges a neutron down quark with the tetrahedron up quark and another exotic charged tetraquark $d\tilde{u}\,d\tilde{d}$ is obtained which decays fast to an electron and an antineutrino:

$$udd\ (n) + u\tilde{d}d\tilde{u}\ (tetrahedron,*) \rightarrow udu\ (\,p^{+}) + d\tilde{u}\,d\tilde{d}(\,\pi^{-*}) \qquad (8a)$$

$$d\tilde{u}\,d\tilde{d}(\,\pi^{-*}) \ \ \rightarrow \ \ e^{-} + \tilde{\nu}_e \qquad (8b)$$

The QCD tetrahedrons enable the nuclear confinement by quark exchange reactions absorbing momentum from an excited quark of a proton when it gets separated more than about a one femtometer from the other two hadron's quarks cooling the excited quark and transferring its extra energy to the QCD tetrahedron ground state condensate. The exchange reactions with the QCD tetrahedrons may repeat until the created separation between the hadron quarks is closed.

$$ud - u\ (\,p^{+,*}) + u\tilde{d}d\tilde{u}\ (tetrahedron) \rightarrow udu\ (\,p^{+}) + u\tilde{d}d\tilde{u}\ (tetrahedron,*) \qquad (9)$$

The quarks exchange reactions may be the reaction mechanism underlying the QFT vector potential gauge transformations.

The hypothesis proposed in this and previous papers[2,3,4,5] is:

1. QCD $u\tilde{d}d\tilde{u}$ tetrahedrons are pseudo-Goldstone bosons that fill space and form the QCD and QED ground state.
2. The QCD ground state transfers forces by exchange reactions of particle with the QCD tetrahedrons. The quark exchange reactions are the underlying processes described by the gauge transformations mathematically.
3. The four stable particles are: $u\,, d,\ \tilde{d}\ and\ \tilde{u}$ quarks and antiquarks.
4. There are equal number of matter and antimatter particles in the universe, the missing antimatter particles are probably hidden under the event horizon of black holes.
5. Leptons are composite particles, $d\tilde{u}$ is the electron, $u\tilde{d}$ is the positron for example. The transition state particles are comprised of various combinations and geometries of the stable $u\,, d,\ \tilde{d},\ \tilde{u}$ quarks and antiquarks, for example: $s = d\tilde{u}\,u\ (linear), c = u\tilde{d}\,d\ (linear),\ b = d\tilde{u}\,d\tilde{d}\,u\ (tetrahedral),\ t = u\tilde{u}\,d\tilde{d}\,u\ \ (tetrahedral)$.
6. The QCD tetrahedrons density in space vary according to the gravitational field and it curves space having nonzero mass. The gravitational force occurs due to the QCD tetrahedrons density gradients via the exchange of particle and antiparticle pairs.
7. The electron pairing mechanism in atoms and molecules forming chemical bonds and in superconductors forming Cooper pairs and the collapse to the superconducting state is enabled by the QCD tetrahedrons by coherent exchange reactions of electron pairs with the polarized QCD tetrahedrons.
8. Active AGNs act as matter reactors[3] that increase the density of the QCD tetrahedrons in space by duplicating the $u\tilde{d}d\tilde{u}$ pseudo-Goldstone bosons in their ergoregion laser cavities[39].

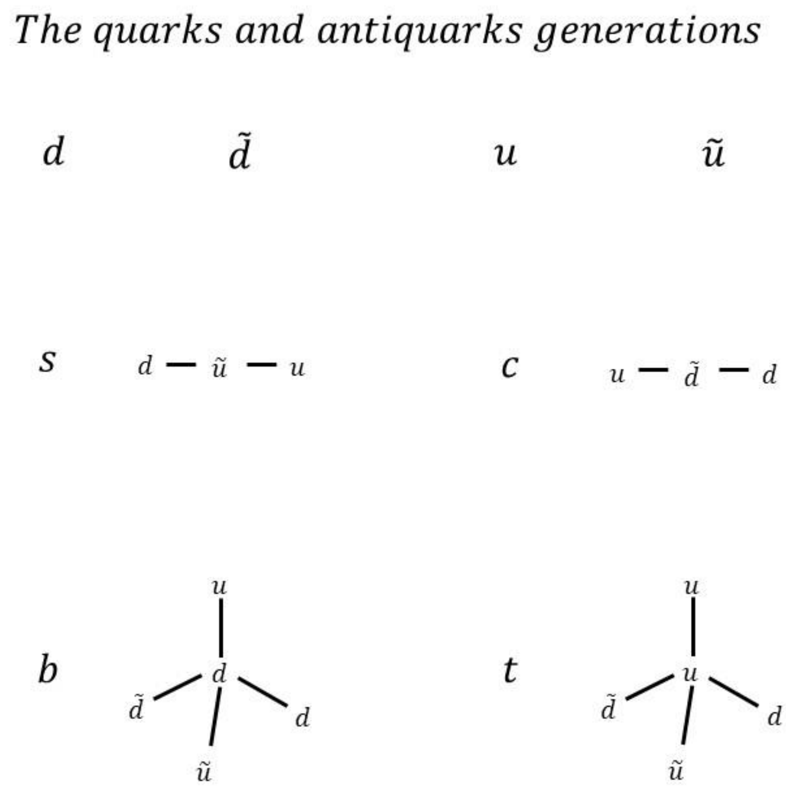


Figure 5 illustrates the proposed quarks and antiquarks generations where the heavy quarks are exotic multi-quarks with linear and tetrahedral geometries.

The lepton generations exotic multiquarks

$$e^- = \mathrm{d}\,\tilde{u} \qquad e^+ = \mathrm{u}\,\tilde{d}$$

$$\mu^- = \mathrm{d}\,\tilde{c} = \mathrm{d}\tilde{u}\tilde{d}\mathrm{d} \qquad \mu^+ = \mathrm{u}\,\tilde{s} = u\tilde{d}\tilde{u}u$$

$$\tau^- = \mathrm{d}\,\tilde{t} = \mathrm{d}\tilde{u}u\tilde{d}d\tilde{u} \qquad \tau^+ = \mathrm{u}\,\tilde{b} = u\tilde{d}u\tilde{d}d\tilde{u}$$

Figure 6 illustrates the proposed lepton generations as exotic multiquarks comprised of the stable up, down, antiup and antidown quarks and antiquarks.

References

[1] Rovelli, C. and Vidotto, F. (2013) Covariant Loop Quantum Gravity. Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9781107706910 https://www.cpt.univ-mrs.fr/~rovelli/IntroductionLQG.pdf

[2] Rom, R., (Apr 2023), “The Quantum Chromodynamics Gas Density Drop and the General Theory of Relativity Ether”, Journal of High Energy Physics , Gravitation and Cosmology, 9, No. 2.

[3] Rom, R., (Apr 2023), “Matter Reactors”, Journal of High Energy Physics, Gravitation and Cosmology, 9, No. 2.

[4] Rom, R., (Apr 2023), "The Principal Role of Antimatter", Journal of High Energy Physics, Gravitation and Cosmology, 9, No. 2.

[5] Rom, R., (Apr 2023), "The Black Hole Spray and the Cosmic Web", Journal of High Energy Physics, Gravitation and Cosmology, 9, No. 2.

{6] Burgess, C.P, (Aug 1999),"Goldstone and Pseudo-Goldstone Bosons in Nuclear, Particle and Condensed-Matter Physics", https://arxiv.org/abs/hep-th/9808176

[7] Crater, H. and Wong, C.Y., "On the Question of the Point-Particle Nature of the Electron", https://arxiv.org/abs/1406.7268

[8] Crater, H., Schiermeyer, J., Whitney, J., Wong, C. H., "Applications of Two Body Dirac Equations to Hadron and Positronium Spectroscopy", https://arxiv.org/pdf/1403.6466.pdf

[9] Weinberger, S., (Nov, 1965) , "A MODEL OF LEPTONS" , https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.19.1264

[10] Dirac, P.A.M. (1928), "The Quantum Theory of the Electron". JSTOR. https://www.rpi.edu/dept/phys/Courses/PHYS6520/DiracElectron.pdf

[11] Feynman, R., (1999) QED. In: Pines, D., Ed., Advanced Book Classics, Westview Press, Boulder, Colorado, p. 69.

[12] Klein, O. (1929) "Die Reflexion von Elektronen an einem Potentialsprung nach der relativistischen Dynamik von Dirac". Zeitschrift fur Physik , 53, 157-165. https://doi.org/10.1007/BF01339716

[13] Brito, R., Cardoso, V. and Pani, P. (2020), "Superradiance". Springer, Cham. https://doi.org/10.1007/978-3-030-46622-0

[14] Cohen-Tannoudji, C, Diu, B., Laloe, F., (1977), "Quantum Mechanics, Volume II, Chapter XII, An application of perturbation theory, the fine and hyperfine structure of hydrogen atom", pages 1209-1245.

[15] Herzberg, G., (1970), "The dissociation energy of the hydrogen molecule", https://www.sciencedirect.com/science/article/abs/pii/0022285270900603

[16] Pachucki, K., and Komasa, J., (Apr 2009), “Nonadiabatic corrections to rovibrational levels of H2”, https://pubmed.ncbi.nlm.nih.gov/19405567/

[17] Puchalski, M., Jacek Komasa, J., Pachucki, K., (Apr 2017), “Relativistic corrections for the ground electronic state of molecular hydrogen”, https://arxiv.org/abs/1704.07153

[18] Ju´arez-Aubry, B.A., Weder, R., (Dec 2021), “A short review of the Casimir effect with emphasis on dynamical boundary conditions”, https://arxiv.org/abs/2112.06824

[19] Bill, A. Kresin, V.Z. and Wolf, S.A.,(Jan 1998), “THE ISOTOPE EFFECT IN SUPERCONDUCTORS”, https://arxiv.org/abs/cond-mat/9801222.

[20] Gray, R., and Dunning-Davies, J, ( ), “A review of redshift and its interpretation in cosmology and astrophysics”, **https://arxiv.org/vc/arxiv/papers/0806/0806.4085v1.pdf**

[21] Zwicky, F., (1929), “On the RedShift of Spectral lines through Interstellar Space”, PNAS15:773-779.

[22] Gallo, C.F. “Redshifts of cosmological neutrinos as definitive experimental test of Doppler versus non Doppler redshifts”, 2003, IEEE Trans on Plasma Science, 31, 1230.

[23] Cooper, L., (November 1956). "Bound Electron Pairs in a Degenerate Fermi Gas". Physical Review. 104 (4): 1189–1190.

[24] Bardeen, J., Cooper, L. N., Schrieffer, J. R., (April 1957). "Microscopic Theory of Superconductivity". Physical Review. 106 (1): 162-164.

[25] Maxwell, E., Phys. Rev. 78, 477 (1950); Reynolds, Serin, Wright, and Nesbitt, Phys. Rev. 78, 487 (1950).

[26] Frohlich, H., Phys. Rev. 79, 845 (1950).

[27] Marsiglio, F. , (Nov 2019), “Eliashberg Theory: a short review”, https://arxiv.org/abs/1911.05065

[28] Klauber, R,. (Dec 2013) ,“Student Friendly Quantum Field Theory”, Chapter 1 (page 6), https://www.amazon.com/Student-Friendly-Quantum-Field-Theory/dp/0984513957

[29] Tong, D,. (2007),“Quantum Field Theory”, Free Fields (page 21-23), https://www.damtp.cam.ac.uk/user/tong/qft/qft.pdf

[30] Rugh, S.E., and Zinkernagel, H., (Dec 2000), “The Quantum Vacuum and the Cosmological Constant Problem”, https://arxiv.org/abs/hep-th/0012253

[31] Hoyer, P., (Feb 2019), “Bound states and QCD”, https://arxiv.org/abs/1807.05598

[32] Fariada-Veiga, P.A., O’Carroll, M., (June 2005), “A Meson-Meson Bound State in a 2+1 Lattice QCD Model With Two Flavors and Strong Coupling”, https://sites.icmc.usp.br/veiga/final_2flavor_2meson.pdf

[33] Yamamoto, N., et al, (Oct 2007) “Phase structure, collective modes, and the axial anomaly in dense QCD”, https://arxiv.org/abs/0704.2654

[34] Song, Y,. and Baym, G,. (Oct 2021), “Generalized Nambu-Goldstone pion in dense matter: a schematic NJL model”, https://arxiv.org/abs/1703.08236

[35] Cheung, G., Thomas, C.E., Dudek, J., Edwards, R., (2017), "Tetraquark operators in lattice QCD and exotic flavor states in the charm sector", https://arxiv.org/abs/1709.01417

[36] Bicudo, P., (Dec 2022), “Tetraquarks and pentaquarks in lattice QCD with light and heavy quarks”, https://arxiv.org/abs/2212.07793

[37] Okiharu, F., Suganuma, H., Takahashi, T. T., (Aug 2005), “Detailed analysis of the tetraquark potential and flip-flop in SU(3) lattice QCD”, https://arxiv.org/abs/hep-lat/0412012

[38] Gyulassy, M., (Mar 2000), “Searching for the Next Yukawa Phase of QCD”, https://arxiv.org/abs/nucl-th/0004064

[39] Corley, S. and Jacobson, T. (1999) Black Hole Lasers. Physical Review D, 59, Article 124011.https://doi.org/10.1103/PhysRevD.59.124011
https://arxiv.org/pdf/hep-th/9806203.pdf