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The Pionic Deuterium and the Pion Tetrahedron Vacuum Polarization

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Abstract

A double-well potential model is proposed for the pionic deuterium that enables to calculate the energy split, the potential barrier height and estimate the pion tetrahedron edge length. We propose that pion tetrahedrons, $\pi^{Td} = u\tilde{d}d\tilde{u}$, play a central role in the Yukawa interaction by enabling quark exchange reactions between protons and neutrons by tunneling through a potential barrier. A vacuum polarization Feynman diagram is proposed for the π^{Td} having chains of fermion loops for the two valence quarks and anti-quarks connected by gluons. With a higher order vacuum polarization diagram, the d and u quark loops are interleaved and the chiral symmetry is broken dynamically. The proposed π^{Td} vacuum polarization integral does not diverge in both the IR and UV limits and vanishes in the limit of an infinite pion tetrahedron condensate. We propose a new Delbruck scattering Feynman diagram that includes d and u quark and anti-quark interleaved loops. We further propose that conversion of gravitons to photons may occur via quark and anti-quark loops that describe the pion tetrahedrons dynamics in the vacuum and may also transfer gravitational waves.

Keywords

Pionic Deuterium (πD), Yukawa Interaction, QCD Vacuum, Double-Well Potential, Chiral Perturbation Theory, Vacuum Polarization, Gravitational Waves

1. Introduction Yukawa Interaction

Yukawa interaction [1] describes the strong force between hadrons mediated by pions. The Yukawa interaction describes also the coupling between the Higgs field and massless quark and lepton fields, where through spontaneous symmetry breaking, the fermions acquire a mass proportional to the vacuum expectation value (VEV). This Higgs-fermion coupling was first described by Steven Weinberg to model lepton masses [2]. The Yukawa interaction term has a single coordinate *r*:

$$L_{Yukawa}\left(\Psi,\varphi\right)=-g\bar{\Psi}\left(r\right)\varphi\left(r\right)\Psi\left(r\right) \tag{1}$$

where g is a coupling constant, $\Psi(r)$ is the fermion field and $\varphi(r)$ is the pion field. The Yukawa potential is:

$$V\left(r\right)=-\frac{g^2 \mathrm{e}^{-\mu r}}{4\pi r} \tag{2}$$

where μ is the Yukawa particle mass that determines the exponential decay of the attractive interaction between hadrons. In the next section we review briefly the pionic hydrogen and pionic deuterium hydrogen-like atoms before describing the role of the pion tetrahedrons in the Yukawa interaction.

2. Pionic Hydrogen and Pionic Deuterium

A pionic hydrogen, $\pi^- p$, is an unstable hydrogen-like atom, where the electron is replaced with the negatively charged pion, π^- ($d\bar{u}$). The Bohr radius of the pionic hydrogen is about 200 femtometer which is shorter than the hydrogen atom Bohr radius but still significantly larger than proton radius and hence the QCD interaction between the proton and the charged pion is expected to be small [3]. The pionic hydrogen atom reveals the influence of the strong force by a negative shift and broadening of the low-lying atomic levels with respect to the pure electromagnetic interaction.

For the pionic deuterium [3], $\pi^- D$, the energy shift, ε_{1s}, is negative and is about −2.3 eV and the energy width, Γ_{1s}, is about 1 eV. The negative sign of the energy shift is due to repulsive interaction that screens the QED attraction between the negative charged pion and the positively charged proton, and the ground state level width is explained by the pion absorption and production by the nucleus (**Figure 1**).

In the next section we propose that pion tetrahedrons mediate the strong force by enabling quark exchange reactions between protons and neutrons. In addition, the pion tetrahedrons enable a pion exchange reaction with the deuterium nucleus that reduces the effective charge of the proton.

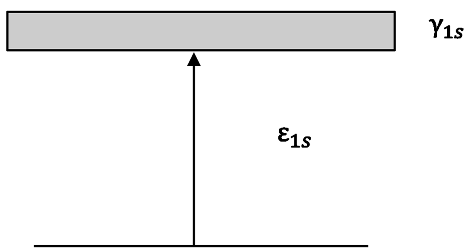


Figure 1. Illustrates the ground state pionic deuterium shift and width of the order of −2.3 and 1 eV, respectively (Strauch *et al.* [3], **Figure 1** page 3).

3. Pionic Deuterium and the Pion Tetrahedron

Inspired by the theory of Loop Quantum Gravity (LQG) [4], we proposed that exotic meson tetraquarks, $\pi^{Td} = u\tilde{d}d\tilde{u}$, introduced in previous papers [5] [6] [7] [8] condense to a tetrahedron geometry and may be part of the QCD ground state pion condensate. We proposed that neutral pions, a superposition of $d\tilde{d}$ and $u\tilde{u}$ mesons, may condense into a $u\tilde{d}d\tilde{u}$ tetrahedron geometry having two chiral states [9] as shown below (**Figure 2**).

$$d\tilde{d} + u\tilde{u} \rightarrow u\tilde{d}d\tilde{u}\left(\text{tetrahedron pion}, \pi_{L,R}^{Td}\right) \tag{3}$$

We propose that in the case of the pionic deuterium, the Yukawa interaction may occur via a transition state complex where two pairs of quarks are exchanged coherently between protons and neutrons by tunneling via a potential barrier. Quark exchange reaction transforms the proton to a neutron and the neutron to a proton concurrently as shown below in **Figure 3** and the Feynman diagram of **Figure 4**.

The quark exchange reaction is triggered by the tetrahedron anti-quarks $\tilde{d}$ and $\tilde{u}$ that capture their quark pairs from the proton and the neutron d and u quarks and replace them with the tetrahedrons' u and d quarks (on the left-hand side). The quark exchange reaction on the right side occurs in the opposite direction transforming the neutron back to a proton and the proton to a neutron. The proposed quark exchange reaction is symmetric, where the reactants and products are the same.

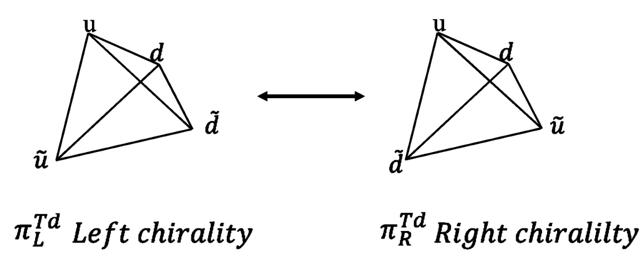


Figure 2. Illustrates the $u\tilde{d}d\tilde{u}$ pion tetrahedron with left π_L^{Td} and right π_R^{Td} chirality.

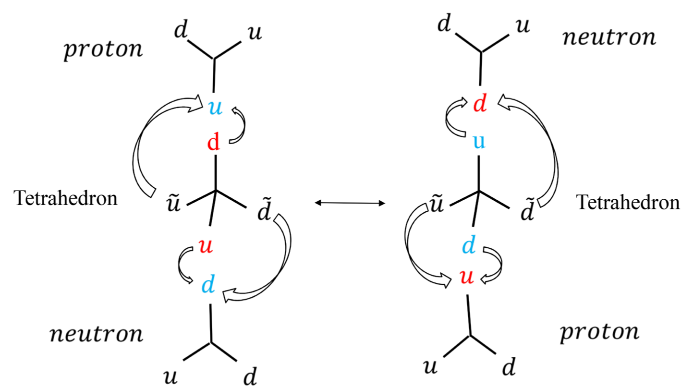


Figure 3. Illustrates the double quark exchange reaction in deuterium nucleus mediated by the pion tetrahedron π^{Td} by tunneling via a potential barrier.

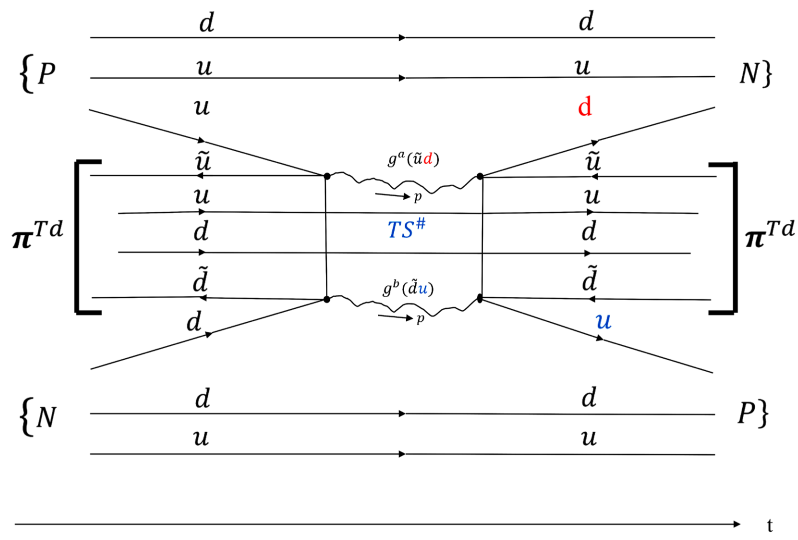


Figure 4. Illustrates the proton and neutron quark exchange reactions enabled by the pion tetrahedron $\pi_{L,R}^{Td}$.

$$uud(P)+u\tilde{d}d\tilde{u}(\pi^{Td})+udd(N)\to udd(N)+u\tilde{d}d\tilde{u}(\pi^{Td})+uud(P) \tag{4}$$

The transition state complex includes the deuterium nucleus proton and neutron and the pion tetrahedron, overall 10 quarks and antiquarks. The transition state complex may have a specific geometry and symmetry where the reaction is activated by the two anti-quarks. The potential surface is a many-body potential surface that however may be simplified by an effective one-dimensional reaction coordinate forming a double well potential as shown in **Figure 5**. The pion tetrahedron (π^{Td}) plays the role of the Yukawa interaction mediator that provides here both the anti-quarks and the two quarks that are exchanged. Note that the quarks and antiquarks numbers are conserved in the quark exchange reaction via the potential barrier (Equation (4) above).

The charged pion $\pi^-(d\tilde{u})$ is scattered by the nucleus where a quark exchange reaction occurs with the pion tetrahedron

$$uud+udd+u\tilde{d}d\tilde{u}+d\tilde{u}(\pi^-)\to udd+uud+u\tilde{d}d\tilde{u}+d\tilde{u}(\pi^-) \tag{5}$$

The double well potential model, which was used to study the ammonia molecule inversion via a potential barrier [10], splits the pionic deuterium energy levels including the ground state to symmetric and anti-symmetric doublets. The strong force that couples the deuterium nucleus and the charged pion, $\pi^-(d\tilde{u})$, shifts and broadens the ground state energy as shown in **Figure 1**. Strauch *et al.* [3] estimated that the shift is negative, about −2.3 eV, reducing the QED attraction between the charged pion and the proton. The charged pion exchange reaction of Equation (5) above generates a negatively charged cloud at the deuterium nucleus vicinity that reduces the effective charge of the proton. The proposed pion exchange reaction is an alternative mechanism to pion absorption and production by the nucleus at low energies [3].

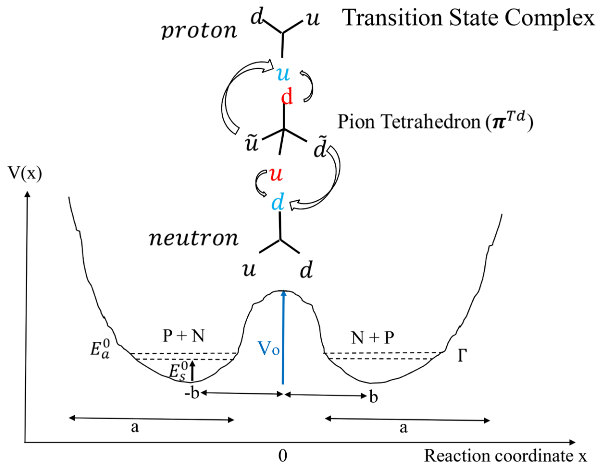


Figure 5. Illustrates quark exchange reaction transforming protons (P) to neutrons (N) and vice versa mediated by the pion tetrahedron ($\pi_{L,R}^{Td}$) forming the double well potential with a potential barrier.

The energy split of the double well potential model can be calculated numerically and it depends on four parameters, the potential barrier height, V_0, two length parameters, a and b, shown in **Figure 5**, and a particle mass m that tunnels through the barrier. We used a = 80 fm for the double well width and $b = b_{Td} + a/2$, where b_{Td} is the pion tetrahedron edge length of about 0.165 femtometer in the model. Based on Strauch *et al.* [3], we assume that Γ_{1s} value is 1 eV and is the double well potential split $E_0^a - E_0^s$, where E_0^s is the ground state symmetric energy and E_0^a is the anti-symmetric energy. The particle mass is assumed to be similar to the Higgs mass m_{Higgs} = 125.35 GeV. We determined the potential barrier value V_0 with a given b_{Td} value (0.165 fm) from the numerical solution of the double well potential model that matches the experimental value for the energy split $\Gamma_{1s} = 1\,\text{eV}$ as shown in **Figure 6**.

$$E_0^a - E_0^s = \Gamma_{1s} = 1\,\text{eV} \tag{6}$$

The numerical solutions of double well potemtial model two transcendental equations is obtained by solving the matching condition of the wavefunction values and derivatives at the barrier potential walls at x = b_{Td} and x = $-b_{Td}$ [10].

$$\tan(k_s a) = -\frac{k_s}{\sqrt{\alpha^2 - k_s^2}} \coth\left(\sqrt{\alpha^2 - k_s^2}\, b_{Td}\right) \tag{7a}$$

$$\tan(k_a a) = -\frac{k_a}{\sqrt{\alpha^2 - k_a^2}} \tanh\left(\sqrt{\alpha^2 - k_a^2}\, b_{Td}\right) \tag{7b}$$

where $\alpha^2 = \frac{2m_{Higgs^-} V_0}{\hbar^2}$, $k_s^2 = \frac{2m_{Higgs^-} E_0^s}{\hbar^2}$ and $k_a^2 = \frac{2m_{Higgs^-} E_0^a}{\hbar^2}$.

Figure 6 shows the numerical solution of Equations (7a) and (7b). We assume that the difference between the symmetric and anti-symmetric solution ground state energy split is ΔE = 1.0 eV and the potential barrier V_0 is 2.23 MeV. The calculated deuterium binding by pion tetrahedron double-well potential model ground state energy is $E_0^s = 0.238 \times 10^{-3}$ MeV.

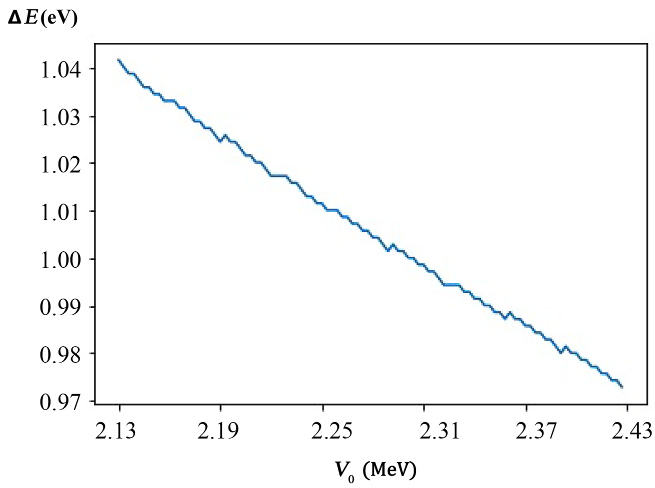


Figure 6. Illustrates the ground state energy split ΔE as a function of V_0 with $b_{Td} = 0.165$ fm.

Figure 7 shows the potential barrier height V_0 as a function of the barrier width, b_{Td}, which models the tetrahedron edge length obtained with the requierement that the energy split ΔE is 1.0 eV. The value of the barrier potential V_0 at the minimum is 2.304 MeV and the tetrahedron edge length b_{Td} is 0.165 fm. The calculated pion tetrahedron π^{Td} edge length is smaller but of the same order of magnitude of the proton diameter of about 0.83 fm. The 1 eV energy split generates a tunneling rate of 6.58×10^{-16} seconds.

4. Pion Tetrahedron and Vacuum Polarization

The mass of the protons and neutrons that comprises most of the mass of the visible universe is not the sum of the rest masses of their valence quarks that contribute only about 9% of their total ~1 GeV mass per particle [11]. The masses of the valence quarks in the proton are estimated to be ~3 MeV per quark while the total proton mass is 938 MeV. According to lattice QCD calculation, the quark kinetic energy and gluon field energy contribute 33% and 37% respectively, the trace anomaly gives a 23% contribution, and the *u*, *d*, and *s* quark scalar condensates contribute about 9% [12].

The QCD Lagrangian is

$$L_{QCD} = \sum_{j=u,d,s,\cdots} \overline{q}_j \left[i\gamma^{\mu} D_{\nu} - m_j \right] q_j - \frac{1}{4} G^{a}_{\mu\nu} G^{a\mu\nu} \tag{8}$$

q_j and $\overline{q}_j$ are the quark and ant-quark field Dirac spinors, the QCD 8 gluon fields that carry the strong force are described by the vector potential $A^a_{\mu}, a = 1,\cdots,8$ that enters the QCD Lagrangian through the covariant derivative D_{ν} and the tensors $G^a_{\mu\nu}$

$$D_{\nu} = \partial_{\nu} + ig\frac{1}{2}\lambda^a A^a_{\mu} \tag{9}$$

$$G^a_{\mu\nu} = \partial_{\mu} A^a_{\nu} + \partial_{\nu} A^a_{\mu} + igf^{abc} A^b_{\mu} A^c_{\nu} \tag{10}$$

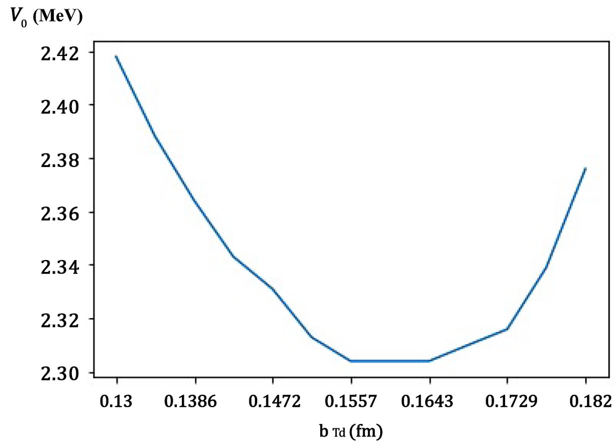


Figure 7. Illustrates the calculated potential barrier height V_0 as a function of the barrier width, b_{Td}, which models the pion tetrahedron $\pi^{Td}_{L,R}$ edge length. V_0 is 2.304 MeV at the minima with π^{Td} edge length of 0.165 fm.

g is the strong force coupling constant, λ^a are the generators of the SU(3) color gauge group and f^{abc} are the SU(3) adjoint group representation coefficients.

Note that the quark exchange reactions of nucleons with the pion tetrahedrons, $\pi^{Td}_{L,R}$, may be seen as gluon exchanges. For example, the symmetric proton to neutron quark exchange reaction of Equation (4), $uud + u\tilde{d}d\tilde{u} + udd \to udd + u\tilde{d}d\tilde{u} + uud$, is described by the following Feynman diagram where quark exchange reactions between the proton and the neutron via the pion tetrahedron transition state complex occurs by two gluons exchange.

The proton's quarks may perform similar quark exchange reactions with the pion tetrahedrons of the vacuum condensate, $\pi^{Td}_{L,R}$, (**Figure 8**) cooling the protons by carrying away part of the proton momentum

$$uud + u\tilde{d}d\tilde{u} \to u\tilde{d}d\tilde{u} + uud \tag{11}$$

The one-loop vacuum polarization Feynman integral diverges and it is renormalized with QED. The QED vacuum polarization amplitude after Wick's rotation is proportional to the integral (with $\hbar = c = 1$) [13]:

$$\pi_2^{\mu\nu}\left(p^2\right) \sim \int_0^\infty \mathrm{d}k \frac{k^3}{\left(\left(k-p\right)^2 + m^2\right)\left(k^2 + m^2\right)} \tag{12}$$

The electron charge is renormalized using the pertubative expansion –

$$e_R^2\left(p^2\right) = e^2 - e^4 \pi_2^{\mu\nu}\left(p^2\right) + \cdots \tag{13}$$

The diverging vacuum polarization integral may be handled by effective running permittivity $\varepsilon_0\left(r\right)$ instead of renormalizing the electric charge [14]. The vacuum polarization one-loop Feynman diagram for an electron-positron pair is shown below as a reference for the proposed pion tetrahedron π^{Td} vacuum polarization Feynman diagram (**Figure 9**).

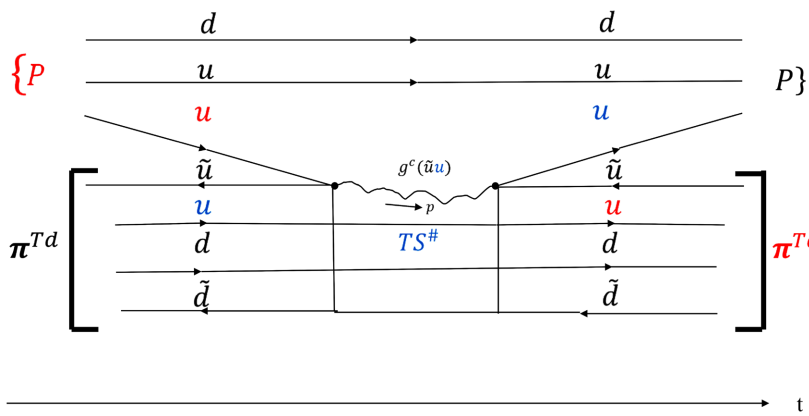


Figure 8. Illustrates proton scattering quark exchange reaction enabled by pion tetrahedron $\pi_{L,R}^{Td}$ that cooling the accelerated proton. The red color illustrates the hot accelerated particles.

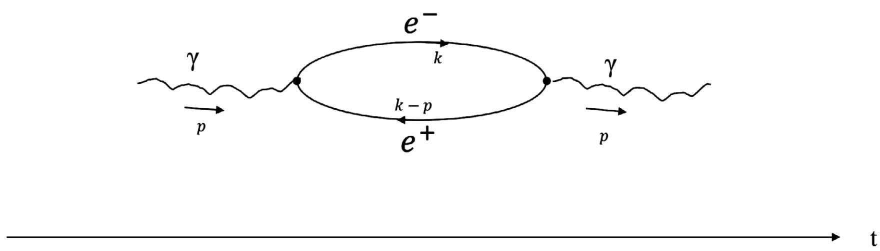


Figure 9. Illustrates the one-loop vacuum polarization Feynamn diagram an an electron-positron pair.

The π^{Td} vacuum polarization Fyenman diagram shown below includes two quark and anti-quark loops, one for the u and $\tilde{u}$ and the second for the d and $\tilde{d}$ quarks of the pion tetrahedron (**Figure 10**).

The π^{Td} vacuum polarization integral may be a sum of the two loops that can be re-normalized [15]. However, we propose considering the joint diagrams shown below. The first vacuum polarization diagram has a rotational ellipsoid shape (**Figure 11(a)**) and the second is a two interleaved quark and anti-quark loops (**Figure 11(b)**). The joint two-loop vacuum polarization Feynman diagram includes the two flavor quarks as coupled loops. We assume that the neutral pion terahedron is a single particle and hence it has only one internal momentum k variable.

The π^{Td} vacuum polarization integral after Wick's rotation does not diverge in both the IR and UV limits

$$\pi_2^{Td}\left(p^2\right) \sim \int_0^{\infty} \mathrm{d}k \frac{k^3}{\left(k^2+m_u^2\right)\left((k-p)^2+m_u^2\right)p^2\left(k^2+m_d^2\right)\left((k-p)^2+m_d^2\right)} \quad (14)$$

Figure 12 illustrates a two body higher order vacuum polarization Feynman diagram including two π^{Td} with two loops each and additional gluons that interleave dynamically the u and d quark loops for the two π^{Td}. The quarks exchange their flavor by exchanging gluons and the result are pion tetrahedrons

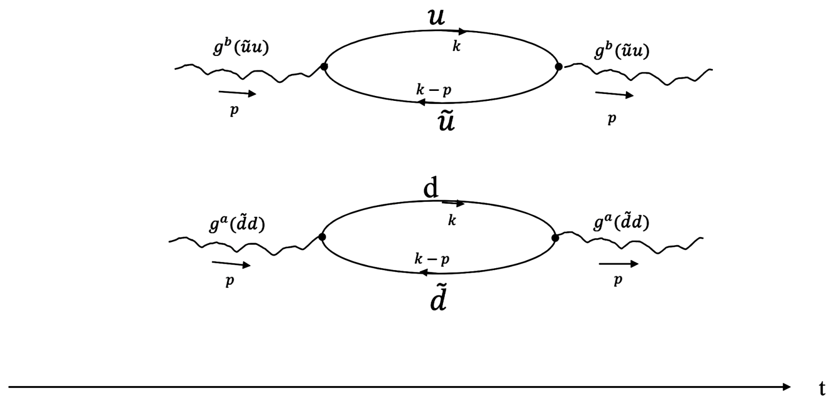
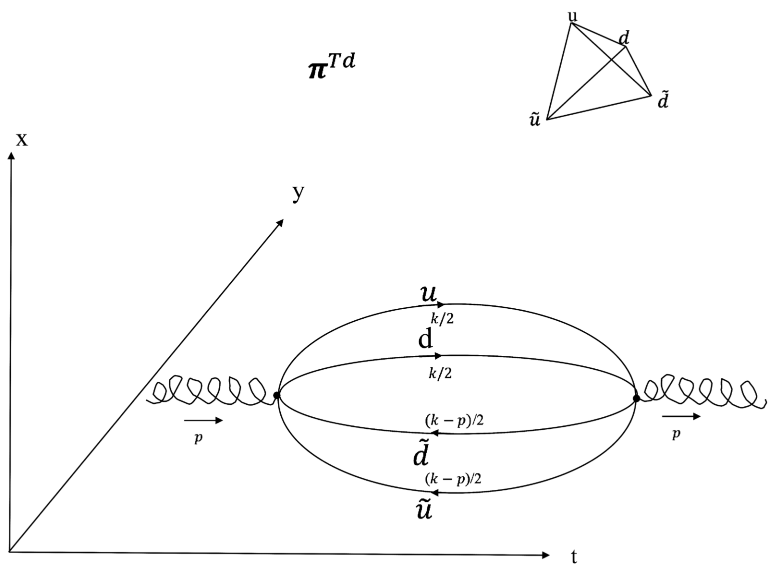
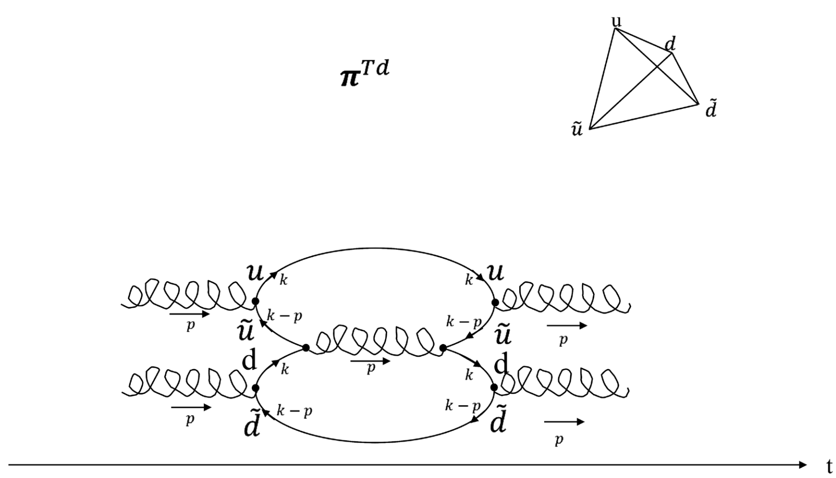


Figure 10. Illustrates the pion tetrahedron π^{Td} vacuum polarization Feynman diagram.



(a)



(b)

Figure 11. Illustrate the pion tetrahedron π^{Td} vacuum polarization Feynman diagram with a rotational ellipsoid shape (a); and coupled two flavor quark and anti-quark interleaved loops (b).

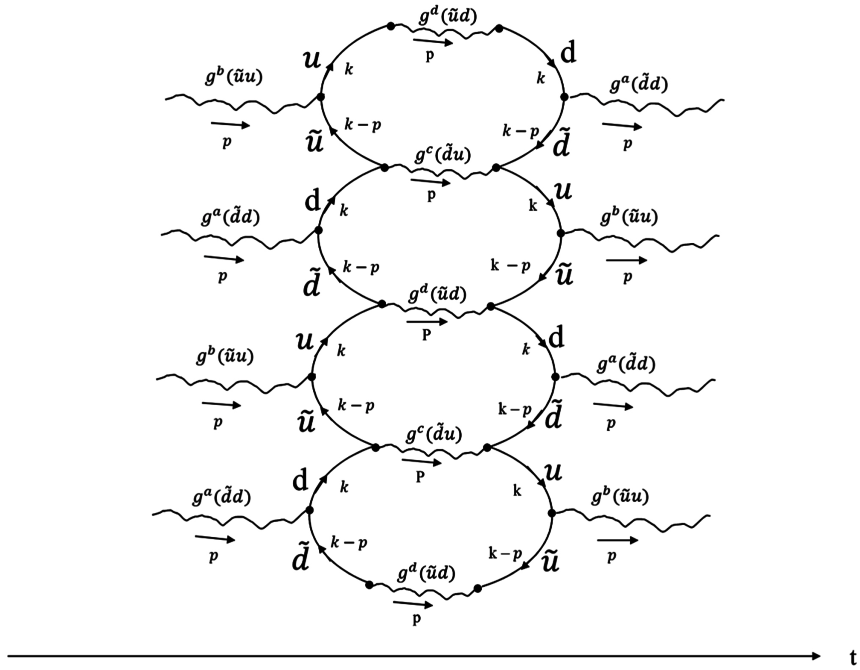


Figure 12. Illustrates two pion tetrahedrons higher order vacuum polarization diagram with additional gluons that interleave the u and d quark loops of the two π^{Td} and may represent the pion vacuum condensate.

with dynamically alternating right and left tetrahedron chirality. The chiral tetrahedron symmetry is broken dynamically by the quark flavor exchange described in Equation (15)

$$\tilde{u}u\tilde{d}d\left(\pi^{Td}\right)+\tilde{d}d\tilde{u}u\left(\pi^{Td}\right)\rightarrow\tilde{d}d\tilde{u}u\left(\pi^{Td}\right)+\tilde{u}u\tilde{d}d\left(\pi^{Td}\right)\tag{15}$$

The π^{Td} decay rate is proportional to the square of the Feynman diagram amplitude π_2^{Td}

$$\Gamma_{\pi^{Td}}\sim\frac{4\pi^2\left(\pi_2^{Td}\left(p^2\right)\right)^2}{\hbar}\tag{16}$$

However, the vacuum polarization pion tetrahedron π^{Td} amplitude will vanish in the limit of an infinite pion tetrahedron condensate where the two body diagram is replicated infinite times representing more coupled pions. The properties of the pions are intimately related to the QCD chiral symmetry and the QCD ground state vacuum. In the chiral limit, the quark masses m_u and m_d vanish, the chiral symmetry becomes exact, the massless Dirac Lagrangian being invariant under the group $SU(2)_R \times SU(2)_L$. The chiral symmetry is assumed to be spontaneously broken to the isospin subgroup $SU(2)_V$ by the pion vacuum condensate. The pions represent the corresponding Goldstone bosons and the vacuum pion condensate is assumed to be the leading order parameter of the spontaneously broken symmetry $\langle 0|u\tilde{u}+d\tilde{d}|0\rangle$ [16]. The QCD chiral perturbation theory is based on the massless Dirac Lagrangian symmetry, however, it does not determine explicitly what is the QCD vacuum content and how the vacuum breaks the chiral symmetry. The proposed pion tetrahedrons have two chiral states, $\pi_{L,R}^{Td}$, determined by the relative positions of the two quarks and the two anti-quarks in the tetrahedron vertices and they may be a realization of the QCD Lagrangian chiral symmetry. The pion tetrahedron has no inversion mirror symmetry similar to topological Weyl Semimetals (WSM) [17]. In solid-state band structures, massless Weyl fermions exist as low-energy excitations of WSM, in which bands disperse linearly in momentum space through Weyl points. If the QCD pion condensate has similar Wyel points, the valence quarks at low energies are massless due to symmetry beyond the chiral perturbation theory approximation that assumes that the valence quarks have small masses on the GeV energy scale.

5. Pionium $A_{2\pi}$ and the Vacuum Expectation Value

A bound state of π^+ and π^-, $A_{2\pi}$, has been observed in 1993 [18]. The pionium has a Bohr radius of about 400 femtometers [19] and lifetime of $2.9 \pm 0.1 \times 10^{-15}$ seconds [20]. The DIRAC lifetime measurement method is based on production of pionium $\pi^+\pi^-$ ($A_{2\pi}$) atoms in a thin Ni target by accelerated protons and subsequent detection of highly correlated $\pi^+\pi^-$ split pairs leaving the target as a result of a breakup (ionization due to electromagnetic interaction with the Ni target) of a part of the $\pi^+\pi^-$ atoms which did not decay within the target.

The pionium $A_{2\pi}$ decay is dominated by the charge exchange annihilation/condensation reaction that leads to neutral pions π^0

$$A_{2\pi} \to \pi^0 + \pi^0 \tag{17}$$

However, the main competing reaction to the $A_{2\pi}$ decay is a breakup by ionization of the two charged pions that the DIRAC experiment measured

$$A_{2\pi} \to \pi^+ + \pi^- \tag{18}$$

The $A_{2\pi}$ lifetime is related to the free path before it is scattered with acattering lengths a_0 and a_2, the S-wave pion-pion scattering lengths for isospin 0 and 2, respectively. The partial decay width of the atomic ground state (principal quantum number $n = 1$, orbital quantum number $l = 0$) depends on the difference between the scattering lengths a_0 and a_2

$$\Gamma_{1s} = \frac{1}{\tau_{1s}} = \frac{2}{9}\alpha^3 p\left|a_0 - a_2\right|^2 (1+\delta) \tag{19}$$

where τ_{1s} is the lifetime of the atomic ground state, α the fine-structure constant, p the π^0 momentum in the atomic rest frame, $\delta = 0.058 \pm 0.012$, is a QED and QCD correction.

The measured scattering lengths are

$$a_0 = \frac{7M_\pi^2}{32\pi F_\pi^2} = 0.22, \quad a_2 = -\frac{M_\pi^2}{16\pi F_\pi^2} = -0.044, \quad a_0 - a_2 = 0.265 \pm 0.004 \tag{20}$$

And the pion mass is

$$M_\pi^2 = \frac{(m_u + m_d)\langle 0|u\tilde{u} + d\tilde{d}|0\rangle}{F_\pi^2} \tag{21}$$

The pion mass and the scattering lengths difference $a_0 - a_2$ is related to the structure of the QCD vacuum expectation value (VEV), $\langle 0 | u\tilde{u} + d\tilde{d} | 0 \rangle$ [21].

The vacuum polarization diagram for a charged pion pair pionium, $A_{2\pi}$, is shown below. The pion tetrahedron condensate may include the vacuum polarization diagrams of **Figure 9**, **Figure 11** and **Figure 13** having different length scales and polarization condition.

6. Delbruck Scattering and the Pion Tetrahedron Condensate

Dunne reviewed the Heisenber-Euler effective action [22] that based on Dirac's positron theory predicted the non-linear light-by-light scattering and vacuum polarization. The extra unaccounted for scattered photons were explained by Delbruck in 1933 as light-by-light scattering interaction with the target heavy atoms that produced electron-positron pairs and next annihilated emitting photons. The Delbruck scattering theoretical calculations do not perfectly match experiments like in other QED phenomena [23] opening the door to QCD corrections [24].

Below we propose a Feynman diagram for the Delbruck scattering that includes interleaved quarks and anti-quarks vacuum polarization loops that describe the pion tetrahedrons $\pi^{Td}\left(u\tilde{d}d\tilde{u}\right)$ vacuum dynamics and polarization (**Figure 14**).

The proposed reaction mechanism involves quark exchanges between interleaved quark vacuum polarization loops that describe two pion tetrahedron exchanging quarks and anti-quarks by gluons that in addition to the quark flavor exchanges can transfer momentum. The Delbruck scattering is elastic and only the photon momentum direction p changes to p'. The Delbruck scattering may be described with a reaction equation as follows where the incoming and scattered photons, γ and γ', are carried by the polarized pion tetrahedron condesate medium $u\tilde{d}d\tilde{u}$. The first pion tetrahedron $u\tilde{d}d\tilde{u}(\gamma)$ on the left side of Equation (22) represents the polarized vacuum that carries the incoming photon and the second pion tetrahedron $u\tilde{d}d\tilde{u}(\gamma_x)$ represents the polarized pion tetrahedron condensate in the vicinity of the target massive atom, uranium, for

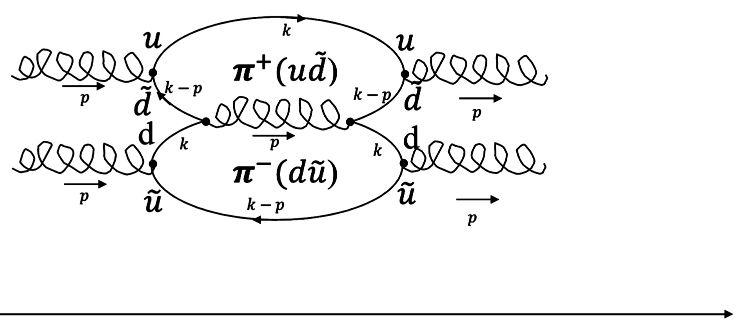


Figure 13. Illustrates the vacuum polarization diagram for a charged pion pair pionium $A_{2\pi}$.

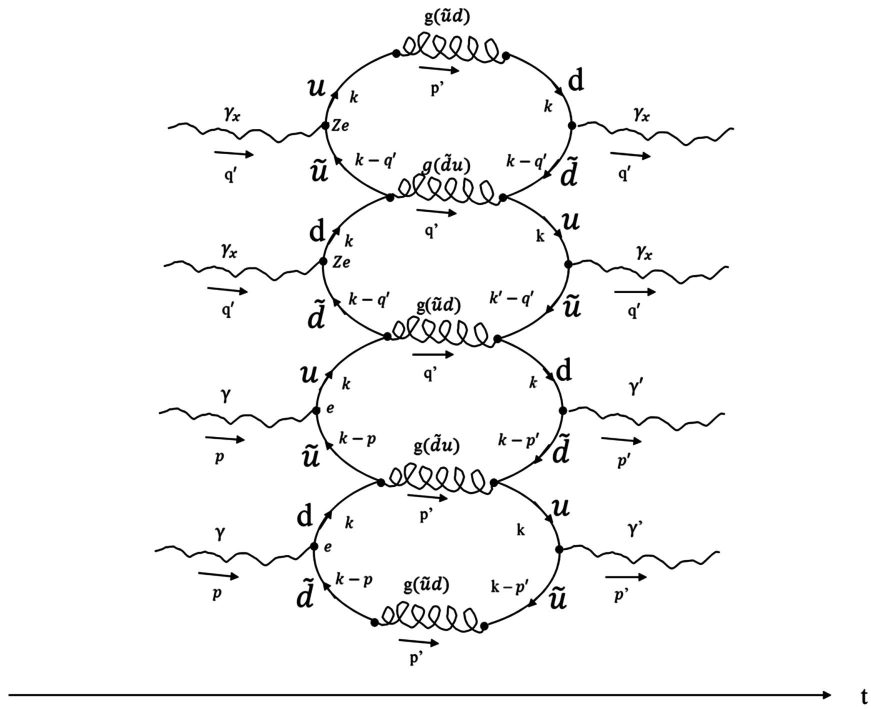


Figure 14. Illustrates the Delbruck scattering Feynman diagram with interleaved vacuum polarization loops that describe a polarized pion tetrahedrons condensate where the momentum direction p' may be different from p.

example, which is polarized by the heavy nucleous. The reaction is light-by-light scattering that occurs via the polarized pion tetrahedron condensate in the vicinity of the target uranium atoms.

$$u\tilde{d}d\tilde{u}(\gamma) + u\tilde{d}d\tilde{u}(\gamma_x) \to u\tilde{d}d\tilde{u}(\gamma') + u\tilde{d}d\tilde{u}(\gamma_x) \quad (22)$$

The proposed Delbruck scattering mechanism and Feynman diagram add the pion tetrahedrons and QCD interactions to the light-by-light scattering. Since photons may be converted to gluons, in the next section we propose that the pion condensate vacuum polarization plays a role in the conversion and also in transferring gravitational waves.

7. Gravitational Waves and the Pion Tetrahedron Condensate

Jones and Singelston reviewed the interaction between gravitational radiation and electromagnetic radiation [25] and Bjerrum-Bohr *et al.* studied graviton-photon scattering [26]. The graviton to photon conversion was assumed to be due to coupling between photon and graviton fields according to Einstein equation.

Does the proposed quark and anti-quark exchange reactions with the pion tetrahedron condensate allow gravitational wave transfer via vacuum polarization loops? The quark and anti-quark exchange reactions below transfer momentum and may carry gravitational waves by quark exchange reactions via the pion tetrahedron condensate medium.

$$dud + u\tilde{d}d\tilde{u} \to dud + u\tilde{d}d\tilde{u} \tag{23a}$$

$$dud + u\tilde{d}d\tilde{u} \to dud + u\tilde{d}d\tilde{u} \tag{23b}$$

For example, the Feynman diagram (**Figure 15**) describes scattering of a neutron by a pion tetrahedron with quark exchange reaction that may heat the pion tetrahedron vacuum and cool the neutron. The momentum transfer of the quark exchange reaction depends on the relative momentum of the neutron and the polarized pion tetrahedron condensate.

We assume that the gravitational force is carried by quark exchange reactions with the vacuum pion tetrhedrons such that particles comprised of quarks take part in the gravitational interaction.

The Fyenman diagram below illustrates a polarized pion tetrahedron vacuum in a gravitational field of a massive star in the origin of axes for example. We assume that the gravitational field affects the massive pion tetrahedron condensate density in space and hence the momentum the pion tetrahedrons transfer depends on their distance from the massive star. Further away from the star, the pion tetrahedron density is reduced and the momentum it can transfer is reduced too. The combination of the quark exchange reactions and the pion tetrahedron density variation due to the gravitational field will accelerate a body comprised of quarks (**Figure 16**).

We propose here that the pion tetrahedron condensate may convert gravitons to photons in the vicinity of nucleons and gluons. The pion tetrahedrons condensate may be polarized by the nucleons forming pion tetrahedrons with electric dipols such that the vacuum polarization loops become instead of neutral pion loops charged pion loops as shown below (**Figure 17**). The charged pion loops may emit and transfer electromagnetic radiation. The four quarks of the pion tetrahedrons are assumed to be positioned at the crossed vertices of a cube and due to external electric or magnetic field the cubes may be compressed to a rectangular shape with a charge separation forming an electric dipole.

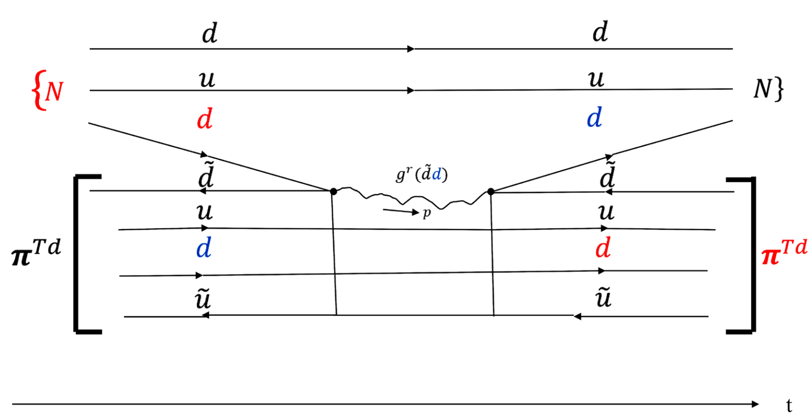


Figure 15. Illustrates scattering of a neutron by a pion tetrahedron with a quark exchange reaction.

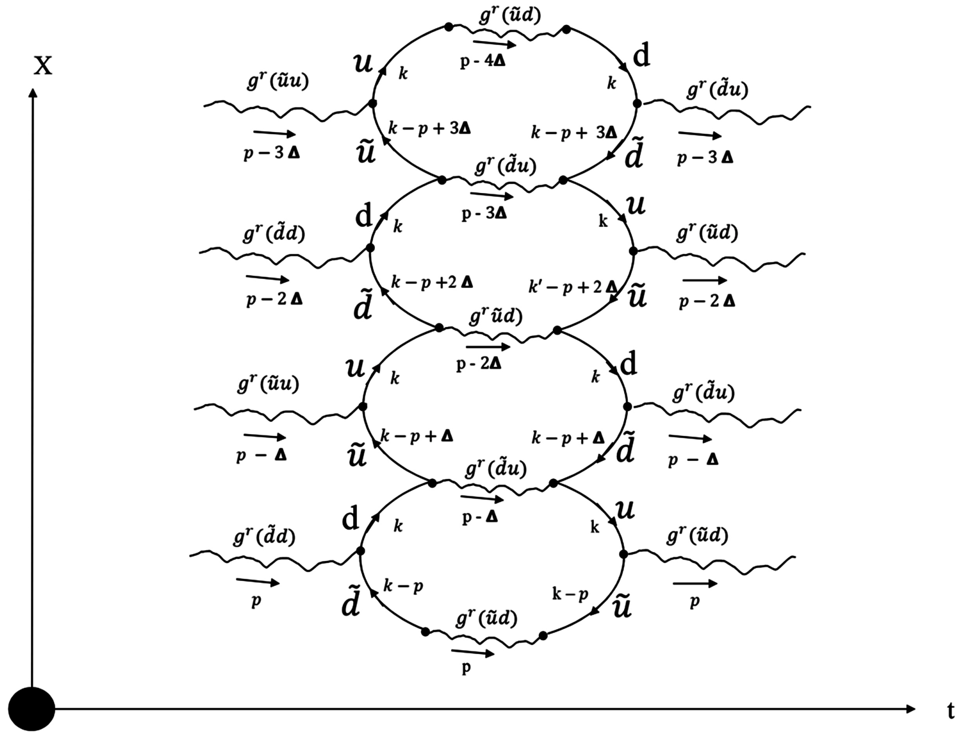


Figure 16. Illustrates the pion tetrahedron vacuum polarization in the gravitational field of a massive body.

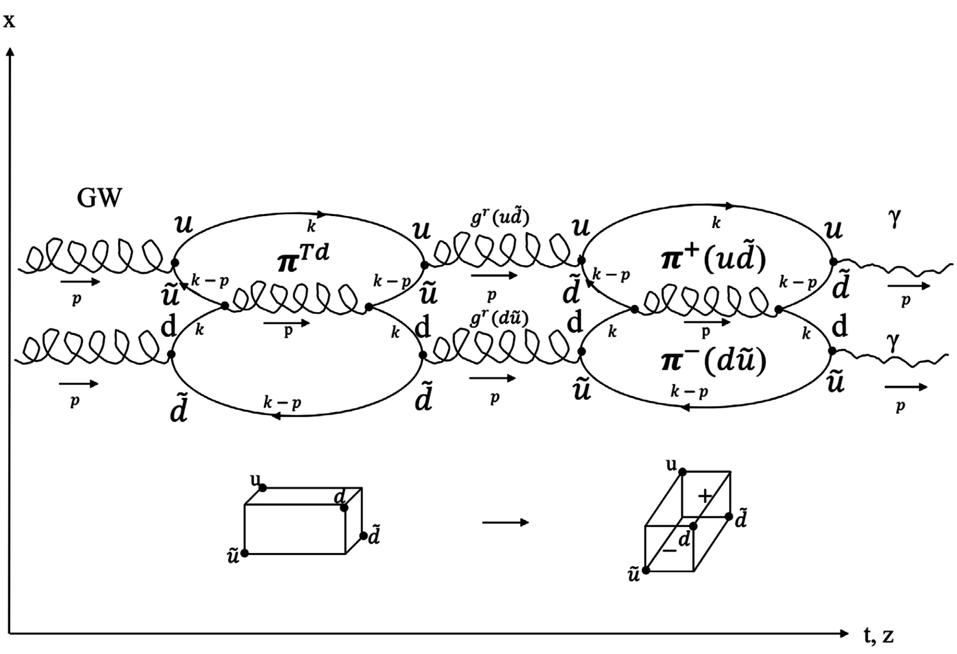


Figure 17. Illustrates conversion of a graviton to a photon by the pion tetrahedron condenste vacuum polarization loops forming a charged pionic pair.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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