

# Thread bonds in molecules

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Unusual chemical bonds are proposed. Each bond is characterized by the thread of a small radius,  $10^{-11}$  cm, extended between two nuclei in a molecule. An analogue of a potential well, of the depth of MeV scale, is formed within the thread. This occurs due to the local reduction of zero point electromagnetic energy. This is similar to formation of the Casimir well. The electron–photon interaction only is not sufficient for formation of thread state. The mechanism of electron mass generation is involved in the close vicinity,  $10^{-16}$  cm, of the thread. Thread bonds are stable and cannot be created or destructed in chemical or optical processes.

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## 1. Introduction

Various types of chemical bonds in molecules are well studied. See for example [1–3]. This is a branch of chemical physics with the well established set of basic phenomena. Methods of quantum chemistry are effectively applied to develop that field. The common feature of chemical bonding is the typical energy. Despite a variety of bond types there is the upper limit of energies involved into the phenomena. It is the atomic scale energy of the order of ten electron volts. Also the typical spatial scale in chemical bonding is no shorter than the atomic size.

The field of mesoscopic biology, where the typical length scale is of the order of nanometers, is actively developed now [4–6]. In this paper thread like electron states are proposed in biological and chemical systems. The thread length can be of the nanometer scale relating to mesoscopic objects in the field.

It looks unusual if energies, involved into molecular bonding, are of the order of 1 MeV and the spatial scale is  $10^{-3}$  of the size of hydrogen atom. At the first sight, it is impossible since chemical bonding is associated with the atomic processes. However, the proposed thread states relate to those parameters.

The point is that the electron state can have a tendency to be singular along the line (thread) connecting two nuclei in a molecule. The origin of such singularity is clear from Schrödinger equation in cylindrical coordinates which can have the solution logarithmically singular on the axis. The electron “vibrates” due to the interaction with zero point

electromagnetic oscillations and the singularity smears out within the thread of a small radius  $\sim 10^{-11}$  cm. The origin of this subatomic length scale in molecular systems is not surprising if to look from the standpoint of the Lamb shift [7].

Under the interaction with photons the electron “vibrates” with the mean displacement  $\langle \mathbf{u} \rangle = 0$  and the mean squared displacement  $\langle u^2 \rangle = r_T^2$  where  $r_T \sim 10^{-11}$  cm [8–11]. This is the fluctuation spreading in addition to the usual quantum mechanical uncertainty. In this language, the “vibrating” electron probes various parts of the potential well and therefore changes its energy (the Lamb shift).

The associated increase of the electron energy  $\hbar^2/mr_T^2 \sim 1$  MeV, which occurs in the thread of the radius  $r_T$ , is compensated by the local (at the same region) reduction of photon zero point energy. The resulting well is of MeV depth. This recalls analogous mechanism, but of a smaller energy, of well formation in Casimir (van der Waals) effect [7,12,13].

The electron–photon interaction, related to quantum electrodynamics, is not sufficient to form the thread state. Effects of generation of electron mass, described by the Higgs mechanism in the Standard Model, should be involved. These mechanisms are responsible for the inner structure of the thin thread. In contrast, its length is determined by arrangement of surrounding atoms in a biological medium. This length, of nanometers size, fits the field of mesoscopic biology.

The high energy parts, involved into thread formation, correspond to the typical time  $10^{-22}$  s. Optical processes

are slow compared to that time. They lead to an adiabatic motion of the thread parameters but absorption probability of such quanta is exponentially small. Also the thread bond cannot be created in chemical processes. Relatively high energy impact is required to create the thread state. It can be, for example, an irradiation by keV ions.

These thread bonds, coupling two strands of a DNA molecule, prevent DNA replication. One can put a general question on a role of such thread bonding in biological processes.

### 2. Two Coulomb centers

Electrons wave function in a molecule is complicated. The electron motion is collective and is not reduced to a single electron problem. The electron wave function is smooth in the space. We focus on the certain specificity of this function. If to consider usual atomic sizes the electron wave function can be formally singular on some line connecting two nuclei in the molecule.

Therefore the problem is separated in two parts. First one should find the singular solution of quantum mechanical equations for electrons in the molecule. Second one should analyze mechanisms of smearing of that singularity. In this section we focus on the singularity formation on the line connecting two nuclei which can be treated in the molecule as static ones according to the Born–Oppenheimer approximation.

Instead of solving the problem in full one can simplify it considering a single electron. The main features of the singular wave function can be demonstrated studying the artificial situation when one electron is in the field of two positive charges fixed at two points. The singularity line, connecting two nuclei in the molecule, is associated with large energies and is hardly influenced by chemical forces. For this reason the singularity line between two real nuclei in the molecule is of the same type as between two point charges formally fixed in the space.

#### 2.1. Formalism

To study the electron in the Coulomb field of two positive point charges at the points  $z = \pm\sigma$  it is convenient, instead of cylindrical coordinates  $r = \sqrt{x^2 + y^2}$ ,  $z$ , and  $\theta$ , to use the elliptic ones  $\xi$ ,  $\eta$ , and  $\theta$  [14]

$$\xi, \eta = \frac{r_2 \pm r_1}{2\sigma}. \tag{1}$$

Here  $r_{1,2} = \sqrt{(z \mp \sigma)^2 + r^2}$  are distances to the Coulomb centers shown in Fig. 1. The surface of a constant  $\xi$  is the ellipsoid

$$\frac{z^2}{\sigma^2 \xi^2} + \frac{r^2}{\sigma^2 (\xi^2 - 1)} = 1 \tag{2}$$

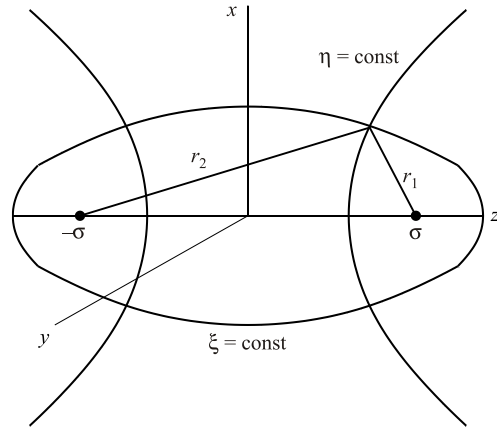


Fig. 1. Intersections of surfaces of constant elliptic coordinates  $\xi$  and  $\eta$  with the plane  $y = 0$  are shown. Two Coulomb centers are at the points  $z = \pm\sigma$ .

with the focuses at  $z = \pm\sigma$ . The surface of a constant  $\eta$  is hyperbolic

$$\frac{z^2}{\sigma^2 \eta^2} - \frac{r^2}{\sigma^2 (1 - \eta^2)} = 1 \tag{3}$$

with the focuses at the same points. The coordinate  $\xi$  takes values from 1 to  $\infty$  and  $\eta$  from  $-1$  to 1. Intersections of the surfaces (2) and (3) with the plane  $y = 0$  are shown in Fig. 1.

The Coulomb interaction potential is

$$U = -\frac{Ze^2}{r_1} - \frac{Ze^2}{r_2} = -\frac{2Ze^2}{\sigma} \frac{\xi}{\xi^2 - \eta^2}, \tag{4}$$

where  $Ze$  is the positive charge at each center. The Schrödinger equation for the electron

$$-\frac{\hbar^2}{2m} \nabla^2 \psi + U\psi = E\psi \tag{5}$$

in elliptic coordinates takes the form

$$-\frac{\hbar^2}{2m\sigma^2(\xi^2 - \eta^2)} \left[ \frac{\partial}{\partial \xi} (\xi^2 - 1) \frac{\partial \psi}{\partial \xi} + \frac{\partial}{\partial \eta} (1 - \eta^2) \frac{\partial \psi}{\partial \eta} \right] - \frac{2Ze^2}{\sigma} \frac{\xi}{\xi^2 - \eta^2} \psi = E\psi. \tag{6}$$

We consider an axially symmetric wave function. Since the variables are separated it has the form  $\psi(\xi, \eta) = \psi_1(\xi)\psi_2(\eta)$ . One can introduce dimensionless parameters  $v = -2m\sigma^2 E/\hbar^2$  and  $p = 4Z\sigma/r_B$  where  $r_B = \hbar^2/(me^2)$  is the Bohr radius.

After separation of variables the two Schrödinger equations are

$$-\frac{\partial}{\partial \xi}(\xi^2 - 1) \frac{\partial \psi_1}{\partial \xi} = (p\xi + \beta - v\xi^2)\psi_1 - \quad (7)$$

$$-\frac{\partial}{\partial \xi}(1 - \eta^2) \frac{\partial \psi_2}{\partial \eta} = (v\eta^2 - \beta)\psi_2, \quad (8)$$

where  $\beta$  is some constant.

The variable  $\eta$  can be written as  $\eta = \cos \chi$ . Then Eq. (8) has the form

$$\frac{1}{\sin \chi} \frac{\partial}{\partial \chi} \left( \sin \chi \frac{\partial \psi_2}{\partial \chi} \right) = (\beta - v \cos^2 \chi) \psi_2. \quad (9)$$

The solution, non-singular at  $\chi = 0$ , should be also non-singular after continuation to  $\chi = \pi$ . This is the condition to choose the parameter  $\beta$  for a given  $v$ . When two Coulomb centers coincide ( $\sigma = 0$  and therefore  $v = 0$ ) that condition turns to  $\beta = -l(l+1)$  as for Legendre polynomials [15]. In that case the variable  $\chi$  coincides with the azimuthal angle.

## 2.2. Close Coulomb centers

Below two close Coulomb centers are considered under the condition  $\sigma \ll r_B$ . We study the state which is isotropic ( $l = 0$ ) in the limit  $\sigma = 0$ . At a finite  $\sigma$  there is the small correction to the wave function which can be written as  $\psi_2 = 1 + \delta\psi_2$ . Using the relation

$$\sin \chi \frac{\partial \delta\psi_2}{\partial \chi} = \int d\chi (\beta - v \cos^2 \chi) \sin \chi, \quad (10)$$

one can obtain

$$\delta\psi_2 = \left( \frac{v}{3} - \beta \right) \ln \left( 2 \cos^2 \frac{\chi}{2} \right) - \frac{v}{6} \sin^2 \chi. \quad (11)$$

The solution (11) is finite at  $\chi = 0$  ( $\eta = 1$ ). In order to get it finite at  $\chi = \pi$  ( $\eta = -1$ ) it should be  $\beta = v/3$ . Note that  $v \sim p^2 \sim \sigma^2/r_B^2$  are small.

At  $\sigma \ll r_B$  there is a small region of the size  $\sigma$  around the centers in Fig. 1. This region corresponds to  $\xi \sim \eta \sim 1$ . The region of the order of the Bohr radius  $r_B$  is much larger and relates to large  $\xi$ . We consider this region first. In Eq. (7) one can omit  $\beta$  and to write  $\xi^2 - 1 \approx \xi^2$ . In the limit  $1 \ll \xi$  Eq. (7) takes the form

$$-\frac{\partial^2 \psi_1}{\partial \xi^2} - \frac{2}{\xi} \frac{\partial \psi_1}{\partial \xi} - \frac{p}{\xi} \psi_1 = -v \psi_1, \quad (12)$$

which coincides with the radial Schrödinger equation with  $l = 0$  in the Coulomb field of the point charge  $2Ze$  [15]. The solution of (12), decaying on infinity, is finite at small distances and corresponds to the eigenvalue  $v = p^2/4$ . This value relates to the ground state energy in the Coulomb field of the point charge  $2Ze$ .

For our purposes one needs a solution which also decays on infinity but is singular at  $r = 0$  and  $z^2 < \sigma^2$ . To

obtain that one should write the solution of (12) in the form [15]

$$\begin{aligned} \psi_1(\xi) &= \xi^{p/(2\sqrt{v})-1} \exp(-\xi\sqrt{v}) \times \\ &\times G \left( 1 - \frac{p}{2\sqrt{v}}, -\frac{p}{2\sqrt{v}}, -2\xi\sqrt{v} \right), \end{aligned} \quad (13)$$

where

$$G(\alpha, \beta, v) = 1 + \frac{\alpha\beta}{1v} + \frac{\alpha(\alpha+1)\beta(\beta+1)}{2!v^2} + \dots \quad (14)$$

To obtain the solution at shorter distances one should use the asymptotics of the function (14) at  $v \ll 1$ . Thus at small  $[1 - p/(2\sqrt{v})]$  one can obtain from Eq. (13) [15]

$$\psi_1(\xi) = 1 + \left( 1 - \frac{p}{2\sqrt{v}} \right) \frac{1}{2\xi\sqrt{v}}, \quad 1 \ll \xi \ll r_B/\sigma. \quad (15)$$

On the other hand, at not large  $\xi$  the left-hand side of Eq. (7) is the principal one and the solution is

$$\psi_1(\xi) = 1 + \frac{1}{4\sqrt{v}} \left( 1 - \frac{p}{2\sqrt{v}} \right) \ln \frac{\xi+1}{\xi-1}, \quad 1 < \xi \ll r_B/\sigma. \quad (16)$$

Equation (16) goes over into the form (15) when their applicability intervals overlap.

The wave function along the line, connecting two Coulomb centers in Fig. 1, now can be written at  $|z^2 - \sigma^2|$ ,  $r^2 \ll \sigma^2$  in the form

$$\begin{aligned} \psi(r, z) &= 1 - \frac{r_B}{16Z\sigma} \left( 1 - \frac{E}{E_0} \right) \times \\ &\times \ln \frac{8\sigma^2}{z^2 - \sigma^2 + \sqrt{(z^2 - \sigma^2)^2 + 4\sigma^2 r^2}}, \end{aligned} \quad (17)$$

where  $E_0 = -m(2Ze^2)^2/(2\hbar^2)$ . Equation (17) is also valid in the vicinity ( $r^2 \ll (\sigma^2 - z^2)$ ) of the entire line ( $z^2 < \sigma^2$ ) between the centers, where

$$\psi(r, z) = 1 - \frac{r_B}{8Z\sigma} \left( 1 - \frac{E}{E_0} \right) \ln \frac{2\sqrt{\sigma^2 - z^2}}{r}. \quad (18)$$

At large distances, as follows from (13), (14) and the definition (1),

$$\psi(r, z) = R^{\sqrt{E/E_0}-1} \exp \left( -R \frac{2Z}{r_B} \sqrt{\frac{E}{E_0}} \right), \quad r_B \ll R, \quad (19)$$

where  $R^2 = r^2 + z^2$ .

The wave function of the electron in the Coulomb field of two positive point charges  $Ze$  exponentially decays at large distances (19). But on the line, connecting two charges,  $\psi$  has the logarithmic singularity (18) if the energy does not coincide with the eigenvalue  $E_0$ . The absence of singularities is a usual condition to determine an eigenvalue. The eigenvalue  $E_0$  coincides with one in the Cou-

lomb field of one point charge  $2Ze$ . In the limit considered,  $\sigma \ll r_B$ , corrections to that eigenvalue are small.

When the energy differs from  $E_0$  the singular wave function is not physical at the first sight. But the situation is more complicated as shown below.

### 2.3. Singularity

The electron wave function for the artificial case of two point charges and the wave function for two partner nuclei in a real molecule have common properties. This happens since at short distances (less than  $r_B$ ) atomic forces are not significant. In the real molecule close to a nucleus, that is below the shell of inner electrons, the wave function is of the type (17). The same is valid for the nucleus at a partner site. Between the partner sites the wave function is logarithmically singular, as (18), along the connecting line  $-\sigma < z < \sigma$ . In a real molecule  $\sigma \sim r_B$ . In a close vicinity ( $r \ll \sigma$ ) of the line, connecting two partner sites, the wave function, with the logarithmic accuracy, can be written in the form

$$\psi = \begin{cases} A(\sigma) \ln[\sqrt{(z-\sigma)^2 + r^2} + (z-\sigma)], & |z-\sigma| \ll \sigma, \\ 2A(z) \ln r, & \sqrt{\sigma^2 - z^2} \sim \sigma, \\ A(-\sigma) \ln[\sqrt{(z+\sigma)^2 + r^2} - (z+\sigma)], & |z+\sigma| \ll \sigma. \end{cases} \quad (20)$$

Here  $A(z)$  is the certain function accounting for real intramolecular forces. The exact form of this function is not crucial for our purposes.

The nature of the formal singularity along the line  $-\sigma < z < \sigma$  is easy to understand. At short distances to the line the first term in Eq. (5) dominates. To get it zero the wave function should be  $\psi \sim \ln r$ . To support this solution in the right-hand side of (5) the term  $\delta(\mathbf{r})$  (or a slightly smeared  $\delta$  function) should be. In reality such term is absent and the singular solution does not exist even formally.

### 3. Close to the singularity line

Under the interaction with the fluctuating fields of photons the electron “vibrates” and the singularity gets washed out. However this process does not convert the state into a physical one since the smeared distribution is a superposition of non-existing state. For this reason, let us formally consider the free electron on very short distances. As the second step, we will include fluctuating fields and average on them. On very short distances the fluctuating field is not electromagnetic one only.

#### 3.1. Scale of the electron Compton length

The Schrödinger description (5) is valid when the distance  $r$  to the singularity is larger than the electron Compton radius  $r_c = \hbar/mc \approx 3.86 \cdot 10^{-11}$  cm. At shorter distances one should use the Dirac formalism with the bispinor

$\psi = (\varphi, \chi)$  where  $\varphi$  and  $\chi$  are two spinors satisfying the equations for free electron

$$(\varepsilon + i\hbar c \vec{\sigma} \nabla) \varphi = mc^2 \chi, \quad (\varepsilon - i\hbar c \vec{\sigma} \nabla) \chi = mc^2 \varphi, \quad (21)$$

where  $\varepsilon$  is the total relativistic energy and  $\vec{\sigma}$  are Pauli matrices. Equations (21) follow from the Dirac Lagrangian [7]

$$L = i\hbar c \bar{\psi} \gamma^\mu \partial_\mu \psi - mc^2 \bar{\psi} \psi, \quad (22)$$

where  $\gamma^\mu$  are Dirac matrices,  $\bar{\psi} = \psi^* \gamma^0$  is the Dirac conjugate, and the partial derivatives are  $\partial_\mu = (\partial/\partial ct, \nabla)$ .

It follows from (21) that

$$(\varphi - \chi) = -\frac{i\hbar c}{\varepsilon + mc^2} \vec{\sigma} \nabla (\varphi + \chi). \quad (23)$$

To be specific, one can choose the spinor  $(\varphi + \chi)$  in the form

$$(\varphi + \chi) = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 1 \end{pmatrix} F, \quad (24)$$

where  $F$  satisfies the equation

$$\left( -\nabla^2 + \frac{mc^2}{\hbar^2} \right) F = \frac{\varepsilon^2}{\hbar^2 c^2} F. \quad (25)$$

We accounted for the relation  $(\vec{\sigma} \nabla)(\vec{\sigma} \nabla) = \nabla^2$ . When the wave function does not depend on  $z$ , the solution of (25) is the Neumann function [16]

$$F(\mathbf{r}) = CN_0 \left( \frac{r}{\hbar c} \sqrt{\varepsilon^2 - m^2 c^4} \right) \quad (26)$$

with the asymptotics  $N_0(z) \approx (2/\pi) \ln z$  at small argument. The electron density [7]

$$n = \frac{1}{2} |\varphi + \chi|^2 + \frac{1}{2} |\varphi - \chi|^2 \quad (27)$$

takes the form

$$n = \frac{1}{2} |F|^2 + \frac{\hbar^2 c^2}{2(\varepsilon + mc^2)^2} |\nabla F|^2. \quad (28)$$

The second term in (28) is principal one at  $r_c < r$  where the non-relativistic quantum mechanics is applicable and  $n \sim (\ln r)^2$ . The second term in (28) dominates at short distance  $r < r_c$  (relativistic region) where  $n \sim 1/r^2$ .

We see again that the singular solution  $F \sim \ln r$  of Eq. (25) is not supported by a singularity source. This solution requires the  $\delta$  function term in (25) that does not exist. For this reason, one has to analyze shorter distances, compared to  $r_c$ , from the linear singularity.

### 3.2. Scale of the electron mass generation

Below we analyze what happens to the singularity on much shorter distances compared to the electron Compton length  $r_c$ .

According to the Standard Model, masses of electron, other leptons,  $W^\pm$  and  $Z$  weak bosons, and quarks are generated by the Higgs field [17–19]. Electron acquires its mass through the connection between the fermion field  $\psi$  and the Higgs field  $\phi$ . In our case of singularity we are restricted by the contribution from electrons to fermionic fields. The mass in Dirac equations (21) is generated by the expectation value of the Higgs field,  $mc^2 = G\langle\phi\rangle$ , where  $G \sim m/\mu \sim 10^{-5}$  and  $\mu \sim 100 \text{ GeV}/c^2$  is the mass of the Higgs boson.

As the first step, we consider the problem without fluctuating field of vector bosons  $W^\pm, Z, A$  ( $A$  relates to photons) and the fluctuating part of the Higgs field. They can be included, as the second step, as given functions of space-time with the subsequent average on them.

The electron field  $\psi$ , in turn, influences the Higgs field  $\phi$ . Since  $\psi$  varies in space due to the singularity, the expectation value  $\langle\phi\rangle$  also acquires a singular correction proportional to  $G$  [20]. Accordingly the electron mass becomes variable in space. The Eq. (25) is modified

$$\left(-\nabla^2 + \frac{\nabla mc^2}{\varepsilon + mc^2} \nabla + \frac{mc^2}{\hbar^2}\right) F = \frac{\varepsilon^2}{\hbar^2 c^2} F. \quad (29)$$

As follows from [20], the small mass correction is

$$\frac{\delta m(r)}{m} \sim G^2 \begin{cases} R_c^2/r^2, & R_c < r, \\ (\ln R_c/r)^2, & r < R_c, \end{cases} \quad (30)$$

where  $R_c = \hbar/\mu c \sim 10^{-16} \text{ cm}$  is the Compton length of the Higgs boson.

The solution  $F = \ln r$  of the equation  $\nabla^2 F = 0$  does not exist even formally since it should be supported in the right-hand side by  $\delta(\mathbf{r})$ . This term plays a role of singularity source. In our case the  $\nabla m$  term in Eq. (29), proportional to  $(\partial F/\partial r)/r$ , is also singular as  $\nabla^2 F$ . Therefore the  $\nabla m$  term in Eq. (29), localized at  $r \lesssim R_c$ , is the singularity source. The both terms,  $\nabla^2 F$  and  $(\nabla m)(\nabla F)$ , form the singular solution of (29) as a sum of powers of  $\ln R_c/r$ . Now a  $\delta(\mathbf{r})$  in the right-hand side is not required to obtain that formally singular solution.

This situation recalls Bessel functions. The equation for singular  $K_0(r)$  formally requires  $\delta(\mathbf{r})$  (a point “charge”) in the right-hand side but the equation for singular  $K_p(r)$ , with a small  $p$ , does not.

### 4. Smearing of the singularity

The solution, obtained in Sec. 2, for free electron remains singular until fluctuations of gauge fields  $W^\pm, Z, A$  and of the Higgs field enter the game. These fluctuations

wash out the singularity around the line. The main contribution to this effect comes from the massless photon field  $A$ . Fluctuations of gauge bosons and the Higgs field result in a weaker smearing due to their large masses. Therefore, studying the singularity smearing, one can account for solely spatial electron fluctuations produced by its interaction with photons.

With electromagnetic fluctuations the electron “vibrates” within the certain region of the size  $r_T$ . The mean displacement  $\langle\mathbf{u}\rangle = 0$  but the mean squared displacement  $\langle u^2 \rangle = r_T^2$ . As follows from [8–11],

$$r_T = r_c \sqrt{\frac{2e^2}{\pi\hbar c} \ln \frac{\hbar c}{e^2}} \approx 0.82 \cdot 10^{-11} \text{ cm}. \quad (31)$$

The same effect of electron “vibrations” leads to the Lamb shift of discrete energy levels since the smeared electron probes various parts of a potential well [7].

#### 4.1. Smooth peak of the electron density

Under the action of electromagnetic fluctuations the singular electron density  $n \sim 1/r^2$  (28) is washed out within the thread, along the  $z$  axis, of the radius  $r_T$ . Without the  $\nabla m$  term in (29) it would be  $\nabla^2 F \sim \delta(\mathbf{r})$ . After the average the  $\delta$  function becomes smeared over the region  $r \sim r_T$  resulting in the nonexisting term extended in space. With  $\nabla m$  term in (29) the kinetic part  $\nabla^2 F \sim G^2/r^2$  exists at any  $r \rightarrow 0$  and after the average it goes over into the smooth part that is physical.

Note that solely electron-photon interaction is not sufficient for formation of the thread state. That interaction shifts the singularity position  $\delta(\mathbf{r} - \mathbf{u})$  only. After the average on  $\mathbf{u}$  this still results in the non-existing term. The relation  $\nabla^2 F \sim G^2/r^2$  at small  $r$  comes from the mass generation mechanism.

The singularity of  $F(r)$  is distributed roughly as  $\langle F(|\mathbf{r} - \mathbf{u}|) \rangle$  and the kinetic part of (29) is approximately estimated as

$$-\frac{\hbar^2}{2m} \nabla^2 \langle F(|\mathbf{r} - \mathbf{u}|) \rangle \sim \frac{\hbar^2}{mr_T^2} F(r \sim r_T). \quad (32)$$

This part is localized at  $r \lesssim r_T$  and corresponds to the local energy increase that should be compensated by some counter-part. This part in the electron–photon system comes from a local reduction of the electromagnetic zero point energy  $\sum \hbar\omega/2$ . This occurs due to a local reduction of photon density of states and can be called anomalous well. The uncertainty of the electron momentum  $\hbar/r_T$  at the region  $r \lesssim r_T$  is caused by the momentum transfer from photons. The characteristic momentum of photons  $\hbar/r_T$  relates to the reduction  $\hbar c/r_T \sim 1 \text{ MeV}$  of their zero point energy. This recalls the known example of creation of a well by spatial variations of the vacuum energy in the Casimir effect. In this case the zero point photon energy

also becomes variable due to a spatial variation of the photon density of states [7,12,13].

The singularity along the line at  $-\sigma < z < \sigma$  turns to the subatomically narrow thread of the radius  $r_T$ . Within this thread the enhanced electron energy  $(m^2c^4 + \hbar^2c^2/r_T^2)^{1/2} \approx \hbar c/r_T \sim 1$  MeV coexists with the energy reduction  $\hbar c/r_T$  responsible for anomalous well.

States in the well are exact, their continuous spectrum is non-decaying, that is with zero imaginary part of energy. The continuous non-decaying spectrum of a particle (connected to a medium) in a well is not forbidden in nature. Such spectrum is revealed in Ref. 21 on the basis of the exact solution.

### 5. Thread bonds

The exact state, where the thread is formed, is steady and is characterized by the certain total energy which is conserved. In terms of multidimensional quantum mechanics, where photon degrees of freedom are the infinite set of oscillators [7], it would be an energy eigenvalue. The state, considered either far from the thread or inside it, corresponds to the same energy. The thread state with the chemical energy scale of the electron  $E \sim (1-10)$  eV corresponds to upper energy states in the deep potential well of the order of 1 MeV and of the radius  $r_T$ . This well is extended along the thread.

At distances  $r_T < r$  radiative effects are small and one can use the quantum mechanical description of the electron. At  $r_c < r$  this is the Schrödinger formalism but at  $r_T < r < r_c$  one should apply Dirac equations. In this case, besides the term  $\ln r$ , the wave function also contains the large term  $r_c/r$ . At  $r < r_T$  the electron-photon interaction is essential and a quantum mechanical description is not valid. The total number of electrons is determined by the region  $r \sim r_B$  outside the thread as in a covalent bond. The fraction of electrons in the region  $r < r_c$  is small as  $r_c^2/r_B^2 \sim (e^2/\hbar c)^3$ .

We emphasize that the interpretation in terms of the potential well is approximate since this is not a single particle quantum mechanics but coupling to the electromagnetic system. The well is adjusted to an electron state. In a molecular system or in a solid the thread bond is shown in Fig. 2.

The thread state can be destroyed by quanta absorption. The high energy parts, involved into thread formation, correspond to the typical time  $10^{-22}$  s. Optical processes are slow compared to that time. They lead to an adiabatic motion of the thread parameters but the absorption probability of such quanta is exponentially small [15]. The thread exists until a high energy particle or  $\gamma$ -quantum destroys it.

The thread bond cannot be created in chemical or optical processes. A different type of impact is necessary for that. The direct way to form the thread state from the usual covalent one is to use an external perturbation when the matrix element between those states is not small. Such

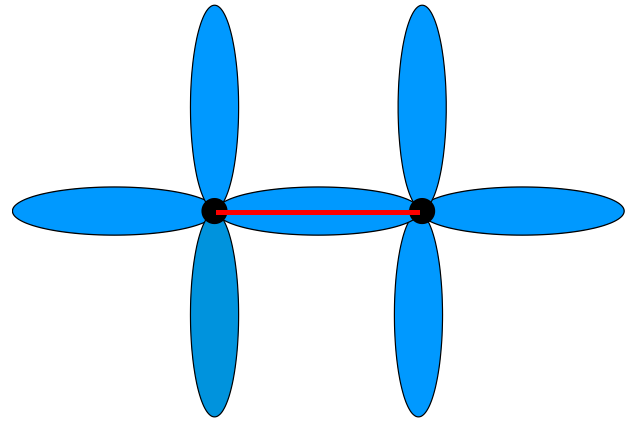


Fig. 2. Schematic representation of molecular covalent bonds. The thread bond between two nuclei is shown by the line.

perturbation may be the certain charge density varying in space on the range of  $r_T$ . This charge distribution may be created, for example, by an incident charge particle which is reflected by lattice sites in a solid. The resulting density, related to such particle, is due to the interference of its incident and reflected waves. This static charge density is approximately proportional to  $\cos(2R\sqrt{2ME_p}/\hbar)$  where  $M$  is the particle mass and  $E_p$  is its energy. If to use deuterons,  $M \approx 3.35 \cdot 10^{-24}$  g, one can estimate

$$\text{charge density} \sim \cos \left[ 1.96 \frac{R}{r_T} \sqrt{E_p (\text{keV})} \right], \quad (33)$$

where  $r_T$  is taken to be  $10^{-11}$  cm.

We see that one can bombard a sample by ions with the energy of approximately 1 keV to produce anomalous electron binding within the depth of ions penetration.

The energy gain, of the order of 1 MeV, is due to deeply localized electron(s) in the anomalous well. The length of the thread can be flexible to reduce that MeV scale energy. The energy pay, caused by the associated violation in covalent bonds, is of the eV scale and does not play a role in this process. The optimal length of the thread is a matter of a further study.

A form of the outer electron cloud, associated with the thread, is determined by chemical mechanisms of interaction with surrounding electrons. The electron density is mainly localized outside the thread on the usual distance as in a covalent bond.

An unusual role of thread bonds can be in a DNA molecule sketched in Fig. 3. When two DNA strands are connected by thread bonds the latter cannot be destroyed in chemical processes. Otherwise it would cost a MeV energy. Therefore the DNA replication is stopped when the replication fork approaches locations of the thread bonds. This prevents cell duplication and therefore the biological

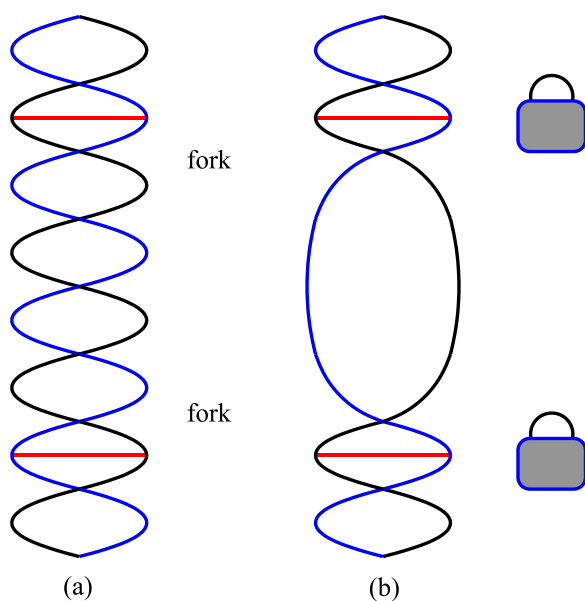


Fig. 3. Thread bonds of the length of nanometer in DNA molecule. (a) Thread bonds connect two DNA strands. (b) The DNA replication process is stopped when replication forks approach the threads. This prevents cell duplication and therefore the biological growth.

growth. Thread bonds can be created by weak shock waves deep inside a biological system to be prevented in the growth.

## 6. Discussions

It looks unusual when energies, involved into molecular binding, are of the order of 1 MeV and the spatial scale is essentially subatomic that is  $10^{-3}$  of the size of hydrogen atom. At the first sight, it is unlikely since chemical bonding is associated with the atomic processes. Nevertheless in chemical and biological systems thread bonds with such extreme parameters are possible.

There are examples of application of quantum electrodynamics in chemistry. The most known one is van der Waals forces when quantum electrodynamics is involved. In that case the certain steady attraction potential between atoms is formed due to a reduction of the energy of electromagnetic zero point oscillations. In formation of threads quantum electrodynamics is unavoidable but not the only element. Solely electron-photon interaction is not sufficient for formation of electron threads since the key point is distances much shorter than the electron Compton radius  $10^{-11}$  cm. Those short distances,  $10^{-16}$  cm, relate to the formation of electron mass (the Higgs mechanism).

On can list the main issues leading to thread states. (i) The wave function of a free electron can be singular on a line. In this case the kinetic energy  $-\hbar^2\nabla^2/2m$  is also singular on that line. This singularity does not exist in reality since it is not supported by a singular source. (ii) According

to the Standard Model (with formally neglecting fluctuating fields), the singularity in space of the electron density results in a singularity of the expectation value of the Higgs field. The latter provides the singularity source. (iii) Subsequent accounting for the fluctuating fields leads to smoothing of the singularity and the state becomes physical.

The length of the thread bond coincides with the distance between neighbor sites in the molecular or solid system. In biological systems it can be of the order of nanometers corresponding to the field of mesoscopic biology. In DNA molecules threads block replication process since the replication fork cannot extend beyond positions of thread bonds. Otherwise the threads have to be destroyed that costs MeV energy.

Electron threads can be formed in solids. In experiments [22] x-ray laser bursts were generated during 20 hours from a “dead” metal that is after switching off the irradiation of it by keV ions. As shown in [11] on the basis of threads formation, this paradoxical phenomenon is possible.

The recent observations of anomalous oscillations of magnetoresistance in superconductors [23] provide another mysterious phenomenon. The paradoxical universality of the periodicity (in particular, material independence) can be explained solely by a subatomic mechanism. The proposed thread states [24] provide an excellent quantitative agreement with the experiments [23].

## 7. Conclusions

Unusual chemical bonds are proposed. Each bond is characterized by the thread of a small radius,  $10^{-11}$  cm, extended between two nuclei in a molecule. An analogue of a potential well, of the depth of MeV scale, is formed within the thread. This occurs due to the local reduction of zero point electromagnetic energy. This is similar to formation of the Casimir well. The electron-photon interaction only is not sufficient for formation of thread state. The mechanism of electron mass generation is involved in the close vicinity,  $10^{-16}$  cm, of the thread. Thread bonds are stable and cannot be created or destructed in chemical or optical processes.

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