Rydberg polarons as a support for TGD view about space-time

M. Pitkänen
Email: matpitka6@gmail.com.
http://tgdtheory.com/.

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Abstract

I learned about very weird looking phenomenon involving Bose-Einstein condensate (BEC) of strontium atoms at ultralow temperature corresponding to $T = 1.5 \times 10^{-7}$ K and thus thermal energy of order 10^{-11} eV. Experimenters create Rydberg atoms by applying a laser beam to BEC of strontium atoms: second valence electron of Sr is kicked to at an orbital with very large classical radius characterized by the principal quantum number n. This leads to a formation of "molecules" of BEC atoms inside the orbit of Rydberg electron - Rydberg polarons as they are called.

The phenomenon is an excellent challenge for TGD, and in this article I will construct a TGD inspired model for it. The model relies on the notion of many-sheeted space-time distinguishing between Maxwellian electrodynamics and TGD. The model assumes a pair of magnetic flux tubes between electrons of opposite spin associated with the Rydberg atom. The flux tubes are parallel space-time sheets in $M^4 \times CP_2$ (same M^4 projection) and are not distinguishable at QFT limit of TGD. They carry monopole fluxes with opposite directions and present in the region between spins, where the sum of the dipole fields vanishes in Maxwellian theory. The members of s^2 electron pairs of BEC atoms are assumed to topologically condense at different parallel flux tubes of the pair minimizing ground state energy in this manner.

The model makes predictions surprisingly similar to the model of experimenters based on Born-Oppenheimer potential but there are also differences. An interesting possibility that if the generation of Rydberg involves time reversal as zero energy ontology (ZEO) suggests then the energy spectrum involved can be positive rather than consisting of bound states. Also a possible interpretation for the "endogenous" magnetic fields central in TGD inspired biology emerges.

Contents

1 Introduction

I learned about very weird looking phenomenon (see popular article at http://tinyurl.com/y96p48u5) involving Bose-Einstein condensate (BEC) of strontium atoms at ultralow temperature corresponding to $T = 1.5\times10^{-7}$ K and thus thermal energy of order 10^{-11} eV. Experimenters create Rydberg atoms by applying a laser beam to BEC of strontium atoms: second valence electron of Sr is kicked to at an orbital with very large classical radius characterized by the principal quantum number n. This leads to a formation of "molecules" of BEC atoms inside the orbit of Rydberg electron - Rydberg polarons as they are called. The term polaron comes from charge separation in the scale of polaron.

It seems strange that a tiny electron would be able to confine BEC molecules inside its orbit. The Rydberg polaron has several counter intuitive properties distinguishing it from ordinary polarons. Skeptic can also ask whether the formation of Rydberg atoms only makes the detection of BEC molecules possible when the atom to become Rydberg atom belongs to an already existing BEC molecule.

1.1 Experimental findings

From the research article [D1] (see http://tinyurl.com/ybqb7bmv) one learns that the experimenters use in a very clever manner the information about low energy scattering of Rydberg atoms in s and p partial waves to deduce so called Born-Oppenheimer potential (BOP). BOP is analogous to that used in molecular physics to deduce electronic states assuming molecular positions fixed. Now however Rydberg state for electron is fixed and one solves the states of BEC in this potential! The idea is that BEC behaves as a single particle. The objection to this is is that the states are reported to be more like molecules of some BEC molecules containing also the Rydberg atom.

BOP is a combination of $|\Psi_R|^2$ and $|\nabla\Psi_R|^2$ with coefficients proportional to s- and p-wave scattering lengths A_s and A_p (which is momentum dependent) deduced from the low energy scattering of Rydberg atoms from BEC. The explicit expression for the BOP is given as

$$V(r) = \frac{2\pi\hbar^2}{m_e}\left[A_s|\Psi_R|^2 + 3A_p|\nabla\Psi_R|^2\right] \quad . \tag{1.1}$$

Here $\Psi(r)$ is the wave function of Rydberg electron. By using rather advanced methods (functional determinant approach (FDA) and mean field theory) the experimenters estimate the bound state energies of BEC atoms in BOP numerically. The bound states would be localized states associated with the minima of the BOP having oscillatory behavior.

The claim is that the experimental findings provide support the existence of these bound states. Usually polarons involve positive energy excitations of the surrounding medium - "cloud" - but now it would be negative energy excitations - bound states - that would be excited. The excitation means that energy is drawn from BEC by dropping some particle to negative energy state: this would be an analog of metabolism.

One can test this proposal experimentally by using two laser beams with frequencies 689 nm and 319 nm. The first beam generates intermediate excitations $5s^2 \rightarrow 5s5p^3P_1$ and latter beam the Rydberg excitations $5s5p^3P_1 \rightarrow 5snp^3S_1$. The frequency of 319 nm beam must be varied to cover the excitations corresponding to various values of n. Since the dependence of the bound states energy is of form $1/n^2$, a rather slight variation is enough to cover a wide range of values of n. One obtains peaks corresponding to various values of n.

The peaks labelled by n have however sub-structure. One can vary the beam frequency slightly downwards from the frequency $\nu_R(n)$, which generates free Rydberg atom. For given n one finds spectral peaks at lower frequencies $\nu = \nu_R(n) - \Delta\nu$. The data is expressed in terms of function $A(\nu)$ telling the intensity of the absorption of laser photons at given frequency ν, and one can estimate binding energies from the values of $\Delta E = h\Delta\nu$. For $n = 38$ $\Delta\nu$ is in the range $[1, 40]$ MHz so that the binding energies ΔE are in the range $[1, 40]\times.4\times10^{-8}$ eV. The peak gets narrower for larger values n scaling like $1/n^3$ suggesting that the values of $\Delta\nu$ scales like $1/n^3$.

Remark: This is true for the ordinary value of Planck constant. For non-standard value $h_{eff}/h = n$ of Planck constant the estimate for the binding energies $\Delta E = h_{eff}\Delta\nu$ would be scaled up. This would mean that also the beam energy is scaled up and this looks unrealistic.

Since the temperature is extremely low, large $h_{eff}/h = n$ is not needed for macroscopic quantum coherence. Indeed, the thermal wavelength $\sqrt{1/2m_eT}$ of electron giving an idea about the scale of spatial quantum coherence is at the temperature considered of order 100 μm.

Fig. 2 of the article (see `http://tinyurl.com/ybqb7bmv`) shows for $n = 38$ clearly the peaks at multiples of -5 MHz corresponding to $\Delta E = -2.1 \times 10^{-8}$ eV for the corresponding energy interpreted as binding energy rather than positive excitation energy in the initial state. The appearance of integer multiples suggests that harmonic oscillator excitations involving one or several oscillators are in question. What looks strange that the the spectrum of excitations has negative rather than positive energies. The finding is interpreted as a direct evidence for the existence of BEC molecules - Rydberg polarons predicted by the model based on scattering length data. For a small number of BEC atoms one can even study the molecules.

Remark: The analogy with harmonic oscillator spectrum leads to ask whether a genuine harmonic oscillator spectrum with positive excitation energies could be in question - say cyclotron energy spectrum for electrons in an external magnetic field B_R assignable to the pair of s-wave electrons of Rydberg atom and having therefore positive excitation energies. The interpretation would be in terms of the analog of metabolism analogy also now. The excited Rydberg atom would drop some BEC atoms to lower energy state and in this manner extract energy from BEC.

Authors report several features distinguishing the Rydberg polaron from ordinary polaron. Ordinary polaron corresponds to a ground state of a many-particle system but now one has multiple excitations from the ground state. Also the importance of bound states would distinguish Rydberg polaron from ordinary polarons. A universal behavior of the spectral line shape decreasing like $1/n^3$ as a function of principal quantum number characterizing the Rydberg electron suggests that quantum criticality. Also the narrowing of the spectral features with n is reported.

In the model of experimenters the binding energy spectrum depends on the value of the principal quantum number n since the positions of zeros of $V(r)$ depend on n. Since $V(r)$ is product of exponent function and polynomial of order $2n$, $dV(r)/dr$ has at most $2n-1$ real zeros and at most n minima. One expects that harmonic oscillator strength has different values for these zeros, which also depends on n. One obtains in harmonic oscillator approximation integer multiples of the basic energy depending on the minimum of $V(r)$.

On basis of the article, I am not able to tell whether the authors have any concrete model for what the assumed (effectively contact -) interaction between the Rydberg atoms and BEC atom is. What this interaction is and how it leads to a generation of bound states (not necessarily!) in the case of BEC atoms but not in the case of ordinary atoms, remains a mystery to me. The question whether TGD might provide some ideas about in this respect, served as the basic motivation for the following considerations. This led to a considerably more detailed understanding about how TGD differs from Maxwellian electrodynamics.

1.2 Could TGD say something interesting about Rydberg polarons?

The obvious question in TGD framework is whether this mysterious interaction giving rise to the BEC molecules (or whatever they are) could be understood using the notions of many-sheeted space-time, magnetic flux quanta, and possibly also the identification of dark matter as phases of ordinary matter with non-standard value of $h_{eff}/h = n$.

1.2.1 Some applications of TGD view about space-time

I have applied this general rule in various scales with inspiration coming from the fractality of TGD Universe.

1. Elementary particles correspond in TGD pairs of wormhole contacts connected by flux tubes at both space-time sheets involved. Hadrons involve color flux tube structures carrying most of the energy of the hadron [K1, K2, K3].

2. Atomic nuclei and their dark variants explaining "cold fusion" are nuclear strings [L1, L5]. Dark nuclear strings are also in central role in TGD inspired quantum biology [L8] and their states are in correspondence with DNA, RNA, tRNA, and amino-acids [L2].

3. In TGD based view about chemistry valence bonds correspond to flux tubes with non-standard value of $h_{eff}/h = n$ [L6]. In biology valence bonds are carriers of metabolic energy with n measuring the amount of metabolic energy and increasing along the row of the Periodic Table. The model conforms with empirical facts and explains why the molecules towards the right end of the rows of the Periodic Table are carriers of metabolic energy.

4. Superconductivity and superfluidity are natural applications [K11, K12]. Flux tubes would serve as correlates for the correlation of the members of Cooper pair. In high T_c superconductivity supra currents flow along the flux tubes [K5, K6].

5. In neuroscience and biology the quantum entangled networks of neurons and cells define the correlates of mental images at the level of brain and body and also the part of magnetic body outside biological body is in central role [L4, L9]. Gravitational and other interactions are mediated along flux tubes and here the notion of gravitational (electromagnetic, etc) Planck constant is very useful [K8, K4, K12]. The notion of gravitational Planck constant $h_{eff} = h_{gr}$ is assignable to the flux tubes mediating gravitational interaction and having very large value is involved also with TGD inspired quantum biology and neuroscience [K9, K10].

6. At the second end of the scale hierarchy there is a model for the formation of galaxies as knots of long flux tubes carrying dark energy and dark matter and having stars as sub-knots of these knots. Second example is nuclear physics and its dark variants.

1.2.2 What guidelines to follow?

The listed successful applications encourage to ask whether the TGD could provide a model for Rydberg polaron. There are several guidelines to follow.

1. The key question concerns the role of Rydberg atom. Does its formation lead to the generation of Rydberg molecules or are they already present in BEC. The mechanism for the formation of the Rydberg molecules depends crucially on the answer to this question. If Rydberg atom is necessary, the magnetic field induced by the formation of Rydberg atom could be crucial for understanding what happens. This would also force the intepretation about the role of bound states unless the arrow of geometric time changes temporarily in the process. If Rydberg atom is not necessary, then alternative options can be considered.

2. The notion of cyclotron BEC as a condensate of cyclotron states of charged bosons or Cooper pairs playing important role in TGD inspired biology is of special interest since it could explain the appearance of excitation energies as basic energy identifiable as cyclotron energy. The BECs of electron Cooper pairs and of biologically important ions or their Cooper pairs are central in TGD based of quantum biology and neuroscience. What is encouraging that the energies identified as bound state energies have scale assignable to cyclotron states in magnetic field which is roughly $3.3 \times B_E$, where $B_E \simeq .5$ Gauss is the nominal value of the magnetic field B_E of Earth.

   Remark: The strength of B_E varies in the range [.25, .65] Gauss and one cannot exclude the possibility that $B_{end} = .2$ Gauss corresponds to minimum value of B_E achieved at equator. In dipole approximation the strength at poles is two times higher.

3. One can of course argue that the introduction of an external magnetic field is unrealistic. I do not know whether this is the case: dark magnetic fields would not be observable using the detection methods of standard physics. On the other hand, the origin of B_{end} has remained a mystery. Could its flux tubes connect charged particles of opposite spin so that B_R and B_{end} would accompany essentially same physical phenomenon?

4. The analogy with metabolism suggests the possible relevance of zero energy ontology (ZEO) leading to the proposal of what I call remote metabolism involving temporary reversal of the arrow of time at some level of the hierarchy of space-time sheets labelled by preferred p-adic primes and values of n and making possible for the system to extract energy from environment in apparent contradiction with the second law.

In the recent case the problem is that one would expect that the energy of laser photon is shared between the Rydberg atom and other BEC atoms. Just the opposite happens. One might argue that this is not a problem since temperature is so low but I am not certain about this. There is also a second problem: if B_R is responsible for the cyclotron states, then the only sensible interpretation is that the arrow of geometric time is temporarily changed since before its cyclotron BEC providing the "metabolic energy" is not present.

In ZEO "big" state function reduction behind TGD inspired theory of consciousness means temporary reversal of arrow of time for the entire system [L7]. Conscious entity as a generalized Zeno effect in turn would correspond to a sequence of ZEO analogs of weak measurements and dying when the big reduction takes place.

What looks for the observed with standard arrow of time like extraction of metabolic energy from BEC would correspond to sharing it with BEC if the arrow of time changes temporarily. This might relate to the finding that the entanglement between electrons of Sr^+ ions lasts surprisingly long time - 15 seconds. Could this time correspond to the duration of the time reversed state.

5. A further possible guideline comes from the general vision replacing many-particle states with tensor networks [L3] having particles as nodes connected by magnetic flux tubes carrying magnetic flux (possibly monopole flux). The general rule is that if there is quantum correlation/entanglement, it has flux tube as a space-time correlate. The model for valence bond based on $h_{eff}/h = n$ hierarchy could help here although the fact that valence bonds are between atoms with opposite electro-negativities suggests that this is not a correct guide line to follow.One can however ask whether Cooper pair as spin singlet bonded by flux tube might replace the valence bond.

One can imagine several options.

1. The energy scale of the excitations is very low suggesting that magnetic interaction energies are in question. Since Sr atoms have vanishing nuclear magnetic moment, the magnetic field generated by the two s-wave electrons of the Rydberg atom could serve as candidate for this external magnetic field. In Maxwellian framework this option fails but in flux tube picture for the magnetic field created by the electrons the situation changes as already briefly described in the interoduction.

2. Could the formation of Rydberg molecules (or whatever they might be) be due to a formation of flux tube contacts between BEC atoms serving as analogs of valence bonds. An immediate objection is that in chemistry valence bond is between states of opposite electronegativity. Pairing might however occur by spin-spin interaction.

   Now Maxwellian expression for the magnetic spin-spin interaction energy varies in a range involving 9 orders of magnitude and for the average distance of order .1 μm it is several orders of magnitude too low. This means a loss of predictivity. One could imagine for instance a molecule of 3 BEC atoms ABC in which the distances between A and B and A and C would be different: this would give a non-trivial binding energy. Again Fermi statistics is a problem: it seem very difficult to avoid p-wave excitations of electrons.

   Flux tubes distinguish TGD microscopically from Maxwell's theory. Could flux tubes be generated between the s-wave electrons of different BEC atoms. Also now the net interaction energy tends to cancel by statistics constraints in Maxwellian approach. TGD based model of superconductivity suggests a solution of the problem: the two s-electrons are condensed at different flux tubes and the spin-spin interaction between them gives rise to binding energy or at least binds them to Cooper pair (strontium-titanate is super-conductor!).

3. TGD inspired quantum biology suggests the most promising approach found hitherto. An external magnetic field would be present: either the Earth's magnetic field B_E with nominal value of .5 Gauss (experimental arrangement might eliminate B_E) or its "endogenous" dark variant with a nominal valued $B_{end} = 2/5B_E = .2$ Gauss possibly characterized by $h_{eff}/h = n > 1$. Actually B_{end} has spectrum of strengths in TGD inspired quantum biology and explains bio-photons as ordinary photons resulting from dark photons in the transition $n > 1$.

The model of authors could be perhaps understood in terms of negative magnetic dipole interaction energy of electrons with this magnetic field. The two electrons in s^2 state would topologically condense at flux tubes with opposite magnetic fluxes and could have negative spin-spin interaction energy binding them to a Cooper pair. There is however a problem: the shape of the spectral peak depends on the principal quantum number n suggesting that the value of the magnetic field involved behaves like $B \propto 1/n^3$.

Skeptic of course argues that the introduction of external magnetic field is a desperate last attempt before giving up. The origin of B_{end} has however remained a mystery. Could it be that B_R and B_{end} are aspects of the same phenomenon? If so then also the $B \propto 1/n^3$ dependence could be understood.

4. An alternative model gives up the assumption that bound states are in question but allows temporarily time reversal. cyclotron excitations of the BEC condensate containing electrons of the BEC atoms still experiencing the Coulomb force would be in question. Magnetic field with strength $3.3 \times B_E \simeq 8B_{end}$ could explain the frequency spectrum quantitatively as cyclotron energy spectrum so that instead of bound states one would have positive energy states but the metabolic analogy would still apply.

1.2.3 Brief summary of TGD based model

TGD inspired model is based on a more detailed model for flux tubes.

1. The strength of the constant valued flux tube magnetic field B_R associated with the flux tube model of electron plays the role of the physical dipole as a region of constant magnetization associated with a real world dipole field. The flux tube carries a monopole flux made possible by CP_2 topology so that the Maxwellian counterpart does not exists for it. This view about dipole magnetic field is a signature of many-sheeted space-time.

2. One can model the quadrupole field B_R associated with two-sheeted closed flux tube connecting 5s and ns electrons of Rydberg atom. In Maxwellian theory B_R would vanish along the line between the dipoles but in TGD it has opposite directions at parallel (essentially same M^4 projection) space-time sheets so that it vanishes only at QFT limit. The members of BEC s^2 electron pairs topologically condense at separate flux tube sheets to minimize the magnetic interaction energy associated with their spins. This mechanism could also give rise to Cooper pairs. Negative energy spectrum could correspond to a generation of several electron pairs in energy minimum.

3. B_R gives rise to the analog harmonic oscillator potential with ground state energy defined by the interaction energy of spins with B_R. If B_R depends on the distance L between the s-wave electrons of the Rydberg atom in a universal manner $B_R \propto 1/L^{3/2}$, one can understand the universal $1/n^3$ dependence of the width of the observed peak.

   The distances associated with the maxima of $|\Psi|^2$ give sub-peaks defining preferred Larmor frequencies so that the structure of the peak gives a map of $|\Psi(r)|^2$. If Rydberg atom moves with respect to BEC, one must add the p-wave contribution just like one does in the model of authors and find maxima for this. The basic difference with respect to the BOP approach of experimenters is that one has maxima rather than minima.

4. ZEO allows also to consider the possibility that the arrow of time is temporily changed in the state function reduction creating the Rydberg atom: this interpretation would allow the excitation of cyclotron states with reversed arrow of time. For an observer living in standard direction of time the process would look like dropping cyclotron electrons to lower energy states to get surplus energy so that the laser photon energy need be so high. This would give harmonic oscillator spectrum for each electron pair behaving like Cooper pair. It should be easy to experimentally test for the correctness of the two proposals.

2 Rydberg polarons in many-sheeted space-time

The basic questions and ideas have been already discussed. In the following I will first consider the general problem of estimating spin-spin interaction energies for atoms: if s^2 pairs transforms to say Cooper pairs, one must be able to estimate the change in energy if one wants to make the model rigorous. To my surprise I found no reference to this problem in web and the simple estimate in the case of atomic electrons gives a logarithmically divergent answer. This motivates this piece of text although it turns out to be necessary for the model to be proposed.

2.1 Maxwellian and TGD pictures for the magnetic interaction energy

TGD suggests that the proper way to model the spin-spin interaction is to use the flux tube picture. Maxwellian approach provides a second approach and one might hope that it could give a reasonable approximation.

2.1.1 Maxwellian approach

QFT limit of TGD with flux tubes replaced with Maxwellian magnetic fields is expected to give a good approximation of electromagnetic interactions. Therefore it is realistic to start from a Maxwellian picture for the electromagnetic fields. If Maxwellian picture gives reasonable order of magnitude estimates one can hope that also the TGD view based on the notion of magnetic body (MB) does so.

1. The obvious idea is that the magnetic field in atom is created by the total electron current of electrons. In particular, valence electrons give to this kind of current via Maxwell's equations: $\nabla \times B = j_e/4\pi$. This would give connection between electron current and B analogous to that appearing in BOP where modulus squared for electron's Schrödinger amplitude and its gradient appear.

   This picture applies also Coulomb interaction: now the charge density of electrons would serve as the source of electric field via $\nabla \cdot E = \rho$.

2. The two electrons of Sr Rydberg atom create a magnetic field, call it B_R. Same applies to the valence electrons of s^2 state of BEC atom. In the first approximation the magnetic moment of the unexcited electron determines the magnetic field at large distances. Since the electron's wave functions depend on the radial coordinate only in s-wave, the current $\overline{j}_e$ due to the gradient of Ψ is radial for both electrons. One can reduce the the equation $\nabla \times \overline{B} = \overline{j}_e/4\pi$ to a Laplace equation by using $\overline{B} = \nabla \times \overline{A}$ and Coulomb gauge $\nabla \cdot \overline{A} = 0$. This gives $\nabla^2 \overline{A} = \overline{j}_e \equiv j\overline{r}/4\pi$.

   Besides this there is a contribution due to the spin of the electron and in the direction of spin projection for spin eigenstates. In the lowest order approximation the $n = 5$ electron looks like point-like magnetic dipole and generates dipole field. Same in principle applies also in the case of s^2 state of two electrons and also in case of electrons inside [Kr] shell (the electronic configuration of Sr is [Kr]s^2).

I do not know whether the above approach has been proposed earlier. In any case, it could be motivated by the following argument.

1. Also the electrons of BEC atom have spin-spin interaction and the first thing that comes into mind is to estimate its contribution to the energy by taking expectation value in the two fermion state defined by s-wave valence electrons. If the pair of s^2 electrons transforms a Cooper pair, one must be able to estimate the change in energy, in particular spin-spin interaction energy.

2. If found no mention about spin-spin interaction in web but found a popular article telling that the measurement of the spin-spin interaction energy is extremely difficult but was carried for a pair of Sr^+ ions (!) at distance of order 2 μm (see `http://tinyurl.com/yasjvufz`): this would partially explain why it has not been calculated. It was also found that the coherence time for entangled electron pair was unexpectedly long: 15 seconds.

In the popular article the calculation of the effect was mentioned to be very difficult. The repulsive interaction between fermions gives a competing contribution which - being expectation of $1/|r_1 - r_2|$ - is finite. As a matter of fact, I realized that the integral defining the expectation value of $1/|r_1 - r_2|^3$ appearing in the expectation value of spin-spin interaction energy in s-wave state in two fermion state diverges logarithmically!

The pragmatic way out of the difficulty would be straightforward: do not try to calculate anything giving an ill-defined answer! To gain more respectability for this view one could formulate the state of affairs as a general rule. One is allowed to estimate only the effects of external fields - say that of nucleus when calculating spin-orbit interaction energy or interactions between atoms - by using this approach. The external field depends in this case on the electron configuration involved so that one cannot regard spin-spin interaction as being due to an external magnetic field.

Atomistic skeptic can however argue that in Born-Oppenheimer approach assumes the configuration of atoms to be given and calculates electron states associated with this and then solves Schrödinger equation for the atoms. Also in the calculation of color-magnetic spin-spin splitting of mesons and baryons this approach is used. Therefore the problem is real and one must solve it.

The proposed approach could however allow to get rid of the divergence associated with spin-spin interaction since the magnetic field determined by the total current defined by electrons gives smoothed out magnetic field free of singularity associated with point-like magnetic dipole.

2.1.2 How flux tubes as mediators of magnetic spin-spin interaction would relate to the Maxwellian picture?

In TGD based approach flux tubes would mediate the magnetic interaction. For two different atoms electrons would be connected by flux tubes and the electrons at its end or possibly moving freely in the interior would interact with essentially 1-D magnetic flux. This picture could apply also to electrons inside single atom. Also Coulomb interaction energy could be estimated in the same manner between electrons of single atom. In the case of separate atoms one can argue that repulsive Coulomb interaction can be neglected in excellent approximation.

Remark: Strong form of holography (SH) implies that at least in the sense of information theory electrons at space-time level can be thought of as being localized at 2-D string world sheets - that is electron states are fixed by 2-D data. In this picture flux tubes are accompanied by fermionic strings with fermions at their ends assignable to the light-like orbits of partonic 2-surfaces at which the signature of the induced metric changes from Minkowskian to Euclidian. At the level of imbedding space $M^4 \times CP_2$ the spinors characterizing ground states of super-conformal representations are however 8-D and it is these spinors that correspond to those of standard model.

One must have rules for how to replace Maxwellian field with flux tubes.

1. Flux tubes carry a conserved magnetic flux. Therefore the magnetic field is essentially constant inside flux tube and the situation is effectively 1-dimensional. One can consider also the possibility that the magnetic flux is quantized. In TGD framework it is also possible to have closed flux tubes carrying monopole flux looking locally like pair of flux tubes with opposite fluxes: they could appear in super-conductors and in cosmology. No currents are needed to create these magnetic fields made possible by the topology of CP_2. The cross section of this kind of flux tube is closed 2-surface rather than a disk with holes. For these flux tube pairs Maxwellian limit does not exist.

2. Flux conservation implies that the spin-spin magnetic interaction energy for given flux tube does not depend on distance.

3. There is a distribution of magnetic flux tubes, which should correspond to the Maxwellian field. The intuitive picture is that the density dn/dS of flux tubes normal to given 2-surface having normal direction $\overline{n}$ multiplied by possibly quantized magnetic flux corresponds to the value of Maxwellian magnetic field:

$$\overline{B} \leftrightarrow \frac{dn}{dS}\Phi\overline{n} \ . \quad (2.1)$$

dn/dS would be determined by the wave function for 3-surfaces in the "world of classical worlds" (WCW). This picture would hold true at larger distances from the source - say dipole.

4. Flux tubes field could mimic Maxwellian field with a better accuracy if the flux tubes can branch at larger distances. This would look natural for dipole fields. The outcome be a kind of fractal tree like structure growing in the radial direction. This would involve reduction of the field strength and possible also the net flux which could be large in the vicinity of dipole but reduce later.

This picture generalizes to electric flux tubes/quanta carrying constant electric flux. By effective one-dimensionality the electric potential is proportional to distance along flux tube.

Interesting questions relate to the possibility of space-time sheets parallel in $M^4 \times CP_2$ and having same M^4 projection: at QFT limit they are replaced region of M^4 with deformed metric.

1. One can imagine that both valence electrons with opposite spins are accompanied magnetic flux tubes such that they correspond 4-surfaces on top of each other and extremely near to each other in $M^4 \times CP_2$ such that the magnetic fluxes are in opposite directions but of the same magnitude. At QFT limit the total magnetic field would vanish on test particle if it touches all parallel sheets and experiences the fields from all of them.

2. Consider a situation involving two magnetic flux tubes as different sheets associated with spins in opposite directions so that magnetic fluxes are opposite at them. One can imagine a deformation implying that space-time sheets at not at top of each other. Now the magnetic spin-spin interaction would be non-trivial in these regions and favor the formation of bound state spin singlet identifiable as Cooper pairs. Could energy minimization favor the formation of pairs of this kind of single-sheeted regions? For instance, the formation of groups of BEC atoms connected by flux tubes could involve this mechanism. In the situation when the flux tubes project to same region of M^4, bound states would not be possible.

2.1.3 What could happen when the Maxwellian approach fails?

To understand the flux tube picture and connect with with the Rydberg polaron, it helps to ponder what happens when the Maxwellian approach fails. For the magnetic dipole field the region near the locus of the dipole represents a situation, where Maxwellian description might indeed fail. One can take the TGD inspired model of electron itself as a starting point.

1. Electron (actually any elementary particle) would be a pair of wormhole contacts (I and II with throats I1,I2 and II1,II2) connecting two space-time sheets with electron at the throat I1 of contact I and left-handed neutrino ν_L at throat II1 and right-handed neutrino $\overline{\nu}_R$ at throat II2 of contact II. The flux tubes would carry monopole magnetic flux flowing also through the contacts and stabilizing it: otherwise the space-time sheets would only touch for some time.

   In scales shorter than the length L of the flux tubes electron would have also weak isospin. At longer scales electron would effectively have only em charge just as standard model predicts.

2. The flux tubes at given space-time sheet would be a correlate for the dipole assigned with dipole magnetic field and carry a constant flux. This corresponds to constant magnetization for a non-ideal dipole created by an inductance in circuit theory.

   Now no current is needed to create the constant magnetic field since monopole flux is in question and the cross section of flux tube is a closed 2-surface. The absence of the current corresponds to the fact that electron's magnetic moment is due to spin and is not created by a current. Monopole flux tube would however give a space-time correlate for the dipole created by spin.

   The strength of the magnetic field would be proportional to $1/S$, S the area of the flux tube projection in M^4. Magnetic dipole would be effectively a pair of magnetic charges (TGD does not however allow isolated magnetic charges) made possible by the topology of CP_2. For non-standard values of h_{eff} these dipoles could have even macroscopic sizes. Monopole fluxes could explain even the mysterious existence of long length scale magnetic fields in cosmological scales.

2.2 A model for Rydberg polaron

The proposd picture for spin dipoples allows to imagine a concrete model for the quadrupole type magnetic field created by a pair of s-wave electrons taken far apart as in the formation of Rydberg atom. This model applies also to Cooper pairs and perhaps even to s^2 pairs of electrons in atom.

1. What happens when one has two electrons identifiable as dipoles with opposite spins as in the case of Rydberg atom? Suppose that the spins are oriented along the connecting line. In the region between electrons the magnetic field vanishes in the Maxwellian world. In many-sheeted space-time it is enough that the magnetic fields have opposite direction but exist as induced magnetic fields at parallel space-time sheets. At QFT limit the field vanishes as sum of these fields.

   One could imagine the following model for the resulting magnetic field. The monopole flux tube pairs associated with electrons would reconnect to a single flux tube pair so that the wormhole throats carrying ν_L and $\overline{\nu}_R$ disappear and $\nu_L\overline{\nu}_R$ pairs at throats opposite to electron carrying throats to take care about the vanishing of weak isospin at longer length scales correlating with the massivation causing the short range of weak forces. The magnetic fields at the opposite throats of both wormhole contacts would have opposite values and at QFT limit the total magnetic field would vanish. This effect is not possible in Maxwellian electrodynamics.

2. The magnetic field would be constant at the flux tubes and equal to $eB = \Phi/S$, $\Phi = BS = n$. One can imagine a topological condensation of the BEC atoms at this flux tube pair. The s^2 electrons of BEC atom would condense at different flux tubes to minimize their magnetic interaction energies $E = -\mu_e \times B$, $\mu_e = e\hbar/2m_e$. Maybe this kind of process could produce the Rydberg polaron.

3. What would be the dependence of the surface area S of the flux tube on the distance L between the electrons? The naive guess that B has dependence $B \propto 1/L^3$ classically would give $S \propto L^3$. This does not make sense as detailed checks demonstrated.

   If I have interpreted correctly the findings about Rydberg atom, the spectral width as the width of absorption spectrum as function of frequency becomes narrower and scales down as $1/n^3$: the experimenters talk about universality. The $B \propto 1/n^3$ scaling of the magnetic interaction energies would explain this. If the magnetic interaction energies are responsible for the observed spectrum then the proportionality of the size scale of Rydberg atom to n^2 would require $S \propto L^{3/2} \propto n^3$. For $n = 38$ one has $\Delta f = -5$ MHz. This gives the rough estimate

   $$\frac{\mu_B \Phi}{S(n=38)} == \frac{\mu_B \Phi}{\pi R^2(n=5)}(\frac{5}{38})^3 = 2.1 \times 10^{-8} \ eV \ .$$

   This condition fixes the radius $R(n = 5)$ of the flux tube at distance $L(n = 5) \sim 6.3$ Angstrom to be $R \simeq 10^4 a_0 \simeq .5$ μm. More generally, the basic length scales of biology might be hidden to many-sheeted atomic physics.

4. One could hope that this dependence of S on the distance L between electrons of opposite spin with the line connecting the electrons serving as quantization axis is universal. Could this idea have some explanatory power?

   In TGD inspired quantum biology one encounters the notion of endogenous magnetic field $B_{end} = 2/5B_E$, which is roughly by factor $x = 1/7.5 \sim 2^{-3}$ weaker than $B(n = 38)$. As a matter of fact, B_{end} must have spectrum reflected directly in the spectrum of bio-photons in visible and UV [K9, K10] and in the spectrum of audible frequencies [K7]. The origin of this magnetic field has remained a mystery. Could it correspond to a magnetic field associated with a flux tube connecting electron dipoles with opposite directions at distance L_{end}?

   The proposed model would give the factor

   $$x = \frac{S(38)}{S} = (\frac{L(38)}{L_{end}})^{3/2}$$

allowing to estimate corresponding distance L_{end} between electrons as

$$L_{end} = x^{-2/3}L(38) = 4 \times L(38) = (\frac{38}{5})^2 L(5) \simeq 231L(5) \quad .$$

Assuming that Sr atom behaves for $n = 5$ state like hydrogen atom with effective nuclear charge $Z_{eff} = 2$ (screening would be due to [Kr] shell), one obtains a rough estimate for $L(5)$ would be $5^2 a_0/2 \simeq 6.3$ Angstrom. This would give $L_{end} \sim 1.5$ μm. It is encouraging that this corresponds to the p-adic length scale $L(169) \simeq 1.5$ μm assignable to cell nucleus size. Note that the p-adic length scale $L(167) = 2.5$ μm corresponds to Gaussian Mersenne $M_{G,n=167} = (1+i)^n - 1$.

The factor 2 would suggest that the B_{end} corresponds to Rydberg atom with $n = 2 \times 38 = 76$. This is only a rough estimate: the estimate for $L(5)$ assumes hydrogen-like atom and this assumes is only approximate since the s^2 electrons spend considerable time inside [Kr] shell which tends to reduce the radius $L(5)$. An interesting question concerns the identification of Rydberg atom(s) possibly responsible for the generation of B_{end}. The spectrum for $B_{end}(n)$ would be of form $1/n^3$. For given n there would br a spectrum along the n:th row of Periodic Table.

Spin-spin interaction energy at temperature of 1.5×10^{-11} eV would correspond to an energy which is by a factor 10^{-3} lower than that associated with $L(n = 38)$. This corresponds to the scaling $n \rightarrow 10n$ and $L(38) \rightarrow 100L(38)$.

5. In the realistic situation the Rydberg electron has wave function Ψ. $|\Psi|^2$ has several maxima and minima which correspond to zeros for a polynomial closely related to the square of Laguerre polynomial and having degree $2n$ so that the number of real maxima would be at most $n - 1$. One would have a quantum superposition of also flux tube pairs with different lengths L.

   The flux tube lengths L associated with the maxima would be visible as peaks in the absorption spectrum. One would have peaks at the corresponding Larmor frequencies (and possibly also cyclotron frequencies if temporary time reversal takes place). This picture includes only s wave scattering length and the reason would be that one indeed has pure s-wave electrons.

   The BOP of authors includes also a term proportional to p-wave scattering length: one must adds to Ψ a term proportional to the gradient of Ψ representing the change of the wave function due to the motion. When the Rydberg atom moves with respect to BEC, the wave function has also p-wave component and the scattering length A_p is indeed momentum dependent going to zero at the limit of vanishing momentum. If one can neglect the cross terms proportional to $p \cdot (\overline{\Psi}\nabla\Psi + c.c)$ one obtains the BOP. It therefore seems that TGD might be able to explain the basic properties of the Rydberg polaron.

To sum up, Rydberg polaron could provide a clearcut evidence for the notions of many-sheeted space-time, flux tube, and ZEO and also allow to assign "endogenous" magnetic fields to Rydberg atoms.

REFERENCES

Condensed Matter Physics

[D1] Camargo F et al. Creation of Rydberg Polarons in a Bose Gas. *Nature.* Available at: `https://arxiv.org/pdf/1706.03717.pdf`, 2018.

Cosmology and Astro-Physics

Books related to TGD

[K1] Pitkänen M. Massless states and particle massivation. In *p-Adic Physics*. Online book. Available at: http://www.tgdtheory.fi/tgdhtml/padphys.html#mless, 2006.

[K2] Pitkänen M. New Particle Physics Predicted by TGD: Part I. In *p-Adic Physics*. Online book. Available at: http://www.tgdtheory.fi/tgdhtml/padphys.html#mass4, 2006.

[K3] Pitkänen M. New Particle Physics Predicted by TGD: Part II. In *p-Adic Physics*. Online book. Available at: http://www.tgdtheory.fi/tgdhtml/padphys.html#mass5, 2006.

[K4] Pitkänen M. Quantum Astrophysics. In *Physics in Many-Sheeted Space-Time*. Online book. Available at: http://www.tgdtheory.fi/tgdhtml/tgdclass.html#qastro, 2006.

[K5] Pitkänen M. Quantum Model for Bio-Superconductivity: I. In *TGD and EEG*. Online book. Available at: http://www.tgdtheory.fi/tgdhtml/tgdeeg.html#biosupercondI, 2006.

[K6] Pitkänen M. Quantum Model for Bio-Superconductivity: II. In *TGD and EEG*. Online book. Available at: http://www.tgdtheory.fi/tgdhtml/tgdeeg.html#biosupercondII, 2006.

[K7] Pitkänen M. Quantum Model for Hearing. In *TGD and EEG*. Online book. Available at: http://www.tgdtheory.fi/tgdhtml/tgdeeg.html#hearing, 2006.

[K8] Pitkänen M. TGD and Astrophysics. In *Physics in Many-Sheeted Space-Time*. Online book. Available at: http://www.tgdtheory.fi/tgdhtml/tgdclass.html#astro, 2006.

[K9] Pitkänen M. Are dark photons behind biophotons? In *TGD based view about living matter and remote mental interactions*. Online book. Available at: http://www.tgdtheory.fi/tgdhtml/tgdlian.html#biophotonslian, 2013.

[K10] Pitkänen M. Comments on the recent experiments by the group of Michael Persinger. In *TGD based view about living matter and remote mental interactions*. Online book. Available at: http://www.tgdtheory.fi/tgdhtml/tgdlian.html#persconsc, 2013.

[K11] Pitkänen M. Criticality and dark matter. In *Hyper-finite Factors and Dark Matter Hierarchy*. Online book. Available at: http://www.tgdtheory.fi/tgdhtml/neuplanck.html#qcritdark, 2014.

[K12] Pitkänen M. Quantum gravity, dark matter, and prebiotic evolution. In *Genes and Memes*. Online book. Available at: http://www.tgdtheory.fi/tgdhtml/genememe.html#hgrprebio, 2014.

Articles about TGD

[L1] Pitkänen M. Cold Fusion Again . Available at: http://tgdtheory.fi/public_html/articles/cfagain.pdf, 2015.

[L2] Pitkänen M. About Physical Representations of Genetic Code in Terms of Dark Nuclear Strings. Available at: http://tgdtheory.fi/public_html/articles/genecodemodels.pdf, 2016.

[L3] Pitkänen M. Holography and Quantum Error Correcting Codes: TGD View. Available at: http://tgdtheory.fi/public_html/articles/tensornet.pdf, 2016.

[L4] Pitkänen M. Artificial Intelligence, Natural Intelligence, and TGD. Available at: http://tgdtheory.fi/public_html/articles/AITGD.pdf, 2017.

[L5] Pitkänen M. Cold fusion, low energy nuclear reactions, or dark nuclear synthesis? Available at: http://tgdtheory.fi/public_html/articles/krivit.pdf, 2017.

[L6] Pitkänen M. Does valence bond theory relate to the hierarchy of Planck constants? Available at: http://tgdtheory.fi/public_html/articles/valenceheff.pdf, 2017.

[L7] Pitkänen M. Re-examination of the basic notions of TGD inspired theory of consciousness. Available at: http://tgdtheory.fi/public_html/articles/conscrit.pdf, 2017.

[L8] Pitkänen M. About the Correspondence of Dark Nuclear Genetic Code and Ordinary Genetic Code. Available at: http://tgdtheory.fi/public_html/articles/codedarkcode.pdf, 2018.

[L9] Pitkänen M. Emotions as sensory percepts about the state of magnetic body? Available at: http://tgdtheory.fi/public_html/articles/emotions.pdf, 2018.