Artificial light and quantum order in systems of screened dipoles

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The origin of light is a unsolved mystery in nature. Recently, it was suggested that light may originate from a new kind of order - quantum order. To test this idea in experiments, we study systems of screened magnetic/electric dipoles in 2D and 3D lattices. We show that our models contain an artificial light – a photon-like collective excitation. We discuss how to design realistic devices that realize our models. We show that the “speed of light” and the “fine structure constant” of the artificial light can be tuned in our models. The properties of artificial atoms (bound states of pairs of artificial charges) are also discussed. The existence of artificial light (as well as artificial electron) in condensed matter systems suggests that elementary particles, such as light and electron, may not be elementary. They may be collective excitations of quantum order in our vacuum. Our models further suggest that a gauge theory is a string-net theory in disguise. Light is a fluctuation of string-nets and charges are the ends of open strings (or nodes of string-nets).

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I. INTRODUCTION

What is light? Where light comes from? Why light exists? Every one probably agrees that those are fundamental questions. But one may wonder if they are scientific questions, philosophical questions, or even religious question? Before answering those questions and the questions about the questions, we would like to ask three more questions: What is phonon? Where phonon comes from? Why phonon exists? [42] We know that those are scientific questions and we know their answers. Phonon is a vibration of a crystal. Phonon comes from a spontaneous translation symmetry breaking. Phonon exists because the translation-symmetry-breaking phase actually exists in nature.

It is quite interesting to see that our understanding of a gapless excitation - phonon - is rooted in our understanding of phases of matter. According to Landau’s theory,[1] phases of matter are different because they have different broken symmetries. The symmetry description of phases is very powerful. It allows us to classify all possible crystals. It also provide the origin for gapless phonons and many other gapless excitations.[2, 3]

However, light, as a U(1) gauge boson, cannot be a Nambu-Goldstone mode from a broken symmetry. Therefore, unlike phonon, light cannot originate from a symmetry breaking state. This may be the reason why we treat light differently than phonon. We regard light as an elementary particle and phonon as a collective mode.

However, if we believe in the equality between phonon and light and if we believe that light is also a collective mode of a particular “order” in our vacuum, then the very existence of light implies a new kind of order in our vacuum. Thus, to understand the origin of light, we need to deepen and expand our understanding of phases of matter. We need to discover a new kind of order that can produce and protect light.

After the discovery of fractional quantum Hall (FQH) effect,[4, 5] it became clear that the Landau’s symmetry breaking theory cannot describe different FQH states, since those states all have the same symmetry. It was proposed that FQH states contain a new kind of order - topological order.[6] The concept of topological order was recently generalized to quantum order[7, 8] that is used to describe new kind of orders in gapless quantum states. In particular, we used quantum order and its projective symmetry group (PSG) description to classify over one hundred different spin liquids that have the same symmetry.[7] Intuitively, we can view quantum/topological order as a description of pattern of quantum entanglements in a quantum state.[8] The pattern of quantum entanglements, being described by complex wave function, is much richer than pattern of classical configurations.

We know that the fluctuations of pattern of classical configurations (such as lattices) lead to low energy collective excitations (such as phonons). Similarly, the fluctuations of pattern of quantum entanglement also lead to low energy collective excitations. However, collective excitations from quantum entanglement can be gapless gauge bosons[9–17] and/or gapless fermions. The fermions can even appear from pure bosonic models on lattice.[7, 13–15, 18–20]

If we believe in quantum order, then the three questions about light will be scientific questions. Their answer will be (A) light is a fluctuation of quantum entanglement, (B) light comes from the quantum order in our vacuum and (C) light exists because our vacuum contains a particular entanglement (ie a quantum order) that supports U(1) gauge fluctuations.

According to the picture of quantum order, elementary particles (such as photon and electron) may not be elementary after all. They may be collective excitations of a bosonic system. Without experiments at Planck scale, it is hard to prove or disprove if photon and electron are elementary particles or not. However, one can make a point by showing that photon and electron can exist as collective excitations in certain lattice bosonic models. So photon and electron do not have to be elementary.

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1+3D excitations, artificial light and artificial electron. It was stressed that the gapless properties of those collective excitations are protected by the quantum order in the spin ground state.[7, 13, 21] Recently, a simpler and more realistic 3D interacting boson model was found to contain an artificial light (but not massless fermions).[17] Exact solvable models and realistic Josephson junction arrays that realize 1+2D $Z_2$ gauge excitations and related topological order[14] can be found in Ref. [19, 20, 22–25]. We see that gauge bosons appear naturally and commonly in quantum ordered states. We do not need to introduce them by hand as elementary particles.

Motivated by lattice gauge theory[26] and projection by energy gap introduced in Ref. [27, 28], in this paper, we will construct realistic 2D and 3D spin models with screened dipole interaction. Our models contain an artificial light as their low energy excitation. Concrete devices that realize our models are also designed. Building those devices and observing artificial light in those devices will show for the first time that elementary particle, such as light, can be created artificially with designed properties (such as designed “speed of light” and designed value of “fine structure constant”).

Through our models, we also find that a $U(1)$ gauge theory is actually a dynamical theory of nets of closed strings.[26] The latter will be called the string-net theory whose definition will be given in section 2. In other words, gauge theory and string-net theory are dual to each other. This duality is directly connected to the duality between statistical $U(1)$ lattice gauge models and statistical membrane models.[29–31] According to the string-net picture, a gapless gauge boson is a fluctuation of large string-nets and charge is the end of open strings.

In the next few sections, we will discuss in detail 2D and 3D spin models and derive their low energy effective theory. For persons who are interested experimental realization of the spin models and experimental probe of artificial light, they can go directly to section X and XI.

II. A 2D MODEL

To construct a realistic model that contains artificial light as its low energy collective excitation, we consider systems formed by integral spins. We will consider two cases. In the first case the spins $S$ carry magnetic dipole moment $m \propto S$. In the second case, we want the spins to carry electric dipole moment $d \propto S$. However, due to the time reversal symmetry in real molecules, it is impossible for a molecules with a finite spin to carry an electric dipole moment proportional to the spin. But it is possible to have a molecule whose ground states are formed by two spin $S$ multiples: $|m, \sigma^z\rangle$, with $m = S,..., -S$ and $\sigma^z = \pm 1$. We will call $\sigma^z$ the $z$-component of isospin. Such a molecule can be viewed as carrying spin-$S$ and isospin-$1/2$. This kind of molecules can carry a finite electric dipole moment $d \propto \sigma^z S$ and have a time reversal symmetry, since under time reversal $(\sigma^z, S) \rightarrow (-\sigma^z, -S)$. We will use the above magnetic dipoles $m \propto S$ or electric dipoles $d \propto \sigma^z S$ to build our systems.

We start with a honeycomb lattice which will be called
the H-lattice. To form a magnetic dipole system, we place an integral spin-$S$ on every link of the H-lattice. For an electric dipole system, we place an integral spin-$S$ and an isospin-1/2 on every link. We note that the spins form a Kagome lattice which will be called the K-lattice. There are two ways to label a spin. We can use a site index $I$ of the K-lattice or we can use a pair of site indices $(ij)$ that labels a link in the H-lattice (see Fig. 1). Using these two labels, our model Hamiltonian can be written as

$$H = U \sum_i \left( \sum_\alpha \sigma^\alpha_{(i,i+\alpha)} S^\alpha_{(i,i+\alpha)} \right)^2 + J \sum_I (s^z_I)^2$$

$$- \frac{1}{S^2} \sum_{(IJ)} \sigma^x_I \sigma^x_J \left( t S^+_I S^-_J + t' S^+_I S^-_J e^{i2\phi_{IJ}} + h.c. \right)$$

(1)

Here $\alpha$ is one of the three vectors that connect a H-lattice site $i$ to its three nearest neighbors. The $U$-term enforces a constraint that the total $S^z$ of the three spins around a site in the H-lattice is zero. Also $\phi_{IJ}$ is the angle of the link $IJ$ in the $xy$-plane and $S^\pm = S^x \pm iS^y$. The summation $\sum_{(IJ)}$ is over all nearest-neighbors in the K-lattice. The above Hamiltonian applies to both magnetic dipole systems and electric dipole systems. For magnetic dipole systems, we regard $\sigma^z$ as a number $\sigma^z = 1$. For electric dipole systems, we regard $\sigma^z$ as the $z$-component of the Pauli matrices.

For the time being, we will treat $\sigma^x$ classically and assume each $\sigma^x_i$ to take a fixed but a random value of +1 or -1. (For magnetic dipole systems, we will set all $\sigma^x_i = 1$.) Let us first assume $J = t = t' = 0$ and $U > 0$. In this case the Hamiltonian is formed by commuting terms which perform local projections. The ground states are highly degenerate and form a projected space. One of the ground states is the state with $\sigma^x_i S^z_j = 0$ for every spin. Other ground states can be constructed from the first ground state by drawing a loop in the H-lattice and then alternatively increase or decrease the $\sigma^x_i S^z_j$ for the spins on the loop by the same amount. Such a process can be repeated to construct all the degenerate ground states. We see that the projected space has some non-local characters despite that it is obtained via a local projection.

Let us introduce string operator which is formed by the product of $S^z_{(ij)}$ operators

$$U(C) = \prod_{(ij)} S^z_{(ij)}$$

(2)

where $C$ is a string connecting nearest-neighbor sites in the H-lattice and the product $\prod_{(ij)}$ is over all the nearest-neighbor links of the H-lattice that form the string. $n_{(ij)} = +1$ if the arrow of the link $(ij)$ points from $i$ to $j$ and $n_{(ij)} = -1$ if the arrow of the link $(ij)$ points from $j$ to $i$. We note that the string operator alternatively increase or decrease the $\sigma^x_i S^z_j$ along the string. If all $\sigma^x_{ij} = 1$, the string operator has the following simple form

$$U(C) = S^+_{(i_1 i_2)} S^-_{(i_2 i_3)} S^+_{(i_3 i_4)} ...$$

(3)

where the string $C$ is formed by the H-lattice sites $i_1, i_2, ...$. Using the string operator, we can create all the degenerate ground states by repeatedly applying closed-string operators to one of the ground states.

We note that the above string operator $U(C)$ can be defined even when the loop $C$ intersects or overlaps with itself. In fact, those self intersecting/overlapping loops are more typical configurations of loops. Such kind of loops looks like nets of closed strings and we will call them closed string-nets. (Nets with open strings will be called open string-nets.) The string operators $U(C)$ will be called string-net operator. The degenerate ground states are formed by closed string-nets.

If $J, t \neq 0$, then the ground state degeneracy will be lifted. The $t$-term will make string-nets to fluctuate and the $J$-term will give strings in string-net a string tension. As we will see later the closed string-net fluctuations become $U(1)$ gauge fluctuations.

The degenerate ground states are invariant under local symmetry transformations generated by

$$U(\phi_i) = e^{i \sum_i (\eta_i \phi_i S^z_i \phi_i S^z_i)}$$

(4)

where $\eta_i = +1$ if the arrows of links $(i, i + \alpha)$ all point to $i$ and $\eta_i = -1$ if the arrows of links $(i, i + \alpha)$ all point away from $i$ (see Fig. 1). The above transformation is called the gauge transformation. Thus we can also say that the degenerate ground states are gauge invariant.

III. A FOUR-SPIN SYSTEM

In this section, we will start to derive the low energy effective theory of our model for the case $t, J \neq 0$ and $t' = 0$. We assume $t$ and $J$ to satisfy $t, J < U$ and $J > 0$. The ground state will no longer be degenerate. The low energy excitations are mainly in the projected space. To understand the low energy dynamics, we assume $S \gg 1$ and use a semiclassical approach.

To understand the dynamics of our model, let us consider a model of four spins described by $S_{(12)}^z, S_{(23)}^z, S_{(34)}^z,$ and $S_{(41)}^z$ (see Fig. 2a):

$$H = \sum_i \left( U(S^z_{(i-1,i)} - S^z_{(i,i+1)})^2 + J(S^z_{(i,i+1)})^2 \right)$$

(5)

where we have assumed $4 + 1 \sim 1$ and $1 - 1 \sim 4$. The Hilbert space is spanned by $|n_{(12)} n_{(23)} n_{(34)} n_{(41)} \rangle$ where
the integer \( n_{(j+1)} \) is the eigenvalue of \( S^z_{(j)} \). If \( U \gg J \), then the low energy excitations are described by \( |nnnn\rangle \) states with energy \( E = 4Jn^2 \). All other excitations have energy of order \( U \). As we will see in section IV, those low energy excitations happen to be identical to the excitations of a \( U(1) \) lattice gauge theory on the same square (see Fig. 2b). Thus our four-spin model describe a gauge theory at low energies.

To obtain an effective lattice gauge theory from our spin model, we would like to write down the Lagrangian (see Fig. 2b). Thus our four-spin model describe a gauge theory. After integrating out \( \Theta \), we derive the Lagrangian in another way. Using the path integral representation of \( H \), we find

\[
Z = \int D(\phi) D(\theta) e^{i \int dt (\sum_i S^z_{(i+1)} \theta_{(i+1)} - H)}
\]

where \( H = \sum_i (J(S^z_{(i+1)})^2 + a_{0,i} S^z_{(i-1,i)} - S^z_{(i,i+1)}) - \frac{a_i^2}{4U} \)

After integrating out \( S^z_{(i+1)} \), we obtain

\[
Z = \int D(\theta) D(a_0) e^{i \int dt L(\theta, \phi, a_0)}
\]

where the Lagrangian

\[
L = \frac{1}{4J} \sum_i \left( \frac{\dot{\theta}_{(i,i+1)} + a_{0,i} - a_{0,i+1}}{a_i} \right)^2 + \frac{a_i^2}{4U}
\]

In the large \( U \) limit, we can drop the \( \frac{a_i^2}{4U} \) term and obtain

\[
L = \frac{1}{4J} \sum_i \left( \dot{a}_{i,i+1} + a_{0,i} - a_{0,i+1} \right)^2
\]

which is just the Lagrangian of a \( U(1) \) lattice gauge theory on a single square with

\[
a_{i+1,i} = \theta_{(i+1,i)}, \quad a_{i+1,i} = -\theta_{(i+1,i)}
\]

as the lattice gauge fields (see Fig. 2b). One can check that the above Lagrangian is invariant under the following transformation

\[
a_{ij}(t) \to a_{ij}(t) + \phi_j(t), \quad a_{0,i}(t) \to a_{0,i}(t) + \phi_i(t)
\]

which is called the gauge transformation.

We note that low energy wave function \( \Psi(a_{12}, a_{23}, a_{34}, a_{41}) \) is a superposition of \( |nnnn\rangle \) states. All the low energy states are gauge invariant, ie invariant under gauge transformation \( a_{ij} \to a_{ij} + \phi_j - \phi_i \).

The electric field of a continuum \( U(1) \) gauge theory is given by \( e = \dot{a} - \theta_0 \). In a lattice gauge theory, the electric field becomes a quantity defined on the links

\[
e_{ij} = \dot{a}_{ij} - (a_{0,j} - a_{0,i})
\]

We see that our lattice gauge Lagrangian can be written as \( L = \frac{1}{4J} \sum_i e_{i+1,i}^2 \). Comparing with the continuum \( U(1) \) gauge theory \( L \sim e^2 - b^2 \), we see that our Lagrangian contains only the kinetic energy corresponding to \( e^2 \). A more general lattice gauge theory also contains a potential energy term corresponding to \( b^2 \).

To obtain a potential energy term, we generalized our spin model to

\[
H = \sum_i \left( U(S^z_{(i+1)} - S^z_{(i,i+1)})^2 + J(S^z_{(i,i+1)})^2 + t(e^{i\theta_{(1,i)}} e^{i\theta_{(1,i+1)}} + h.c.) \right)
\]

We note that \( \langle nnn|e^{i\theta_{(1,i)}} e^{-i\theta_{(1,i+1)}} |nnn\rangle = 0 \). Thus at the first order of \( t \), the new term has no effect at low energies. The low energy effect of new term only appears at the second order of \( t \).

We can repeat the above calculation to obtain the following Lagrangian

\[
L = \frac{1}{4J} \sum_i \left( (\dot{a}_{i,i+1} + a_{0,i} - a_{0,i+1})^2 - t(e^{i(a_{1,i+1} - a_{0,i+1}) + h.c.) + \frac{a_i^2}{4U} \right)
\]

It is a little more difficult to see in Lagrangian why the new term has no low energy effect at the first order of \( t \). Let us concentrate on the fluctuations of the following form

\[
a_{i-1,i} = \phi_i - \phi_{i-1}
\]

In the lattice gauge theory, such type of fluctuations are called the pure gauge fluctuations. After integrating out \( a_{0,i} \), the Lagrangian for the above type of fluctuations has a form \( L = \frac{1}{4J} \dot{\phi}_i m_{ij} \phi_j - \sum_i t e^{i(\phi_{i-1} - \phi_{i+1}) + h.c.} \) with \( m_{ij} = O(U^{-1}) \). We see that, in the large \( U \) limit, the above form of fluctuations are fast fluctuations. Since \( \phi_i \) live on a compact space (ie \( \phi_i + 2\pi \) represent the same point), those fast fluctuations all have large energy gap of order \( U \). Now we see that the \( t \)-term \( t e^{i(\phi_{i-1} - \phi_{i+1})} \) average to zero for fast fluctuations and has no effect at the first order in \( t \). However, at second order in \( t \) there is a term \( t^2 \sum_i e^{i(\phi_{i-1} - \phi_{i+1})} \). Such a term does not depend on \( \phi_{i-1} \) and does not average to zero. Thus we expect the low energy effective Lagrangian to have a form

\[
L = \frac{1}{4J} \sum_i \left( (\dot{a}_{i,i+1} + a_{0,i} - a_{0,i+1})^2 + \frac{a_i^2}{4U} \right) + g \cos \Phi
\]
where \( g = O(t^2/U) \) and \( F = \sum_i a_{i,i+1} \) is the flux of the \( U(1) \) gauge field through the square.

To calculate \( g \) quantitatively, we would like to first derive the low energy effective Hamiltonian. If we treat the \( t \)-term as a perturbation and treat the low energy states as degenerate states, then at second order in \( t \), we have

\[
\langle n', n', n', n'| H_{\text{eff}} | nnnm \rangle = \frac{t^2}{2U} \langle n', n', n', n'| e^{i(\theta_{34} + \theta_{41})} | n', n', n,n \rangle \times \\
\langle n', n', n, n| e^{i(\theta_{12} + \theta_{23})} | nnnm \rangle \\
+ \text{three other similar terms}
\]

(19)

where \( n' = n + 1 \). Thus the low energy effective Hamiltonian is

\[
\sum_i \left( U(S_{(i-1,i)}^z - S_{(i,i+1)}^z)^2 + J(S_{(i,i+1)}^z)^2 \right) - \frac{4t^2}{U} \cos(\Phi).
\]

The corresponding Lagrangian is given by Eq. (18) with

\[
g = \frac{4t^2}{U}.
\]

As discussed before, the pure gauge fluctuations has a large energy gap of order \( U \). The low energy effective theory below \( U \) can be obtained by letting \( U \to \infty \) and we get

\[
L = \frac{1}{4J} \sum_i (\dot{a}_{i,i+1} + a_{0,i} - a_{0,i+1})^2 + g \cos(\Phi)
\]

(22)

which contains both electric energy and magnetic energy.

**IV. QUANTUM GAUGE THEORY**

In this section, we will reverse the above calculation and start with the classical lattice gauge theory described by the Lagrangian Eq. (22). We would like to quantize it and find its Hamiltonian. This will allow us to calculate the energy levels of the lattice gauge theory and compare them with the energy levels of the four-spin model.

As a gauge theory, the path integral

\[
Z = \int D(a) D(a_0) e^{-i \int dt \left( \frac{1}{4U} \sum_i (\dot{a}_{i,i+1} + a_{0,i} - a_{0,i+1})^2 + g \cos(\Phi) \right)},
\]

should not be regarded as a summation over different functions \( (a_{ij}(t), a_{0,i}(t)) \). Here we regard two paths related by the gauge transformation Eq. (13) as the same path. Thus the path integral should be regarded as a summation over gauge equivalent classes of paths. Thus \( (a_{ij}(t), a_{0,i}(t)) \) is a many-to-one label of the gauge equivalent classes. We can obtain a one-to-one label by “fixing a gauge”. We note that \( \sum_j a_{ij} \) transforms as \( \sum_j a_{ij} \to \sum_j \tilde{a}_{ij} = \sum_j (a_{ij} + \phi_i - \phi_j) \) under gauge transformation. By tuning \( \phi_i \), we can always make \( \sum_j \tilde{a}_{ij} = 0 \).

Thus for any path \( (a_{ij}(t), a_{0,i}(t)) \), we can always make a gauge transformation to make \( \sum_j a_{ij} = 0 \). Therefore, we can fix a gauge by choosing a gauge fixing condition

\[
\sum_j a_{ij} = 0
\]

(24)

Such a gauge is called the Coulomb gauge, which has a form \( \partial \cdot a = 0 \) for a continuum theory. In the Coulomb gauge our path integral becomes

\[
Z = \int D(a) D(a_0) \prod_i \delta(\sum_j a_{ij}) \\
e^{-i \int dt \left( \frac{1}{4U} \sum_i (\dot{a}_{i,i+1} + a_{0,i} - a_{0,i+1})^2 + g \cos(\Phi) \right)}
\]

(25)

We note that a coupling between \( a_{0,i} \) and \( a_{ij} \) has a form \( a_{0,i} \sum_j \tilde{a}_{ij} \). Thus for \( a_{ij} \) satisfying the constraint \( \sum_j a_{ij} = 0 \), \( a_{0,i} \) and \( a_{ij} \) do not couple. Since \( a_{0,i} \) has no dynamics (ie no \( a_{0,i} \) terms), we can integrate out \( a_{0,i} \). The resulting path integral becomes

\[
Z = \int D(a) \prod_i \delta(\sum_j a_{ij}) e^{-i \int dt \left( \frac{1}{4U} \sum_i (\dot{a}_{i,i+1} + g \cos(\Phi) \right)}
\]

(26)

which is the path integral in the Coulomb gauge.

In general, a path integral in the Coulomb gauge can be obtained by the following two simple steps: (a) inserting the gauge fixing condition \( \prod_i \delta(\sum_j a_{ij}) \) and (b) drop the \( a_{0,i} \) field.

For our problem, the constraint \( \prod_i \delta(\sum_j a_{ij}) \) makes \( a_{12} = a_{23} = a_{34} = a_{41} = \theta/4 \). The path integral takes a simple form

\[
Z = \int D(\theta) e^{-i \int dt \left( \frac{1}{4U} \dot{\theta}^2 + g \cos(\theta) \right)}
\]

(27)

we note that the configuration \( (a_{12}, a_{23}, a_{34}, a_{41}) = (\pi/2, \pi/2, \pi/2, \pi/2) \) is gauge equivalent to \( (a_{12}, a_{23}, a_{34}, a_{41}) = (2\pi, 0, 0, 0) \) (ie there is a gauge transformation that transform \( (\pi/2, \pi/2, \pi/2, \pi/2) \) to \( (2\pi, 0, 0, 0) \)). Also \( a_{12} = 2\pi \) is equivalent to \( a_{12} = 0 \) since \( a_{1,i+1} = \theta_{(i,i+1)} \) live on a circle. Thus \( \theta = 2\pi \) and \( \theta = 0 \) correspond to the same physical point. The path integral Eq. (27) describes a particle of mass \( (8J)^{-1} \) on a unit circle. Then the flux energy \( -g \cos(\theta) \) is the potential experienced by the particle. When \( g = 0 \), the energy levels are given by \( E_n = 4Jn^2 \) which agrees exactly with the energy levels of Eq. (5) at low energies. Hence Eq. (5) is indeed a gauge theory at low energies.

**V. EFFECTIVE GAUGE THEORY OF LATTICE SPIN MODEL**

Using the similar calculation, we find that our 2D lattice model Eq. (1) can be described by the following Lagrangian in the large \( U \) limit

\[
L = \frac{1}{4J} \sum_{(ij)} [\dot{a}_{ij} + a_0(i) - a_0(j)]^2 \\
+ g \sum_p \eta_p \cos(\Phi_p) + J_1 \sum_{(IJ)} \sigma_i^p \sigma_j^p
\]

(28)
Here \(a_{ij} = \theta_{ij}\) if the arrow of link (see Fig. 1) points from \(i\) to \(j\) and \(a_{ij} = -\theta_{ij}\) if the arrow points from \(j\) to \(i\). \(p\) labels the plaquettes in the H-lattice and \(\Phi_p = a_{13} + a_{03} + \ldots + a_{61}\), where 1,...,6 are the six sites around the plaquette \(p\). The \(\sum_{\{IJ\}}\) sums over all the nearest neighbor sites \(\langle IJ \rangle\) in the K-lattice. \(\eta_p = 1\) if all \(\sigma_i^z\), \(\sigma_j^z\) are equal and \(0 \leq \eta_p \leq 0.5\) otherwise. In the small \(t\) limit \(J = J\).

Let us first explain the potential term \(-J_1 \sum_{\langle IJ \rangle} \sigma^z_I \sigma^z_J\).

We start with a low energy state in the projected space \(\langle \Psi \rangle\). The action of the \(t\)-term \(tS^z \sigma^z_I S^z_I S^z_J\) on such a state gives us a high energy state with an energy \(4U - 2 \sigma^z_I \sigma^z_J U\). The second order perturbation in \(t\) gives rise to the following contribution \(-2 \times t^2 S^z / (4U - 2 \sigma^z_I \sigma^z_J U)\).

We see that \(\sigma^z_I \sigma^z_J = 1\) has a lower energy than \(\sigma^z_I \sigma^z_J = -1\). The energy difference is \(2t^2 \times S^z / 3U\). We find that \(J_1 = t^2 S^z / 3U\). The dynamics of the isospin \(\sigma^z\) is described by the Ising model. The ground state is a ferromagnetic state with all \(\sigma^z_I = 1\) (or \(\sigma^z_I = -1\)).

At second order, the \(t\)-term can also generate the \(J\)-term in Eq. (1). Thus \(J = J \sim t^2 / U\).

Second, let us explain the potential term \(-g \sum_p \eta_p \cos(\Phi_p)\). We first note that the gauge transformation Eq. (4) changes

\[a_{ij} \rightarrow a_{ij} + \phi_i - \phi_j\]  \(\text{Eq. (29)}\)

The \(t\)-term in Eq. (1) can be written as \(S^z \cos(\sigma^z_{ij}, a_{ij} + \sigma^z_{jk}, a_{jk})\) which is not gauge invariant. Thus the average of the \(t\)-term in the projected space is zero. Non zero potential terms can only be generated from the \(t\)-term via higher order perturbation, and the resulting potential term must be gauge invariant. The simplest gauge invariant term has a form \(\cos(\Phi_p)\) which is generated at the third order in \(t / U\). Hence \(g \sim t^3 S^z / U^2\).

In the small \(t\) limit, the second order \(J_1\) term will make all \(\sigma^z_I = 1\). In the following we will calculate the \(g\)-term assuming \(\sigma^z_I = 1\).

At third order, the effective Hamiltonian in the projected space has the following matrix elements

\[\langle \Psi_1 | H_{eff} | \Psi_2 \rangle = \sum_{m,n} \langle \Psi_1 | H_t | m \rangle \langle \langle m | H_I | n \rangle \langle n | H_I | \Psi_2 \rangle (E_m - E_\Psi)(E_n - E_\Psi)\]  \(\text{Eq. (30)}\)

where \(E_\Psi \sim 0\) is the energy of \(|\Psi_1, 2\rangle\), \(\sum_{m,n}\) is a sum over all high energy states \(|m\rangle\) and \(|n\rangle\) that are not in the projected space, and \(H_t = t S^z \sum_{\langle IJ \rangle} \sigma^z_I \sigma^z_J S^z_I S^z_J\). When \(|\Psi_1\rangle = e^{\Phi_1} |\Psi_1, 2\rangle\), we find \(\langle \Psi_1 | H_{eff} | \Psi_2 \rangle = 6 \times 2 \times t^3 S^z / (2U)^2\).

In a numerical calculation, we considered our model on a single hexagon - a single cell of the H-lattice and assumed \(S = 1\). Solving the six-spin model exactly, we found that the low energy sector and the high energy sector start to mix when \(g \sim 0.25U\). In that case perturbation theory breaks down.

The \(J_1\)-term favors a ground state with all \(\sigma^z_I = 1\) or \(\sigma^z_I = -1\). Such a ground state spontaneously breaks the time reversal symmetry. The time reversal symmetry breaking happens even when we include the quantum fluctuations of \(\sigma^z_I\) generated by \(\delta H = J' \sum_I \sigma^z_I\) as long as \(J' \lesssim \max(|g|, t^2 / U)\). In the time reversal symmetry breaking phase, Eq. (28) describes a \(U(1)\) lattice gauge theory.

When \(t' \neq 0\), more complicated term of form \(\cos(\Phi_p + \phi)\) can be generated, where \(\phi\) depends on \(\sigma^z_{12}, \ldots, \sigma^z_{61}\). In this case, \(\sigma^z_I\) might have a certain pattern in the ground state which can break translation and/or rotation symmetry. But as long as \(J'\) is small, the quantum fluctuations of \(\sigma^z_I\) can be ignored and the model contains a \(U(1)\) gapless gauge boson if we ignore the instanton effect.

However, in \(2+1D\), we do have an instanton effect. Due to the instanton effect, a \(U(1)\) gauge excitation develops a gap.\[\text{Eq. (32)}\] The instanton effect is associated with a change of the \(U(1)\) flux \(\Phi\) from 0 to \(2\pi\) on a plaquette. To estimate the importance of the instanton effect, let us consider a model with only a single plaquette (ie the single-hexagon model discussed before). Such a model is described by

\[L = \frac{1}{24J} \dot{\theta}^2 + g \cos \theta.\]  \(\text{Eq. (31)}\)

The instanton effect corresponds to a path \(\theta(t)\) where \(\theta\) goes from \(\theta(-\infty) = 0\) to \(\theta(+\infty) = 2\pi\). To estimate the instanton action, we assume

\[\theta(t) = \begin{cases} 0, & \text{for } t < 0 \\ 2\pi/t, & \text{for } 0 < t < T \\ 2\pi, & \text{for } T < t \end{cases}\]  \(\text{Eq. (32)}\)

The minimal instanton action is found to be

\[S_c = \pi \sqrt{2g/3J}\]  \(\text{Eq. (33)}\)

when \(T = \pi/2\sqrt{3gJ}/2\). From the density of the instanton gas \(\bar{J} ge^{-S_c}\), we estimate the energy gap of the \(U(1)\) gauge boson to be

\[\Delta \sim \sqrt{\bar{J} ge^{-\pi \sqrt{2g/3J}}}\]  \(\text{Eq. (34)}\)

Thus to have a nearly gapless gauge boson, we require the above gap to be much less than the bandwidth of the gauge field \(\sqrt{gJ}\). This requires

\[g \lesssim 0.25U, \quad e^{-2.4\sqrt{\gamma}} \ll 1\]  \(\text{Eq. (35)}\)

If the above condition is satisfied, we can ignore the mass gap of the gauge boson and regard the \(U(1)\) gauge theory as in the deconfined phase. Therefore, Eq. (35) is the conditions to have an artificial light in our 2D model.

VI. STRING-NET THEORY AND STRING-NET PICTURE OF ARTIFICIAL LIGHT AND ARTIFICIAL CHARGE

As mention before, the low energy excitations below \(U\) are describe by closed string-nets of increased/decreased
\[ \sigma^z S^z. \] (see Fig. 1). To make this picture more precise, we would like to define a closed-string-net theory on a lattice.

The Hilbert space of the closed-string-net theory is a subspace of the Hilbert space of our model (1) (here we assume all \( \sigma^z = 1 \)). The closed-string-net Hilbert space contains a state with all \( S^z = 0 \). If we apply the closed-string-net operator (2) to the \( S^z = 0 \) state, we obtain another state in the closed-string-net Hilbert space. Such a state is formed by the \( S^z = \pm 1 \) along the closed loop, or more generally a closed string-net C if we include self intersection and overlap. Thus \( U(C) \) in Eq. (2) can be viewed as a string-net creation operator. Other states in the closed-string-net Hilbert space correspond to multiple-string-net states and are generated by repeatedly applying the closed-string-net operators Eq. (2) to the \( S^z = 0 \) state.

The Hamiltonian of our closed-string-net theory is given by

\[
H_{cst} = \sum_i \hat{J}(S^z_i)^2 - \sum_p \frac{1}{2}(gW_p + h.c.) \quad (36)
\]

where \( \sum_p \) sums over all the plaquettes of the H-lattice, and \( W_p \) is the closed-string-net operator for the closed string around the plaquette \( p \). One can check that the above Hamiltonian acts within the closed-string-net Hilbert space. The \( \hat{J} \) term gives strings in string-nets a finite string tension, and the \( g \) term causes the string-nets to fluctuate.

From the construction, it is clear that the closed-string-net Hilbert space is identical to the low energy Hilbert space of our model Eq. (1) which is formed by states with energy less than \( U \). From our derivation of effective lattice gauge theory Eq. (28), it is also clear that the closed-string-net Hamiltonian Eq. (36) is directly related to the lattice gauge Lagrangian Eq. (28). In fact, the Hamiltonian of the lattice gauge theory is identical to the closed-string-net Hamiltonian Eq. (36). The string tension \( \sum_i \hat{J}(S^z_i)^2 \) term in the string-net theory corresponds to the \( \frac{1}{2J} \sum_{(ij)} [\hat{a}_{ij} + a_{ij}(i) - a_{ij}(j)]^2 \) term in the gauge theory, and the string hopping \( \sum_p \frac{1}{2} g(W_p + h.c.) \) term in the string-net theory corresponds to the \( g \sum_p \eta_p \cos(\Phi_p) \) term in the gauge theory. Since the \( S^z \sim \hat{\theta}_{ij} = \hat{a}_{ij} \) corresponds to the electric flux along the link, A closed loop of increased/decreased \( \sigma^z S^z \) corresponds to a loop of electric flux tube. A string-net corresponds a “river” network of electric flux.

We see that the \( U(1) \) gauge theory Eq. (28) is actually a dynamical theory of nets of closed strings. Typically, one expects a dynamical theory of closed-string-nets to be written in terms of string-nets as in Eq. (36). However, since we are more familiar with field theory, what we did in the last a few sections can be viewed as an attempt trying to describe a string-net theory using a field theory. Through some mathematical trick, we have achieved our goal. We are able to write the string-net theory in a form of gauge field theory. The gauge field theory is a special field theory in which the field does not correspond to physical degrees of freedom and the physical Hilbert space is non-local (in the sense that the total physical Hilbert space cannot be written as a direct product of local Hilbert spaces). The point we try to make here is that gauge theory (at least the one discussed here) is a closed-string-net theory in disguise. Or in other words, gauge theory and closed-string-net theory are dual to each other. We would like to point out that in Ref. [29, 30] various duality relations between lattice gauge theories and theories of extended objects were reviewed. In particular, some statistical lattice gauge models were found to be dual to certain statistical membrane models.[31] This duality relation is directly connected to the relation between gauge theory and closed-string-net theory in our dipole models.

In the large \( J/g \) (hence large \( \Delta_{gauge} \)) limit, the ground states for both the dipole model and string-net model are given by \( S^z = 0 \) for every spin. In this phase, the closed string-nets or the electric flux tubes do not fluctuate much and have an energy proportional to their length. This implies that the \( U(1) \) gauge theory is in the confining phase. In the small \( J/g \) limit, the closed string-nets fluctuate strongly and the space is filled with closed string-nets of arbitrary sizes. According to the calculation in the previous section, we note that the small \( J/g \) phase can also be viewed as the Coulomb phase with gapless gauge bosons. Combining the two pictures, we see that gapless gauge bosons correspond to fluctuations of large closed string-nets.

After relating the closed strings (or closed string-nets) to artificial light, we now turn to artificial charges. To create a pair of particles with opposite artificial charges for the artificial \( U(1) \) gauge field, we need to draw an open string (or an open string-net) and alternatively increase and decrease the \( \sigma^z S^z \) of the spins along the string (see Fig. 1). The end points of the open strings, as the end points of electric flux tubes, correspond to particles with opposite artificial charges. We note that charged particles live on the H-lattice. In the confining phase, the string connecting the two artificial charges does not fluctuate much. The energy of the string is proportional to the length of the string. We see that there is a linear confinement between the artificial charges.

In the small \( J/g \) limit, the large \( g \) cause strong fluctuations of the closed string-nets, which lead to gapless \( U(1) \) gauge fluctuations. The strong fluctuations of the string connecting the two charges also changes the linear confining potential to the \( \log(r) \) potential between the charges.

To understand the dynamics of particles with artificial charges, let us derive the low energy effective theory for those charged particles. Let us first assume \( J = t = t' = 0 \). A pair of charged particles with opposite unit artificial charges can be created by applying the open-string operator Eq. (2) to the ground state. We find that each charge particle has a energy \( U \) and the string costs no energy. Let us first treat charge particles as independent particles. In this case the total Hilbert space of charged particles is formed by state \( \{|n_i \rangle \} \), where \( n_i \) is the number of artificial charges on the site \( i \) of the H-lattice. \( \{|n_i \rangle \} \) is an energy eigenstate with energy \( E = \)
where $\varphi_i$ is an angular variable. The creation operator of the charged particle is given by $e^{i\varphi_i}$. Now, let us include the fact that the charged particles are always the ends of open strings (or nodes of string-nets). Such a fact can be implemented by including the $U(1)$ gauge field in the above Lagrangian. Using the gauge invariance, we find the gauged Lagrangian has a form

$$L = \sum_i \frac{1}{4U} \varphi_i^2$$

where the gauge invariant operator $\varphi_i = e^{i\varphi_i} |a_i\rangle$ is no longer physical since it is not gauge invariant. The gauge invariant operator

$$e^{-i\varphi_ie^{ia_1a_2}...e^{ia_N-1}}N^{-1}e^{i\varphi_1N}$$

always creates a pair of opposite charges. In fact the above gauge invariant operator is nothing but the open-string-net operator Eq. (2). We also see that the string-net operator Eq. (2) is closely related to the Wegner-Wilson loop operator.\[33-35\]

The $t$-term generates a hopping of charged particles to the next-nearest neighbor in the H-lattice. Thus, if $t \neq 0$, the charged particles will have a non-trivial dispersion. The corresponding Lagrangian operator is given by

$$L = \sum_i \frac{1}{4U} (\varphi_i + a_0(i))^2 - \sum_{(ij)} t(e^{i(\varphi_i - \varphi_j - a_{ik} - a_{jk})} + h.c.)$$

where $(ij)$ are next-nearest neighbors in the H-lattice, and $k$ is the site between site $i$ and site $j$. The above Lagrangian also tells us that the charged particles are bosons. We also note that a flipped spin corresponds to two artificial charges. Therefore each unit of artificial charge corresponds to a half-integer spin.

Using the string-net picture, we can give more concrete answers to the three questions about light:

| What is light? | Light is a fluctuation of closed string-nets of arbitrary sizes. |
| Where light comes from? | Light comes from the collective motions of “things” that our vacuum is made of. \[43\] In particular, light comes from the large closed string-nets that fill the vacuum. |
| Why light exists? | Light exists because our vacuum contains strong fluctuations of loop-like objects (the closed string-nets) of arbitrary size. |

We would like to stress that the above string-net picture of the actual light in nature is just a proposal. There may be other theories that explain what is light and where light comes from. In this paper, we try to argue that the string-net picture is at least self consistent, since there are actual models that realize the string-net picture of light. We also try to argue that the string-net picture of light is more natural than the current theory of light where light is regarded as a vector gauge field which is introduced by hand.

VII. A 3D MODEL

Our 2D model and the related calculations can be easily generalized to 3 dimensions. To construct our 3D model, we first construct a 3DH-lattice which is formed by layers of H-lattices stacked on top of each other. Note that a H-lattice can be divided into two triangular sublattices (see Fig. 3). We link the sites in one sublattice to the corresponding sites in the layer above and link the sites in the other sublattice to the layer below. The spins are placed on the links of the 3DH-lattice. The lattice formed by the spins is called 3DK-lattice. Actually, the 3DK-lattice is nothing but the corner-sharing tetrahedron lattice or the pyrochlore lattice. The 3D Hamiltonian still has a form Eq. (1). But now $i$ label the sites in the 3DH-lattice and $I$ the sites in the 3DK-lattice. $\alpha$ connects the site $i$ to its four linked neighbors in the 3DH-lattice. The low energy effective theory still has the form Eq. (28) and the conditions to observe artificial light are still given by Eq. (35). The main difference between the 1+2D model and 1+3D model is that the artificial light, if exist, is exactly gapless in 1+3D. The effective Lagrangian for the charged particles still has the form in Eq. (40).

VIII. EMERGING QUANTUM ORDER

Our 3D model contains two $T = 0$ quantum phases with the same symmetry. One phase (phase A) appears in $\tilde{J} \gg |g|$ limit and is gapped (see Eq. (35)). The other phase (phase B) appears in $|g| \gg \tilde{J}$ limit. The phase B contains a non-trivial quantum order which is closely related to the artificial light in it.

By including the $t$-term between spins beyond nearest neighbors, our model can even support different kinds of non-trivial quantum orders. For example, by adjusting the different $t$-terms, we can independently tune the value and the sign of $g$ in $g \cos(\Phi_p)$ for different kind of plaquettes. If all $g$ are positive, then we get the phase B discussed above, where there is zero gauge flux through
all the plaquettes: \( e^{i\mathbf{d} \cdot \mathbf{p}} \sim 1 \). If we tune \( g \) to be negative for the plaquettes in the layers of the 3DH-lattice and positive for the plaquettes between the layers, then we get a phase (phase C) with a new quantum order. In phase C there is \( \pi \) flux through the plaquettes in the layers and zero flux through the other plaquettes. The phase C has the same symmetry as the phase A and B, and contains a gapless artificial light. The phase B and phase C are separated by phase A that appears in small \( g \) limit.

Quantum orders in phase B and C can be more precisely characterized by the projective symmetry group or PSG.[7, 8] In semiclassical limit, the phase B is described by ansatz where all \( \langle e^{i\alpha_{ij}} \rangle \sim 1 \). While the phase C is described by ansatz where some \( \langle e^{i\alpha_{ij}} \rangle \sim 1 \) and other \( \langle e^{i\alpha_{ij}} \rangle \sim -1 \). The PSG for an ansatz is formed by all the combined gauge and symmetry transformations that leave the ansatz invariant.[7, 8] We find the PSG’s for the ansatz of phase B and the ansatz of phase C are different. It was shown that PSG is a universal property of a quantum phase that can be changed only through phase transitions.[7, 8] The different PSG’s for the phase B and phase C indicate that phase B and phase C are indeed different quantum phases which cannot be changed into each other at \( T = 0 \) without a phase transition. Using PSG we can also describe more complicated quantum orders (or flux configurations). We can even use PSG to classify all the quantum orders in our model (in semiclassical limit).

The different quantum orders in the phase B and phase C can be distinguished in experiments by measuring the dispersion relation of the charge particle. From Eq. (40), we see that the hoping of the charged particles is affected by the flux through the plaquettes.

**IX.Emerging Low Energy Gauge Invariance**

After seeing the importance of gauge transformation Eq. (4) in obtaining artificial light and in PSG characterization of quantum orders, we are ready to make a remark about the gauge invariance. We note that after including the higher order \( t/U \) terms, the Lagrangian formally is not invariant under gauge transformation Eq. (29). As a result, the so-called pure gauge fluctuations (which should be unphysical in gauge theory) actually represent physical degrees of freedom. However, those fluctuations all have a large energy gap of order \( U \).[27, 28] The low energy fluctuations (assuming there is a finite energy gap between the low energy and high energy excitations) should be gauge invariant, and the effective Lagrangian that describes their dynamics should be gauge invariant.

Due to the finite mixing between the low energy and high energy excitations caused by the \( t \)-term, the low energy excitations are not invariant under the particular gauge transformation defined in Eq. (4). However, since the mixing is perturbative, we can perturbatively modify the gauge transformations such that the low energy excitations are invariant under a modified gauge transformation. To obtain the modified gauge transformation, we continuously change \( t \) from zero to a small value. This will cause the eigenstates of our model to rotate. The rotation is generated by a unitary matrix \( W \). Then the modified gauge transformation is given by \( \tilde{U}(\phi) = W e^{\sum_i (\eta_i \phi_i \sum \sigma_{i,i+\alpha}^z S_{i,i+\alpha})} W^\dagger \). By definition, the modified gauge transformation will leave the low energy excitations invariant. The non-trivial point here is that the modified gauge generator \( W \sum_i (\eta_i \phi_i \sum \sigma_{i,i+\alpha}^z S_{i,i+\alpha}) W^\dagger \) is still a local operator. This is likely to be the case if \( f \) is not too large to destroy the energy gap between the low and high energy excitations. We see that both the \( U(1) \) gauge structure and the PSG are emerging properties in our model.

We would like to remark that the key to obtain a low energy effective gauge theory is not to formally derive an effective Lagrangian that have a gauge invariance, but to show all the pure gauge fluctuations to have a large energy gap. In this limit, as we have seen for the \( t \)-term, all the gauge non-invariant terms will drop out from the low energy effective theory. Only gauge invariant combinations can appear in the effective theory.[27, 28]

**X. Realistic Devices**

In the following, we will discuss how to design realistic devices that realize our 2D and 3D models. First we note that our 2D model Hamiltonian Eq. (1) can be realized by magnetic or electric dipoles which form a Kagome lattice (assuming only dipolar interactions between the dipoles). For such a system \( t = S^2 U/2, t' = 3S^2 U/2 \) and \( J = -2U \). So the coupling constants do not have the right values to support an artificial light. Thus the key to design a working device is to find a way to reduce the coupling between \( S^\pm \). We need to reduce the \( t \)-term and \( t' \)-term by a factor \( \sim 4S^2 \). We also need to introduce an anisotropic spin term \( (S^\pm)^2 \) to bring \( J \) close to zero.

We can use molecules with a finite electric dipole moment \( \mathbf{d} \) as our spins. For a fixed \( \mathbf{d} \), the molecule should have two degenerate ground states with angular momentum \( \pm S \) in the \( \mathbf{d} \) direction. If we allow the molecule to rotate, the ground states of the molecule will contain \( 2(2S + 1) \) states \( |S^z, \sigma^z \rangle \). \( S^z = -S, ..., S \) and \( \sigma^z = \pm 1 \). \( S^z \) corresponds to the spin degree of freedom and \( \sigma^z \) the isospin degree of freedom. The tunneling between the \( \pm S \) states generates a term \( \delta H = J' \sigma^z \) which leads to quantum fluctuation of \( \sigma^z \). We also need to put the molecule, say, in a \( C_8 \) buckyball so the dipole can rotate freely. We note that endohedral \( S_2 A_2 N @ C_80 \)[36] is commercially available from Luna Nanomaterials (http://www.lunanomaterials.com), where \( A \) is a...
The low energy effective theory Eq. (28) contains only sketched in Fig. 5. Both 2D and 3D electric dipole systems \( J = J_s + J_g \) with coupling constants \( g \) are determined by \( \tilde{g} \).

The 3D model can be realized by the device in Fig. 4b. Circular holes of diameter \( d \) are drilled through the film to form a Kagome lattice. The dipoles are placed in the holes. A large \( h \) will reduce \( t \). The screening of the superconducting film also make the dipoles to tend to point horizontally (ie \( S^z = 0 \)). In this case \( J \) can be tuned by changing \( d/l \). If we choose \( l = 10 \)nm, \( S = 2 \) and dipole moment 0.1e-\( \)nm, we find \( U \sim 40 \)mK. The operating temperature to observe artificial light is about 1mK, which is achievable.

The 3D model can be realized by the device in Fig. 4b. We note that the 3D K-lattice is formed by alternatively stacking K-lattices and triangular lattices together. The top and the bottom layers in Fig. 4b are screened K-lattices just like Fig. 4a, while the middle layer is a screened triangular lattice. The distance between layers and \( d/l \) need to be tuned to reproduce the \( U \)-term. The \( t \)-term and \( J \)-term can be adjusted similarly as in the 2D device.

### XI. PHYSICAL PROPERTIES OF 2D AND 3D DEVICES

The 2D and 3D devices are described by model Hamiltonian Eq. (1) with coupling constants \( U, J, t \) and \( t' \). The low energy effective theory Eq. (28) contains only two coupling constant \( \tilde{J} \) and \( g \) in large \( U \) limit. \( \tilde{J} \) and \( g \) are determined by \( U, J, t \) and \( t' \). If \( U = 40 \)mK, we can tune \( t \) to make \( g = 6 \)mK. We can tune \( J \) to make \( \tilde{J} = g/2 = 3 \)mK.

The phase diagrams of the 2D and 3D devices are sketched in Fig. 5. Both 2D and 3D electric dipole systems have a phase transition at \( T_c \sim t^2S^{-1}/U \) which breaks the time reversal symmetry. The 3D system also has a quantum phase transition at \( g/\tilde{J} \sim 1 \). The quantum phase transition separates the confined phase where the artificial light has an energy gap and the Coulomb phase where the artificial light is gapless.

In the 2D electric dipole system, there is no zero-temperature quantum phase transition and the artificial light always has a finite energy gap \( \Delta \) (see Eq. (34)). The thin solid line in Fig. 5a marks the scale of the energy gap. When the energy gap is much less than the bandwidth \( \sqrt{Jg} \) of the artificial light, we say the artificial light exists.

Both type of the transitions are between the same pair of phases – the Coulomb and the confined phases. Both type of transition can appear in our 3D dipole model. However, in the large \( U \) limit, we expect the quantum phase transition from the Coulomb phase to the confined phase to be the second type and to be continuous. The continuous phase transition will become a smooth cross over at finite temperatures (see Fig. 5b). If \( U \) is not large enough, the quantum phase transition can be the first type which is a first order phase transition. Such a first order phase transition will extend to finite temperatures.

In the 2D electric dipole system, there is no zero-temperature quantum phase transition and the artificial light always has a finite energy gap \( \Delta \) (see Eq. (34)). The thin solid line in Fig. 5a marks the scale of the energy gap. When the energy gap is much less than the bandwidth \( \sqrt{Jg} \) of the artificial light, we say the artificial light exists.

Our 2D and 3D dipole systems have boundaries. Some interesting questions arise. To the artificial light, what is the properties of the boundary? If we shine artificial light onto the boundary, does artificial light get reflected or absorbed? If we place an artificial charge near the boundary, whether the charge is attracted or repelled by the boundary? Those questions can be answered by our string-net picture of artificial light and artificial charges. We note that the closed strings are always confined in the sample. The ends of open strings always cost an energy of order \( U \) even when the open string is ended on the boundary. This means that the closed strings do not break up near the boundary. Since the closed strings represent electric flux tube, we find that the electric flux of the artificial light can never leave the sample neither can end at the boundary of the sample. Therefore, the artificial light, the outside of the sample behaves like a perfect dia-electric media which repels the artificial electric flux. If we place an artificial charge near the boundary, the charge will be repelled by the boundary.

To understand the physical properties of the artificial light...
light in the 2D model, we can take the continuum limit by writing

\[ a_{ij} = \delta_{x}(ij) \cdot a(x) \]
\[ a_{0i} = a_{0}(x), \]

where \( \mathbf{a} = (a_{x}, a_{y}) \) is a 2D vector field (the vector gauge potential in 2D), \( a_{0} \) corresponds to the potential field, \( x \) is near the site \( i \), \( \delta_{x}(ij) \) is the vector that connect the \( i \) and \( j \) sites in the H-lattice, and \( l \) is the distance between the neighboring sites in the H-lattice. In the continuum limit, the Lagrangian Eq. (28) becomes

\[ L = \int d^{2}x \left( \frac{1}{4J\sqrt{3}}e^{2} - \frac{3\sqrt{3}gI^{2}}{4b^{2}} \right) \]

where \( e = \partial_{t}a - \partial_{x}a_{0} \) and \( b = \partial_{x}a_{y} - \partial_{y}a_{x} \) are the corresponding artificial electric field and artificial magnetic field. We see that the velocity of our artificial light is \( v = \sqrt{\frac{3gI^{2}}{4b^{2}}/a_{c}} \). For each angular momentum constant, the mass of the charged boson \( m_{b} \) is \( (9tI^{2})^{-1} \) and \( mc_{a}^{2} \sim 2.3mK \). The artificial atom has an energy level spacing \( \frac{5}{2}mc_{a}^{2} \sim 0.01mK \) and a size of order \( 1/\alpha mc_{a} \sim 6\pi\sqrt{2l} = 87l \).

The speed of artificial light is \( c_a = \sqrt{g_{a}J^{2}/\hbar^{2}} \). If we take \( J = 3mK \), \( g = 6mK \) and \( l = 10nm \), we find the speed of the artificial light is about \( c_a = 20m/s \). The band width of the artificial light is about \( \Delta \sim 0.06E_a \).

From Eq. (40), we find the continuum Lagrangian that describes the charged particles in the 2D model (in the \( U \gg t \) limit)

\[ L = \int d^{2}x \sum_{l=1,2} \left( \phi_{l}^{\dagger}(i\partial_{t} - a_{0} - U)\phi_{l} - \frac{9tI^{2}}{2}|(i\partial_{t} + ia_{l})\phi_{l}|^{2} \right) \]

where \( \phi_{l} \) describe the positively charged bosons, \( \tilde{\phi}_{l} \) describe the negatively charged bosons, \( \psi_{1}, \psi_{2} \) describe the charged bosons on the even sites of the H-lattice, and \( \tilde{\psi}_{1}, \tilde{\psi}_{2} \) describe the charged boson on the odd sites of the H-lattice. It costs energy \( 2U \) to create a pair of charged bosons. The mass of the bosons is \( m = (9tI^{2})^{-1} \) and \( mc_{a}^{2} \sim 2.3mK \). We would like to note that the boson velocity can be larger than the speed of artificial light.

The potential energy between a positive and a negative charge is \( V(r) = \frac{\sqrt{3}e_{z}}{2}\ln r \). A bound state of a positive charge and a negative charge (an artificial atom) has a size of order \( l\sqrt{3\sqrt{3}\pi t/\bar{J}} = 6.6l \). For each angular momentum \( mh \), the lowest energy level of the artificial atom is of order \( \frac{ln(m)\sqrt{\bar{J}}}{\alpha} = 1.7ln(m) mK \).

For the 3D model, if the layer separation is \( l_{z} \), we find the Lagrangian in the continuum limit is given by

\[ L = \int d^{3}x \frac{1}{4J\sqrt{3l_{z}}} \left( e_{x}^{2} + e_{y}^{2} + \frac{l_{z}^{2}e_{z}^{2}}{t^{2}} \right) \]
\[ - \int d^{3}x \frac{3\sqrt{3}gI^{2}}{4l_{z}} \left( \frac{2l_{z}^{2}b_{x}^{2}}{3l^{2}} + \frac{2l_{z}^{2}b_{y}^{2}}{3l^{2}} + b_{z}^{2} \right) \]

where \( e \) and \( b \) are the artificial electric field and artificial magnetic field in 3D. We see that, in general, the speed of artificial light is different in different directions. For simplicity, we choose \( l_{z} = l \) and ignore the anisotropy in the speed of artificial light. That is we work with the following simplified Lagrangian

\[ L = \int d^{3}x \left( \frac{1}{4J\sqrt{3l_{z}}} e^{2} - \frac{3\sqrt{3}gI^{2}}{4b^{2}} \right) \]

where \( \alpha = \frac{1}{2\pi}\sqrt{J/3g} = 1/15 \) is the artificial fine structure constant. The mass of the charged boson \( m \) is of order \( (9tI^{2})^{-1} \) and \( mc_{a}^{2} \sim 2.3mK \). The artificial atom has an energy level spacing \( \frac{5}{2}mc_{a}^{2} \sim 0.01mK \) and a size of order \( 1/\alpha mc_{a} \sim 6\pi\sqrt{2l} = 87l \).

In the following, we will discuss one experiment that can detect some of the above properties in the 2D system. (Note it is easier to create a 2D device.) If we place a tip of scanning tunneling microscope near an electric dipole, we can induce the following coupling \( \delta H = E(t)S_{I}^{+} + h.c. \) to the electric dipole. \( S_{I}^{+} \) flips a spin on a link which create a pair of bosons on the two ends of the link. The two bosons carry positive and negative artificial charges. If we measure the high frequency capacitance of the tip,[41] we can see peaks at the energy levels of the artificial atom \( \omega = 2U + \frac{ln(m)\sqrt{\bar{J}}}{\alpha} = (80 + 1.7ln(m))mK = (1668 + 35ln(m))MHz \). We also note that a AC voltage on the tip at lower frequencies can generate artificial light. However, the tip of scanning tunneling microscope is not an efficient antenna to generate artificial light.

From the above discussion, it is clear that the electric dipole systems, if can be created, really provide a model for artificial light, artificial charge, and artificial electromagnetic interaction in both two and three dimensions. We know that the SU(3)-spin model that realize 3D artificial light, artificial electron and artificial proton[13] is not realistic. The dipole systems discussed here contain only artificial light. It would be very interesting to design a realistic device that has artificial light, artificial electron and artificial proton. In that case, we can have an artificial world sitting on our palm.

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[42] Note that the term phonon always refers to gapless phonon in solid in this paper.
[43] Note that our vacuum is not empty. It is filled with “things” that form the space-time.