The quantum theory and experiments have approved that vacuum can be polarized. The quantum polarization can be used to interpret the gravitation [1, 2, 3], which reaches an insightful description of the vacuum around the gravitational matter with changeable permittivity $\varepsilon$ and permeability $\mu$ [12, 3] or graded refractive index $n$ [12, 5, 4, 3, 2, 8, 9]. A vacuum polarization interpretation of the gravitational field endows the space of vacuum with physical qualities. It is just what Einstein hoped and predicted [10]. A reasonable extrapolation is that the electromagnetic fields can also be interpreted as the effects of vacuum polarization. Such an interpretation claims for a vacuum whose properties are somewhat like those of dielectric medium [11].

Exhilaratingly, facts and theories all indicate that vacuum is actually a special kind of medium [12, 13]. Casimir effect [14, 15] tells that vacuum is not just a void, but a special physical existence full of zero-point energy. Vacuum can be polarized by electromagnetic field, which leads to the well-known effects of Lamb shift and anomalous magnetic moment of the electron [12]. If the electromagnetic field is extremely powerful, the vacuum will be excited to produce $e^−-e^+$ pairs [16]. Dupays et al. pointed out that the optical properties of quantum vacuum could be modified by magnetic field, which will influence the propagation of light emitted by a magnetized neutron star [13]. Rikken and Rizzo predicted that magnetoelastic birefringence will occur in vacuum when magnetic and electric fields are perpendicularly applied [17]. The phenomena that the propagation of light can be modified by applying electromagnetic fields to the vacuum are just similar to the Kerr electro-optic effect and the Faraday magneto-optic effect in dielectric medium. This similarity between the vacuum and the dielectric medium implies that vacuum must also have its inner structure, which could be influenced by electric charges or currents.

In this letter, both the electric field and magnetic field will be analysed on the basis of vacuum polarization. The energy of electric and magnetic fields will be figured out by using the intensity of vacuum polarization. The electrical and magnetic forces will be discussed considering the action of the nearby virtual dipoles in vacuum. By doing this, the relation between the electromagnetic fields and the quantum vacuum will be clarified. The electromagnetic wave will then be described as an effect of successional changing of vacuum polarization. Also, it will be shown that the virtual dipoles around an elementary charge have a characteristic half length on average, which leads to some interesting findings further.

First, examining the electric displacement vector $D$ in a dielectric medium:

$$D = P + \varepsilon_0 E, \quad (1)$$

where $P$ represents the polarization of dielectric medium, $\varepsilon_0$ is the permittivity of vacuum, $E$ denotes the electric field intensity in the medium. It is noticed that in the equation $\varepsilon_0 E$ can be interpreted as the polarization of vacuum $P'$ [12], that is

$$P' = \varepsilon_0 E. \quad (2)$$

The vacuum polarization is based on the knowledge that there are virtual positive-negative charges, for example, but not limited to, virtual $e^−-e^+$ pairs, being randomly created and annihilated in vacuum. Similar to a dielectric medium, the virtual charge pairs in a vacuum will be polarized and aligned by the real charges, or by the so-called “external electric field”. For example, a vacuum will be polarized in a spherical symmetry by a positive electric charge $+Q$ as shown in Fig. 1, where the solid $\bigoplus$ denotes the real charge $+Q$. The dashed $\bigcirc$ is a simplified representation of a polarized virtual charge pair in the vacuum, and the direction from the negative virtual charge to the positive one indicates the direction of the electric field.

The intensity of vacuum polarization can be defined as $P' = \sum p'/V$, where $p'$ is the electrical dipole moment of a single polarized virtual charge pair, and $V$ is a volume. If there are $N$ virtual vacuum dipoles in volume $V$, each dipole has an electrical dipole moment $p' = q' \cdot 2a$ ($2a$ is the average distance between the two vacuum virtual charges $\pm q'$ — the reason we say “average” here is that, for an individual virtual dipole, the length $2a$ can be quite different due to the uncertainties in quantum mechanics), we have

$$P' = N \frac{q'}{V} \cdot 2a. \quad (3)$$
Eq. (2) can be rewritten as \( E = \frac{P'}{\varepsilon_0} \), which means that an electric field is just a polarized distribution of the vacuum virtual charge pairs. At a given point, the field direction depends on the polarization direction. And the field intensity is directly proportional to the intensity of vacuum polarization or to the areal density of virtual polarization charges of the vacuum. For the vacuum around a real charge \( Q \), the areal density of virtual polarization charges \( \sigma' \) at a distance \( r \) from the centre of the charge \( Q \) is \( \sigma' = Q' / 4\pi r^2 \), where \( Q' \), being equal to \( Q \) in magnitude, is the total virtual polarization charges of the vacuum on the spherical Gaussian surface of radius \( r \). Therefore, the field intensity is found to be

\[
E = \frac{P'}{\varepsilon_0} = \frac{\sigma'}{\varepsilon_0} = \frac{1}{4\pi \varepsilon_0} \frac{Q}{r^2}. \tag{4}
\]

Under the above interpretation of electric field, the field energy in a vacuum can be understood as the polarization energy of the vacuum, i.e., the potential energy of the virtual polarization charges. That is, the energy density of an electric field (EF) in vacuum will be \( w_{\text{EF}} = N(2 : \frac{1}{2} k a^2) / 2aS \), where \( N \) is the number of virtual vacuum dipoles in a volume of \( V = 2aS \), \( S \) is an area perpendicular to the direction of polarization, and the areal density of virtual polarization charges is \( \sigma' = N q' / S \), \( k \) is the stiffness factor, which satisfies \( F = ka = q' E = q' \sigma' / \varepsilon_0 \). Combining these relations, we have

\[
w_{\text{EF}} = \frac{1}{2} \frac{\sigma'^2}{\varepsilon_0} = \frac{1}{2} \varepsilon_0 E^2. \tag{5}\]

Using the concept of vacuum polarization, the force exerted by an electric field on a test charge can be analyzed as the action of the nearby virtual dipoles in vacuum. Fig. 2 sketches the vacuum polarized by the resultant field of an external field \( E \) and a test charge \( +q \), where we can see that there will be an attraction between the test charge and the nearby virtual dipoles. But the vacuum on the right side of the test charge is more polarized than that on the left side. Then the test charge tends to move to the right side, i.e., in the direction of the external field. This is what we say that the test charge is exerted an electrical force \( F = qE \).

Second, examining the magnetic intensity vector \( H \) in a magnetic medium

\[
(-H) = \mathbf{M} + \left( -\frac{\mathbf{B}}{\mu_0} \right), \tag{6}\]

where \( \mathbf{M} \) is the magnetization intensity of the medium, \( \mu_0 \) is the permeability of vacuum, \( \mathbf{B} \) is the magnetic induction intensity, the last term \( (-\mathbf{B}/\mu_0) \) can be conceived as the magnetization of vacuum \( \mathbf{M}' \), that is

\[
\left( -\frac{\mathbf{B}}{\mu_0} \right) = \mathbf{M}' = \frac{\sum \Omega'}{V} = \frac{N}{V} i' \mathbf{s}_0,
\tag{7}\]

where \( \mathbf{\Omega}' = i' \mathbf{s}_0 \) is the magnetic moment of a vacuum virtual circular current \( i' \) with an enclosed area \( \mathbf{s}_0 \), \( \mathbf{s}_0 \) is the unit vector, being opposite to the magnetic direction, \( N \) is the total number of the virtual circular currents in volume \( V \).

Generally, there is neither free charge nor molecular current in a vacuum. But still, there could be virtual circular currents formed in a magnetized vacuum. This is illuminated in Fig. 3,
where a charge \(+Q\) is moving rightward in vacuum. From the figure, we can see that the vacuum polarization will be in a continuous rearrangement when the charge \(Q\) is in a directional movement. For example, the virtual dipole at a certain point in vacuum will rotate an angle of \(\Delta\theta\) when \(Q\) moves a distance of \(\Delta l = v\Delta t\) (here \(v\) is the velocity of \(Q\), \(\Delta t\) is the time interval). At the same time, the original direction of polarization at this point will translate a distance of \(\Delta l\). This translation is equivalent to a virtual circular current, which is lined out with a parallelogram in the figure (where the right translation of \(-q'\) equals to a left translation of \(+q'\)). It is the virtual currents of this type that constructed the magnetic field \(\mathbf{B}\) in vacuum. Using Eqs. (2), (3) and (7), the magnetic field in Fig. 3 can be deduced as

\[
\mathbf{B} = -\mu_0 \frac{N}{V} q' \frac{2a\Delta l}{\Delta t} \sin \theta_0 = -\mu_0 v P' \sin \theta_0 = -\mu_0 e_0 E v \sin \theta_0 = \frac{v}{c^2} \times \mathbf{E},
\]

(8)

where \(c = 1/\sqrt{\mu_0 \varepsilon_0}\) is the velocity of light in vacuum.

The above result is just in agreement with what we have known in electromagnetics and is correct in the cases of relativity. It indicates that a magnetic field is also based on the polarization of vacuum, or in more detail, a magnetic field is a rearrangement of the vacuum polarization which contains a series of virtual circular currents in vacuum. These currents are in fact a visual effect of the rotation of the vacuum virtual dipoles caused by the movement of charge \(Q\). This rotation as shown with a curved arrow and \(\Delta\theta\) in Fig. 3 corresponds to a kinetic energy of the vacuum virtual charges, which is just the energy of a magnetic field. Considering that the angular velocity of the dipole rotation is \(\omega = \Delta l/\Delta t = v \sin \theta / r\), the energy density of the magnetic field (MF) in vacuum around a moving charge \(Q\) can be given as

\[
w_{\text{MF}} = \frac{N}{V} \cdot \frac{1}{2} \frac{m'(\omega a)^2}{(m' \cdot q')^2} = \frac{1}{2} \frac{B^2}{\mu_0} \cdot \left( \frac{4\pi}{\mu_0 q'} \cdot \frac{a}{Q} \right),
\]

(9)

where \(m'\) is the equivalent mass of the virtual charge \(q'\). This equation is just the well-known formula of magnetic energy density \(w_{\text{MF}} = B^2/2\mu_0\) when

\[
\left( \frac{4\pi}{\mu_0} \cdot \frac{m' \cdot a}{q' \cdot Q} \right) = 1,
\]

(10)

where \(m'/q'\) is the mass-to-charge ratio of a vacuum virtual charge, and \(a/Q\) is the ratio of the dipole average length to the moving charge \(Q\).

Similar to the electrical force, we say that the magnetic force exerted on a test moving charge can be understood as the action of the nearby virtual circular currents in the magnetized vacuum. Fig. 4 sketches such an interaction, where the magnetization intensity of vacuum caused by an external uniform magnetic field \(\mathbf{B}\) and a moving charge \(+q\) is represented by the chromatic diagram and the contour lines. In each contour map, the line labeled by “0” denotes the boundary between the two opposite (i.e., the clockwise and anticlockwise) circular currents in vacuum. According to the figure and what we have known about the behavior of a moving charge in an external magnetic field, it is reasonable to suppose that a moving charge tends to move along this boundary. Since the larger the external field \(\mathbf{B}\), the more curved the boundary line as shown with thick arrows in the figure, we then know that the stronger the field \(\mathbf{B}\), the heavier the force \(\mathbf{F}\) exerted perpendicularly on the moving charge. It is compatible with the definition formula \(\mathbf{F} = q\mathbf{v} \times \mathbf{B}\).

The above analysis of the electromagnetic energy and force demonstrated that there can be an intrinsic connection between the electromagnetic field and the quantum vacuum. That is to say, both the electric field and magnetic field can be understood as the effect of vacuum polarization. To emphasize this, we will present two key points below:

1) An electric field is a polarized distribution of the vacuum virtual dipoles, and a magnetic field in vacuum is a rearrangement of the vacuum polarization.

This result can help us understand the electromagnetic phenomena on a more profound basis. For example, the formation of electromagnetic wave can then be interpreted through the vacuum polarization. Since an electric field is a polarized distribution of the vacuum virtual dipoles, when an electric field is changed, there will be a virtual polarization current occurring in the vacuum. This polarization current, or the so-called “displacement current”, will then cause a magnetic field. On the other hand, a magnetic field is a rearrangement of vacuum polarization, or in other words, a rotation of the virtual dipoles, which in effect forms the virtual circular currents in vacuum. When a magnetic field is changed, there will be a tendency of keeping the original dipole rotations or the original vacuum circular currents, which serves as a rotational electric field. In brief, a changing electric field generates a magnetic field, and a changing magnetic field induces an electric field. The repetition of this process gives rise to a propagation of electromagnetic wave in space.

2) The vacuum virtual dipoles around an elementary charge \(e\) have a characteristic half length on average:

\[
a = \frac{\mu_0}{4\pi} \cdot \frac{q'}{m' \cdot Q},
\]

(11)

which is obtained from Eq. (10). Substituting the charge-to-mass ratio \(q'/m' = e/m_e = 1.758 \times 10^{11}\) C/kg, and the elementary charge \(Q = e = 1.6 \times 10^{-19}\) C, into Eq. (11), we found that:

\[
a = 2.8 \times 10^{-15}\ \text{m}.
\]

(12)

It is interesting to find that this length is just the electron
FIG. 4: The vacuum magnetized by an external uniform magnetic field $B$ pointing out of the page and a right moving charge $+q$ simultaneously: (a) $B = 0$; (b) $B = B_0$; (c) $B = 2B_0$.

classical radius or about the size of a proton.

This result will lead to further findings. For example:

a) The step distribution of the energy density of the electric field around an electron.

According to Eqs. (3), (4), (5) and (11), we see that there can be a step change of the energy density of the electric field around an electron as shown in Fig. 5, where the step width $2a$ is the average length of the vacuum virtual dipoles, and the energy density unit is $A = e^2/32\pi\varepsilon_0a^4$; whereas in the classical theory the energy density of the field is inversely proportional to $r^4$ in a smooth way ($r \in [0, \infty]$ is the distance from the electron).

Just as that the energy quantum solved the problem of “ultraviolet catastrophe” in black body radiation, the step distribution of energy density will eliminate the divergence in calculating the electrostatic energy of an electron. This divergence, as we know that, is inevitable in the classical theory of electromagnetism. In the quantum theory of fields, the divergence is constrainedly evaded through the introduction of renormalization. But here, according to the step distribution of the energy density as shown in Fig. 5, the calculation of the electron’s electrostatic energy turns to be:

$$W = \int w_{\text{EF}} dV$$
$$= \int \frac{1}{2} \varepsilon_0 E^2 \cdot 4\pi r^2 dr$$
$$\sim \int_{a/2}^{\infty} \frac{1}{2} \varepsilon_0 \left( \frac{1}{4\pi\varepsilon_0} \frac{e^2}{r^2} \right) \cdot 4\pi r^2 dr$$
$$= \frac{1}{4\pi\varepsilon_0} \frac{e^2}{a} = m_ec^2 \neq \infty. \quad (13)$$

This calculation differs from the semiclassical models incorporating short-distance cutoffs as the work of Boyer [18], etc., both in method and in idea.

b) The relation between the fine structure constant and the vacuum polarization distribution.

Ever since it was discovered, the fine structure constant $\alpha = e^2/4\pi\varepsilon_0\hbar c$ has been a great mystery. Now the step distribution of the vacuum polarization energy offers us a clue to

FIG. 5: The energy density distribution of the electric field around an electron.
understand the constant. From Eq. (11) we know that, for a moving electron in an atom, the corresponding average half length \( a \) of the surrounding virtual dipoles satisfies

\[
\frac{a}{R} = \alpha^2,
\]  

(14)

where \( R \) is the Bohr radius. This equation implies that there exists a deep relation between the fine structure constant and the vacuum polarization.

With the above relation, we can then calculate the energy difference when the electron in a ground-state hydrogen atom has a change of radial position \( \Delta r = 2a \) from the Bohr radius \( R \), that is

\[
\Delta W = \left| \Delta \left( \frac{1}{8\pi\varepsilon_0} \frac{e^2}{r} \right) \right| = \left| -\frac{1}{4\pi\varepsilon_0} \frac{e^2}{R} a^2 \right| \alpha^2,
\]  

(15)

which is just the energy order of the atomic fine structure.

c) An extremely high energy density of the electromagnetic field.

Fig. 5 indicates that there can be an extremely high energy density of the electric field around an electron at \( r \in [0, 2a] \), that is:

\[
w_{\text{max}} = \frac{1}{2} \varepsilon_0 E_a^2 = \frac{1}{2} \varepsilon_0 \left( \frac{1}{4\pi\varepsilon_0} \frac{e}{a^2} \right)^2 = 1.5 \times 10^{29}\text{J/m}^3.
\]  

(16)

The order of this result can also be obtained supposing that all the virtual dipoles are composed of charge pairs \( e^- - e^+ \) with the average space between every two neighboring dipoles being \( 2a = 5.6 \times 10^{-13}\text{m} \).

Since the energy density of a magnetic field has the same order as that of an electric field, the above value can be considered as a corresponding extremely high energy density of the electromagnetic field. This energy density can be converted into an optical power density:

\[
I = w_{\text{max}} \cdot c \sim 10^{33}\text{W/cm}^2,
\]  

(17)

which is 4 order higher than that of the Schwinger critical intensity (\( \sim 10^{29}\text{W/cm}^2 \)) for \( e^- - e^+ \) pair production in vacuum [16].

The above obtained extremely high energy density of the electromagnetic field or extremely high optical power density is significant to the ultrastrong-field physics, the pursuing of super powerful light source and the pair production in vacuum, etc.

In summary, according to the analysis of the energy and force of the electric and magnetic fields on the basis of vacuum polarization, it is concluded that an electric field is a polarized distribution of the vacuum virtual dipoles, and that a magnetic field in vacuum is a rearrangement of the vacuum polarization. Thus, the electromagnetic wave can be regarded as a successional changing of the vacuum polarization in space. Also, it is found that the virtual dipoles around an elementary charge possess an average half length \( a = 2.8 \times 10^{-15}\text{m} \). This result leads to the knowledge that an electric field has a step distribution of the energy density, which eliminated the divergence in calculating the electron’s electrostatic energy. And it is known that there is a relation between the fine structure constant and the vacuum polarization distribution, which reduced the mystery of the constant \( \alpha \). Finally, it is figured out that an extremely high energy density of the electromagnetic field can be \( \sim 10^{29}\text{J/m}^3 \), which implies an optical power density \( \sim 10^{33}\text{W/cm}^2 \) far higher than the Schwinger critical value. With these interesting findings, we anticipate that the vacuum polarization investigation of the fields will be developed further and applied to more fundamental problems of physics.

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