Negative Energy: From Lamb Shift to Entanglement

Shou-Liang Bu

School of Physics and Optical Information Technology,
Jiaying University, 514015 MeiZhou, China

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Abstract

“Negative energy” has been one of the most enduring puzzles in quantum theory, whereas the present work reveals that it actually plays a central role in clarifying various controversies of quantum theory. The basic idea is contained in a hypothesis on negative energy, and it is shown that the idea: (1) is compatible with both relativistic quantum mechanics and known experimental results; (2) helps to clarify the essence of matter waves, and therefore better understand the reality of the wave function, the so-called ‘wave-packet reduction’ occurring in quantum measurement, and the ghost like correlations between entangled systems; (3) is helpful for distinguishing the vacuum from the ground state of the quantized field, and may supply a possible way for removing the deep-rooted infinities in quantum field theory. The vacuum energy density of the electromagnetic field is calculated here as an example. By employing the same idea, the Lamb-Shift is recalculated in a different way from conventional renormalization method, yet the same result as Bethe’s can be definitely obtained.

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*Electronic address: shouliang@jyu.edu.cn
I. INTRODUCTION

Controversies continuously associate with quantum mechanics since its foundation in the early twentieth century, ranging from the reality of the wave function, the so-called ‘wave-packet reduction’ occurring in quantum measurement, the series of infinities emerging in quantum field theory, to the latest nonlocal correlations between quantum entangled systems.

For instance, more and more theoretical and experimental works demonstrate that entangled systems may violate the separability principle\[1–3\], i.e., two dynamically independent systems possess their own separate state, advocated by Einstein et al. One cannot but ask how the ‘nonlocal correlations’ between entangled systems are established, by considering that there exist bounds on the speed of transmission of signals or physical effects as specified by special relativity.

The problem of negative energies is another most enduring puzzle in quantum theory. It is well known that relativistic quantum mechanics contains negative energy states as well as familiar positive ones. In order to ensure the completeness of state space, these negative energy states can not be simply discarded, however if people directly accept these negative energy states, one problem then arises, namely an electron in a positive energy state should be able to emit a photon and then make a transition to a negative energy state; moreover the process could even evolve into a disastrous cascades by continuously emitting an infinite amount of photons. Historically, in order to solve this problem, Dirac had imagined that all the states of negative energy are occupied and the Pauli exclusive principle thus keeps positive energy electrons from making transitions to negative energy states\[4\]. However, this theory faces a number of new and immediate difficulties such as what about all that change and negative energy, where is electric field of the ubiquitous negative energy electron, why is there an asymmetry in the vacuum between negative and positive energy, and so forth.

In the present work, it is demonstrated that the negative energy is not only compatible with the theory, but also helpful for solving various puzzles and controversies in quantum theory. Briefly speaking, once the existence of negative energy (and matter) is identified, we can more deeply understand the reality of the matter waves, the relations between particle and wave, and the essence of the so-called ‘wavepacket reduction’; and we can further reveal the secrets hidden in the double-slit interference and the entangled systems. Moreover, by
using of the property of matter with negative energies, the infinity of vacuum energy density emerged in the traditional quantum field theory can be easily removed, and the Lamb-shift can also be correctly derived in a completely different way from conventional renormalization method. Additionally, in the light of the idea presented here, we may rethink about the nature of the vacuum, and distinguish the vacuum from the ground state of the quantized field, and this may further point out a possible way for removing other infinities rooted in the traditional quantum field theory.

The basic idea is contained in the following hypothesis: *For each kind of particle with positive energy, there always exists a kind of negative energy particle which owns completely opposite intrinsic properties, and the physical laws both kinds of particle obey have the same covariant form.*

In particular, the intrinsic property includes the rest mass of the particle.

The structure of the paper is as follows. First, in section 2, the mathematical descriptions of negative as well as the positive energy matter are presented. Then in section 3 and 4, the vacuum energy density and the Lamb-Shift is recalculated in the light of the present idea. In section 5, the essence of matter waves, relations between particle and wave, the so-called ‘wave packet reduction’, etc. are deeply explored. Section 6 focuses on the superposition state, in particular, the double-slit experiment and the entangled systems are analyzed. Finally, in section 7, some discussions about the vacuum versus the ground state of the quantized field are given, and it is illustrated that the traditional quantum field theory is actually equivalent to an extreme case: the vacuum has an infinite formal temperature.

II. THE MATHEMATICAL DESCRIPTIONS

Here, a mathematical description for both positive and negative energy field is developed, for specification, we take the electromagnetic field and the Dirac field as typical examples. *The Electromagnetic Field* — Let $A^{(\pm)}_{\mu}(x)$ describe the photons fields with superscripts $(\pm)$ denoting positive and negative energy, according to the hypothesis, the covariant Maxwell equations for free electromagnetic field are

$$\Box A^{(\pm)}_{\mu}(x) = 0. \quad (1)$$
To derive Eq. (1), let’s set the Lagrangian density of positive and negative energy field as follows,

$$\mathcal{L}^{(\pm)} = \mp \frac{1}{2} \left( \partial_{\mu} A^{(\pm)}_{\mu}(x) \right) \left( \partial^{\nu} A^{(\pm)\nu}(x) \right),$$

(2)

with the constraint $\partial_{\mu} A^{(\pm)\mu}(x) = 0$. It should be noted that Lagrangian density proposed here is not necessary the only possible choice for mathematical realization of the hypothesis.

In order to quantize the electromagnetic fields, one takes

$$A^{(\pm)\mu}(x) = \sum_{r\kappa} \sqrt{\frac{\hbar c^2}{2V\omega_k}} \left[ \varepsilon_\mu^\pm(k) a^{(\pm)}(k)e^{-ikx} + \varepsilon_\mu^\mp(k) a^{(\pm)\dagger}(k)e^{ikx} \right],$$

(3)

with $r = 0, \cdots, 3$, $k^0 = \omega_k/c = |k|$, and the vectors $\varepsilon_\mu^\mu(k)$ describe four linearly independent polarization states. The commutation relations are

$$[a^{(\pm)}_r(k), a^{(\pm)\dagger}_{r'}(k')] = \zeta_r \delta_{r'r} \delta_{kk'},$$

$$[a^{(\pm)}_r(k), a^{(\pm)}_{r'}(k')] = [a^{(\pm)\dagger}_r(k), a^{(\pm)\dagger}_{r'}(k')] = 0,$$

(4)

here, $\zeta_r = 1$ for $r = 1, 2, 3$, and $-1$ for $r = 0$.

From Eq. (11) - (3), the Hamiltonian operator of the positive and negative energy fields are given by

$$\mathcal{H}^{(\pm)} = \int d^3x \left[ \pi^{(\pm)\mu}(x)A^{(\pm)\mu}(x) - \mathcal{L}^{(\pm)} \right]$$

$$= \sum_{r\kappa} (\pm\hbar \omega_k) \zeta_r \left[ a^{(\pm)\dagger}_r(k) a^{(\pm)}_r(k) + \frac{1}{2} \right],$$

(5)

here $\pi^{(\pm)\mu}(x) = \frac{\partial \mathcal{L}^{(\pm)}(x)}{\partial A^{(\pm)\mu}(x)} = -\frac{1}{2} \dot{A}^{(\pm)\mu}(x)$. Other observables such as momentum, angular momentum etc. can be similarly obtained.

Eq. (5) shows that, as $a^{(\pm)\dagger}_r(k)a^{(\pm)}_r(k)$ being the number operator of the positive energy photon ($+\hbar \omega_k$), $a^{(\mp)\dagger}_r(k)a^{(\pm)}_r(k)$ denotes the number operator of the negative energy photon ($-\hbar \omega_k$). Let $\{|n^{(\pm)}_r(k)\rangle, (n^{(\pm)}_r(k) = 0, 1, 2, \ldots\}$ denote the orthonormal eigenvectors of $a^{(\pm)\dagger}_r(k)a^{(\pm)}_r(k)$, then it is familiarly known that $a^{(\pm)\dagger}_r(k)|n^{(\pm)}_r(k)\rangle = \sqrt{n^{(\pm)}_r}\langle n^{(\pm)}_r|n^{(\pm)}_r(k)\rangle = n^{(\pm)}_r|n^{(\pm)}_r(k)\rangle$ and $a^{(\pm)}_r(k)|n^{(\pm)}_r(k)\rangle = \sqrt{n^{(\pm)}_r}\langle n^{(\pm)}_r|n^{(\pm)}_r(k) - 1\rangle$ (with $n^{(\pm)}_r(k) \neq 0$). Analogously, for negative energy field, let $\{|n^{(\mp)}_r(k)\rangle, (n^{(\mp)}_r(k) = 0, 1, 2, \ldots\}$ denote the orthonormal eigenvectors of $a^{(\mp)\dagger}_r(k)a^{(\mp)}_r(k)$, i.e., $a^{(\mp)\dagger}_r(k)a^{(\mp)}_r(k)|n^{(\mp)}_r(k)\rangle = n^{(\mp)}_r(k)|n^{(\mp)}_r(k)\rangle$ and $a^{(\mp)}_r(k)|n^{(\mp)}_r(k)\rangle = \sqrt{n^{(\mp)}_r(k)|n^{(\mp)}(k) - 1\rangle$ (with $n^{(\mp)}_r(k) \neq 0$).
From Eq. (3), \( \mathcal{H}^{(+)}|n_r^{(+)}(k)\rangle = +\hbar\omega_k(n_r^{(+)}(k) + \frac{1}{2})|n_r^{(+)}(k)\rangle \), while \( \mathcal{H}^{(-)}|n_r^{(-)}(k)\rangle = -\hbar\omega_k(n_r^{(-)}(k) + \frac{1}{2})|n_r^{(-)}(k)\rangle \). For the positive energy field, \( \{+\hbar\omega_k(n_r^{(+)}(k) + \frac{1}{2})\} \) \( (n_r^{(+)}(k) \geq 1) \) are the energy of the \( n \)th excited state, while \( \{-\hbar\omega_k(n_r^{(-)}(k) + \frac{1}{2})\} \) \( (n_r^{(-)}(k) \geq 1) \) the energy of the \( n \)th excited state of the negative energy field. In the case of positive energy, the height of a state’s energy is considered to be determined by the amount of the number of photons \( (+\hbar\omega_k) \), symmetrically, the height of a state of negative energy field should also be determined by the amount of the number of photons \( (-\hbar\omega_k) \). Therefore, just like \( (+\mu_r^{(+)}(k) + \frac{1}{2})\hbar\omega_k \) is a higher level than \( (+\nu_r^{(+)}(k) + \frac{1}{2})\hbar\omega_k \) when \( \mu_r^{(+)}(k) > \nu_r^{(+)}(k) \), \( -(\mu_r^{(-)}(k) + \frac{1}{2})\hbar\omega_k \) is also a higher level than \( -(\nu_r^{(-)}(k) + \frac{1}{2})\hbar\omega_k \) for negative energy field if \( \mu_r^{(-)}(k) > \nu_r^{(-)}(k) \). The statements discussed here can be easily generalized to other quantized fields.

The Dirac Field — In terms of the hypothesis, the Dirac equation for positive and negative rest mass \( \pm m \) has the same form

\[
(i\hbar\gamma^\mu\partial_\mu - mc) \psi^{(\pm)}(x) = 0, \tag{6}
\]

with \( m > 0 \) and \( \gamma^\mu \) \( (\mu = 0, 1, 2, 3) \) are Dirac \( 4 \times 4 \) matrices. To derive the Dirac equation (6), set the Lagrangian density of positive and negative energy field as

\[
\mathcal{L}^{(\pm)} = \pm c\bar{\psi}^{(\pm)}(x) (i\hbar\gamma^\mu\partial_\mu - mc) \psi^{(\pm)}(x), \tag{7}
\]

with \( \bar{\psi}^{(\pm)}(x) = \psi^{(\pm)t}(x)\gamma^0 \).

By expanding it in terms of the complete set of plane wave solutions, the Dirac field is quantized,

\[
\psi^{(\pm)}(x) = \sum_{r,p} \sqrt{\frac{mc^2}{VE_p}} \left[ c_r^{(\pm)}(p)u_r(p)e^{-ipx/\hbar} + d_r^{(\pm)}(p)v_r(p)e^{ipx/\hbar} \right], \tag{8}
\]

with \( E_p = cp_0 = +\sqrt{m^2c^4 + c^2p^2} \), and the commutation relation:

\[
\begin{align*}
[c_r^{(\pm)}(p), c_s^{(\pm)t}(p')] &= [d_r^{(\pm)}(p), d_s^{(\pm)t}(p')] = \delta_{rs}\delta_{pp'}, \\
[c_r^{(\pm)}(p), c_s^{(\pm)}(p')] &= [d_r^{(\pm)}(p), d_s^{(\pm)}(p')] = 0. \tag{9}
\end{align*}
\]
The Hamiltonian of the Dirac field, from Eq. (6) - (9) is given by

\[ \mathcal{H}^{(\pm)} = \int d^3x \bar{\psi}^{(\pm)}(x) \left[ -i\hbar c \gamma^j \partial_j + mc^2 \right] \psi^{(\pm)}(x) \]

\[ = \int d^3x \left\{ \pi_j^{(\pm)}(x) \dot{\psi}_j^{(\pm)}(x) + \bar{\pi}_j^{(\pm)}(x) \dot{\bar{\psi}}_j^{(\pm)}(x) - \mathcal{L}^{(\pm)} \right\} \]

\[ = \sum_{r \mathbf{p}} (\pm E_p) \left[ c_r^{(\pm)\dagger}(\mathbf{p}) c_r^{(\pm)}(\mathbf{p}) + d_r^{(\pm)\dagger}(\mathbf{p}) d_r^{(\pm)}(\mathbf{p}) - 1 \right], \quad (10) \]

here \( \pi_\alpha^{(\pm)}(x) = \frac{\partial \mathcal{L}^{(\pm)}}{\partial \dot{\psi}_\alpha^{(\pm)}(x)} = i\hbar \dot{\psi}_\alpha^{(\pm)}(x) \), \( \bar{\pi}_\alpha^{(\pm)}(x) = \frac{\partial \mathcal{L}^{(\pm)}}{\partial \dot{\bar{\psi}}_\alpha^{(\pm)}(x)} = 0 \). One notes that, for the ground state, there is an infinite energy for positive or negative field alone. In principle, it is not difficult to derive the mathematical forms of other physical quantities, however, this is not the main goal of the present work.

Eq. (10) tells that, if let \( c_r^{(\pm)\dagger}(\mathbf{p}) c_r^{(\pm)}(\mathbf{p}) \) and \( d_r^{(\pm)\dagger}(\mathbf{p}) d_r^{(\pm)}(\mathbf{p}) \) denote the number operator of the particle \((+m, -e)\) and \((+m, +e)\), respectively, \( c_r^{(-)\dagger}(\mathbf{p}) c_r^{(-)}(\mathbf{p}) \) and \( d_r^{(-)\dagger}(\mathbf{p}) d_r^{(-)}(\mathbf{p}) \) then denote the number operator of the particle \((-m, -e)\) and \((-m, +e)\), respectively. Other observable quantities such as momentum etc. can be similarly derived.

Though we have just investigated the Maxwell and Dirac field here, the same idea can also be applied to other cases such as Klein-Gordon field and gravitation field, etc.

Now, let’s reconsider the fictitious transition between positive and negative energy states. In previous considerations, it is taken for granted that the same one positive mass particle has equally the positive and negative energy states, and this assumption further leads to the unreal transitions between positive and negative energy states. As seen from Eq. (11), (5), (6) and (10), different kinds of particle may obey the same covariant equation, whereas the positive and negative energy states are respectively attributed to particles with positive and negative energy. As is known for positive energy states, the energy level of a state is considered to be higher, if this state contains more number of quantum. Thus, the lowest energy state is \( \{ | + \frac{1}{2} \hbar \omega_k \rangle \} \), and the excited states are \( \{ | n \hbar \omega_k + \frac{1}{2} \hbar \omega_k \rangle \} \) with \( n \geq 1 \). It is similar for negative energy states, if a state contains more number of quantum, its energy level is more high. Therefore, the lowest energy state is \( \{ | - \frac{1}{2} \hbar \omega_k \rangle \} \), and the excited states are \( \{ | - n \hbar \omega_k - \frac{1}{2} \hbar \omega_k \rangle \} \) \( (n \geq 1) \), respectively. Negative energy particle jumping from the ground state to the excited state, or from the state \( \{ | - n_1 \hbar \omega_k - \frac{1}{2} \hbar \omega_k \rangle \} \) to \( \{ | - n_2 \hbar \omega_k - \frac{1}{2} \hbar \omega_k \rangle \} \) with \( n_1 < n_2 \), needs to absorb one ore more negative energy photon(s) with energy \( (-\hbar \omega_k) \) rather than emit positive energy photon(s) with energy \( (+\hbar \omega_k) \), while the fictitious transition between positive and negative energy states does not exist at all.
III. THE VACUUM ENERGY DENSITY

Traditionally, in quantum field theory, all states that do not contain net particle are assumed to be the same one. In particular, the vacuum is assumed to be identical to the ground state of the quantized field, while the ground state of the quantized field is considered to be definite and unique, and it is taken as $\otimes \prod_k | + \frac{1}{2} \hbar \omega_k \rangle$, here $| + \frac{1}{2} \hbar \omega_k \rangle$ denotes the lowest energy state of quantized field with frequency $\omega_k$. This directly or indirectly leads to series of difficulties in the quantum field theory. The first and also the most obvious one is the infinity of vacuum energy density by considering that there are infinite number of vibration freedoms in the quantized field and each has the lowest energy $+ \frac{1}{2} \hbar \omega_k$. Undoubtedly, this is unreasonable.

The present work shows, if the negative energy field as well as the positive one is also considered in the theory, the infinity of the vacuum energy density can be immediately removed. Further, as stated in the final section, by carefully distinguishing various states which all have no net particle, the present work may supply a possible way which does not violate any mathematical rules to remove other infinities emerging in the quantum field theory.

Here, we take the electromagnetic field as an example in the discussions, but the results can be easily generalized to other fields. From Eq. (5), the total Hamiltonian consisting of both the positive and negative energy field is

$$\mathcal{H} = \mathcal{H}^{(+)} + \mathcal{H}^{(-)} = \sum_{rk} \hbar \omega_k \zeta_r \left[ a_r^{(+)}(k)^{\dagger} a_r^{(+)}(k) - a_r^{(-)}(k)^{\dagger} a_r^{(-)}(k) \right].$$

(11)

Since there is no net particle in the vacuum, one immediately gets that the vacuum expectation of $\mathcal{H}$ must be 0. Thus, the total energy density of vacuum is 0, not infinity as given in the traditional quantum field theory.

IV. THE LAMB-SHIFT

It is well-known that, in terms of the Dirac theory, the $2S_{1/2}$ and $2P_{1/2}$ levels of hydrogen are degenerate. In 1947, the measurements by Lamb and Retherford gave about $1000 \text{MHz}$ for the level splitting $E(2S_{1/2}) - E(2P_{1/2})$. This shift of the bound-state energy levels and
the resulting splitting are known as the Lamb-Shift.

Bethe in 1947 gave an approximate non-relativistic derivation of the Lamb-Shift, obtaining a surprising good result considering the nature of the calculation [6].

Here the Lamb-Shift is recalculated in terms of the idea presented in this work. It is shown that, by considering both positive and negative energy field, the correct level shifts can be derived in a very simple and direct way. On the one hand, the classic non-relativistic second-order perturbation method is employed in the derivation as Bethe had done; On the other hand, Bethe’s calculation is mainly based on the idea of mass renormalization of electron, however, the present calculation does not concern the renormalization process at all. It is shown that the same result as Bethe’s can still be obtained. The natural unit is taken in this subsection for simplicity.

The interaction Hamiltonian of matter and positive and negative energy field is

$$H_{I}^{(\pm)} = -\frac{e}{m} \mathbf{A}^{(\pm)} \cdot \mathbf{p}. \quad (12)$$

Based on the present idea, we must consider the contributions of both positive and negative energy field. First, for the positive field, the level shift of a hydrogenic state $$|n\ell\rangle = \phi_{n\ell}(\mathbf{x})$$ (where $$n$$ and $$\ell$$ are the principal and angular momentum quantum number) is given by

$$\delta E^{(+)}(n\ell) = -\sum_{\lambda} \sum_{k} \sum_{r=1,2} |\langle \lambda, n_r(k) = 1 | H_{I}^{(+)} | n\ell \rangle|^2 \frac{1}{E_{\lambda} + k - E_{n}}$$

$$= -\sum_{\lambda} \sum_{k} \sum_{r=1,2} \left( \frac{e}{m} \right)^2 \frac{1}{2Vk} \frac{|\langle \lambda | \mathbf{p} | n\ell \rangle|^2}{E_{\lambda} + k - E_{n}}$$

$$= -\frac{1}{6\pi^2} \left( \frac{e}{m} \right)^2 \int_{0}^{\infty} kdk \sum_{\lambda} \frac{|\langle \lambda | \mathbf{p} | n\ell \rangle|^2}{E_{\lambda} + k - E_{n}}, \quad (13)$$

here the intermediate state $$|\lambda, n_r(k) = 1 \rangle$$ consists of the hydrogen atom in one of the complete set of states $$|\lambda \rangle \equiv \phi_{\lambda}(\mathbf{x})$$ together with one transverse photon, and $$E_{\lambda}$$ and $$E_{n}$$ are the energy eigenvalues of $$|\lambda \rangle$$ and $$|n\ell \rangle$$; in addition, $$\langle \lambda | \mathbf{p} | n\ell \rangle = \int d^3(\mathbf{x}) \phi_{\lambda}^{*}(\mathbf{x})(-i\nabla)\phi_{n\ell}(\mathbf{x})$$.

Next, the contributions of negative energy field to the level shift of a hydrogenic state $$|n\ell \rangle$$ can be similarly derived

$$\delta E^{(-)}(n\ell) = -\frac{1}{6\pi^2} \left( \frac{e}{m} \right)^2 \int_{0}^{\infty} kdk \sum_{\lambda} \frac{|\langle \lambda | \mathbf{p} | n\ell \rangle|^2}{E_{\lambda} - k - E_{n}}. \quad (14)$$

here, virtual photon with negative energy $$(-k)$$ has been taken in the calculations.
From Eq. (13) and (14), the total level shift is

\[
\delta E(n\ell) = \delta E^{(+)}(n\ell) + \delta E^{(-)}(n\ell)
\]

\[
= -\frac{1}{6\pi^2} \left(\frac{e}{m}\right)^2 \int_0^\infty dk \sum_\lambda \left[ \frac{|\langle \lambda | p | n\ell \rangle|^2}{E_\lambda + k - E_n} + \frac{|\langle \lambda | p | n\ell \rangle|^2}{E_\lambda - k - E_n} \right]
\]

\[
= -\frac{1}{6\pi^2} \left(\frac{e}{m}\right)^2 \int_0^\infty dk \sum_\lambda |\langle \lambda | p | n\ell \rangle|^2 \frac{2(E_\lambda - E_n)}{(E_\lambda - E_n)^2 - k^2}
\]

\[
= \frac{1}{6\pi^2} \left(\frac{e}{m}\right)^2 \sum_\lambda |\langle \lambda | p | n\ell \rangle|^2 (E_\lambda - E_n) \int_0^\infty \frac{2dk}{k^2 - (E_\lambda - E_n)^2}.
\]  

(15)

Obviously, the integral in Eq. (15) is logarithmic divergent. By taking a cutoff value \( K_{\lambda n} \sim \sqrt{m(E_\lambda - E_n)} \), one gets

\[
\int_0^{K_{\lambda n}} \frac{2dk}{k^2 - (E_\lambda - E_n)^2} = \ln \frac{m}{(E_\lambda - E_n)}. \quad (16)
\]

In Bethe’s calculation, he took \( K_{\lambda n} = m \). Now, from Eq. (15) and (16), the total level shift is finally given by

\[
\delta E(n\ell) = \frac{1}{6\pi^2} \left(\frac{e}{m}\right)^2 \sum_\lambda |\langle \lambda | p | n\ell \rangle|^2 (E_\lambda - E_n) \ln \frac{m}{(E_\lambda - E_n)}.
\]  

(17)

The present result is exactly equal to Bethe’s one [6].

One notes that, in the derivation of Eq. (17), no concepts such as the mass renormalization of electron and the radiative corrections of electron self-energy, etc., are employed, yet the same result as Bethe’s is still obtained. Therefore, the method presented here suggests and supplies us another possible way for understanding the Lamb-Shift, maybe a more natural way in the mathematics and physics.

V. PARTICLE AND WAVE

E. Schrödinger in 1920s suggested that the wavefunction represents real entities, and a narrow wave packet just stands for a particle [7]. He encountered a stumbling block, in accordance with general mathematical laws, a wave packet describing an isolated microscopic particle would rapidly disperse, yet real particles are obviously more stable. Instead, the Copenhagen interpretation of quantum mechanics, advocated by N.Bohr and W. Hensenberg et al. regards the wavefunction as merely a mathematical tool representing an observer’s subjective knowledge of the system. According to Copenhagen’s point of view, quantum
mechanics does not yield a description of an objective reality but deals with probabilities of measurement outcomes. This leads to a dualism between the wavefunction and the quantum events. How do these quantum events arise? This interpretation refused to go further, and deemed that question such as “where was the particle before I measured its position?” is meaningless.

Dissatisfied with the doctrine of Copenhagen, de Broglie and D. Bohm proposed that the particle is a localized and indivisible entity; the wavefunction describes also a physically real field which guides the movement of particle; without regard to measurement the particle’s location is always well defined[8]. The criticism is if the wavefunction stands for a real field and the pure wave theory itself is satisfactory, then the associated particle seems to be superfluous. And what exactly is this physically real wave field?

Thus, though quantum mechanics has made many remarkable achievements, it is still shrouded a veil of mystery. To remove agnosticism and mysticism, and further better understand the reality of the wave function, one must probe deep into the essence of matter waves, and clarify the relations between particle and wave.

According to the present idea, the matter wave consists of both positive and negative energy field, and the two fields correspond to particles with completely opposite intrinsic properties. For a wave field in pure state, if it consists of the same number of positive and negative energy particles, then no net particle can be observed; whereas if it contains one more positive energy particles than negative ones, this then corresponds to single net particle in the viewpoint of experimental observation, and the corresponding wave field is the so-called ‘single particle wave’. For such a ‘single particle wave’, each positive energy particle within the wave field has a probability to become the observed particle in the measurement, though there is one and only one of them which can become the observed particle in the measurement. Specifically, if the wave field is described by wave function $\psi(x, t)$, then $|\psi(x, t)|^2$ gives the relative probability density that the positive energy particle at $(x, t)$ is observed in a measurement. In particular, for the wave field described by $\psi(x, t) = \exp[i(k \cdot x - \omega t)]$, all positive energy particles within the field have the same probability to be observed in a measurement. On the other hand, if the particle at $(x, t)$ has been observed in measurement, the rest wave field consists of equal number of positive and negative energy particles, and then has no direct observation effect.

Further, the present idea manifests that the so-called ‘wave packet reduction’ known in
the traditional quantum theory is fictional. In line with the viewpoints mentioned above, once the particle at \((x,t)\) within the wave field has been measured, its coupling with the original wave field is then destroyed, and the rest wave field has then no direct observation effect since it now consists of just equal number of positive and negative energy particles. In this sense, the wave packet does not disappear out of nothing, and it just becomes unobserved directly after the measurement.

Not like Schrödinger, according to the present viewpoint, a wave packet is obviously different from any particle within the wave field. The wave packet just tells the region into which particles may be observed with relatively larger probabilities in the measurement. The ‘motion’ of the wave packet also does not mean any particle’s motion at all, and it just tells the change of the most probable region along with the time. Similarly, the ‘expansion’ of the wave packet has nothing to do with any particle’s ‘dispersion’ in the wave field.

Also not like de Broglie and D. Bohm, the present viewpoint shows that the concept of a particle’s trajectory is completely useless, by considering what varies with the time is the oscillating state of the entire wave field and not the placements of any particles within the wave field. In this sense, the present idea is more close to the Copenhagen interpretation than the de-Broglie and Bohm’s.

VI. COHERENT SUPERPOSITION: DOUBLE-SLIT INTERFERENCE, ENTANGLEMENT

As pointed out in previous section, if a wave field in pure state consists of equal number of positive and negative energy particles with opposite intrinsic properties, it has no direct observation effect in measurements; however, this does not mean that such a wave field has nothing to do with any experimental results at all. Actually, many interesting phenomena and puzzling problems in quantum theory arise from such pure wave fields.

For convenience in the following statements, we call a wave field described by \(|\psi\rangle\) the “the recessive wave” if the wave field consists of equal number of positive and negative energy particles, while call a wave field described by \(|\psi\rangle\) “the dominant wave” if the wave field contains more number of positive energy particles than that of negative energy particles. Though the recessive wave alone cannot be observed in experiment, it can still manifest itself by coherently superposing with a dominant wave.
As typical examples, let’s firstly consider the well-known double-slit interference. Specifically, for each individual emission or receiving, the wave field is described by

\[ |\psi\rangle = \frac{1}{\sqrt{2}} (|\psi_1\rangle + |\psi_2\rangle), \]

(18)

death here, \( |\psi_1\rangle \) and \( |\psi_2\rangle \) denote the waves passing through slit 1 and 2, respectively. Either \( |\psi_1\rangle \) or \( |\psi_2\rangle \) is the dominant wave, while another one the recessive wave. Unless it is watched on, we do not know which one on earth, \( |\psi_1\rangle \) or \( |\psi_2\rangle \), is the dominant wave. The interference pattern on the receiving screen originates from coherent superposition of the recessive wave and dominant wave. On the one hand, for each individual emission, there exists one and only one dominant wave which passes through one of the two slits, and on the other hand, there indeed exist two waves which simultaneously pass slit 1 and 2, respectively. Considering that there is one and only one dominant wave, any experiments designed for watching on which way the particle chooses must tell one and only slit through which the particle passes; at the same time, once the coupling between the particle (which has been observed) and the wave field is cut off due to experimental observation, the expected interference pattern is then destroyed.

The same idea can also be applied to entangled systems. Consider a pair of particles with spin-1/2 that are in a state in which the total spin is zero. In such experiments, such two particles can be produced by a single particle decay. They separate, and after a long time no longer interact. On the hypothesis, that are not disturbed, the law of angular momentum conservation guarantees that they remain in a singlet state.

Taking the total spins and its z component as quantum numbers, the singlet state may be written in the form

\[ |\psi\rangle = \frac{1}{\sqrt{2}} (|\uparrow\rangle_1 |\downarrow\rangle_2 - |\downarrow\rangle_1 |\uparrow\rangle_2), \]

(19)

where the subscripts refer to the particles. As is well known, the singlet state (19) is an entangled state and cannot be factorized. In recent years, theoretical and experimental works seem to show that entangled systems may violate the separability principle\[1\]–\[3\]. However, how are the ‘nonlocal correlations’ between entangled systems established? The present work insists that, between entangled systems, there indeed exists a kind of quantum correlation that is different from any classical correlations, however, no superluminal signal transmits between them at all.
The basic idea is: either \(|\uparrow\rangle_1 \downarrow\rangle_2\) or \(|\downarrow\rangle_1 \uparrow\rangle_2\) is the dominant wave, and another one the recessive wave, for each individually prepared pair of particles. Due to the existence of the recessive component (in Eq. (19)), and its coherent superposition with the dominant wave, the correlations between two particles thus become nonclassical, as demonstrated in some correlation experiments which are frequently investigated in recent years. In this sense, the present point of view is obviously different from the hidden variable theory, and closer to the orthodox point of view. On the other hand, in terms of the Copenhagen interpretation, the roles of two components of \(|\psi\rangle\) are completely equal in status, and neither of them is in a subordinate position. Therefore, the orthodox viewpoint insists that the spin value of each particle is indeterminate before measuring, and then if the spin of one particle is determined in a local measuring, the state of another one immediately reduces to the corresponding component with opposite spin value, no matter how far from they are.

In the light of the present idea, the roles of two terms in entangled state (19) are not equal: one and only one of them is the dominant wave which consists of two more positive energy particles than negative ones, and it is this dominant component that definitely specifies what the spin value is for either local measurement. For instance, for a given pair of entangled particles described by Eq. (19), assuming that \(|\uparrow\rangle_1 \downarrow\rangle_2\) \((\downarrow\rangle_1 \uparrow\rangle_2\) is the dominant (recessive) component, then the result of a local measuring along \(z\) direction for particle 1 must tell \(s_{1z} = +\frac{1}{2}\hbar\). More importantly, in accordance with the scheme proposed here, the value of \(s_{2z}\) is independent of any local measuring on the particle 1. The result can obviously be applied to any other directions by considering that the state vector describing entangled state Eq. (19) has the same form in different basis.

VII. DISCUSSIONS: VACUUM VERSUS THE GROUND STATE

As shown previously, to remove the infinity of vacuum energy density, one needs no more knowledge about the property of vacuum, but that there is no net particle in the vacuum. On the other hand, in the traditional quantum field theory, it is taken for granted that, \(|V\rangle = |G\rangle = \otimes \prod_k |\pm \frac{1}{2}\omega_k\rangle\), here \(|V\rangle\) and \(|G\rangle\) denote the vacuum and ground state of the quantized field, respectively, and this means that all the lowest energy states of the field are realized with probability 100% in the vacuum, and further the infinite vacuum energy density then arises.
However, in the light of the present idea, we need consider both positive and negative energy field. On the one hand, the energy density of the vacuum equals 0 as pointed out previously,, and on the other hand, just like $\frac{1}{2}\hbar\omega_k$ is higher than 0 for positive energy field, $-\frac{1}{2}\hbar\omega_k$ is also higher than 0 for negative energy field for each $\omega_k$, thus deviations from 0 to $\pm\frac{1}{2}\hbar\omega_k$ for positive and negative energy field must become increasingly difficult with increasing of $\omega_k$. Without loss of generality, let $Q(\omega_k)$ be the probability with which the lowest energy states $| + \frac{1}{2}\hbar\omega_k \rangle$ and $| - \frac{1}{2}\hbar\omega_k \rangle$ of the positive and negative energy field are realized in the vacuum. A natural supposition is: $Q(\omega_k) \rightarrow 0$ as $\omega_k \rightarrow +\infty$, and $Q(\omega_k) \rightarrow 1$ as $\omega_k \rightarrow 0$. The requirements can be easily fulfilled by taking

$$Q(\omega_k) = \exp\left(-\frac{\hbar\omega_k}{2k_B T_0}\right),$$

(20)

here, $k_B$ is the Boltzmann constant, and $T_0$ a formal temperature owned to the vacuum.

First, if $T_0 = +\infty$, from Eq. (20), $Q(\omega_k) = 1$ for $\forall \omega_k \in (0, +\infty)$. Actually, this is just the choice implied in the traditional quantum field theory. In other words, the traditional quantum field theory implies that the vacuum has an infinite formal temperature.

Second, if $T_0 = 0$, from Eq. (20), $Q(\omega_k) = 0$ for $\forall \omega_k \in (0, +\infty)$. This means that no any ground state of the field can be realized at all in the vacuum, and this further means that all second and higher order corrections based on perturbation method be zero.

Finally, for $0 < T_0 < +\infty$, one gets $0 < Q(\omega_k) < \infty$ for $\forall \omega_k \in (0, +\infty)$.

Discarding the above mentioned two extreme cases, i.e., $T_0 = +\infty$ and $T_0 = 0$, by using Eq. (20), the energy density of the positive energy field in the vacuum can then be calculated,

$$\rho_{0}^{(+)} = \frac{\hbar c}{(2\pi)^2} \left(\frac{2k_B T_0}{\hbar c}\right)^4 \Gamma(4).$$

(21)

On the other hand, the vacuum energy density of the negative energy field $\rho_{0}^{(-)} = -\rho_{0}^{(+)}$. For instance, for $T_0 = 3K$, one gets $\rho_{0}^{(+)} = 0.225 \times 10^{-12} J/m^3$.

How do we determine that a state with no net particle is the vacuum state or not in the theory? First, if a particle is created from or annihilated to the vacuum state, it must be a virtual particle. Second, considering that a matter system cannot directly exchange energy, momentum, or any other observed quantities, with the vacuum, a virtual particle accompanying with the vacuum state must not change the state of an isolated matter system, i.e., the initial and final state must be the same state. A state which fulfill both requirements is the vacuum state.
According to the present idea, the ground state of the field is different from the vacuum state; in the vacuum state, neither net particle nor net field exist, whereas in the ground state, although no net particle but the positive energy field still exists in principle.

In traditional quantum field theory, the ground state of the field is assumed to be unique, and taken as: $\otimes \prod_k \left| \frac{1}{2}\hbar \omega_k \right\rangle$. This leads to infinite energy for the ground state. However, if the negative energy field is considered in the theory, it is found that the above assumption about the ground state is completely unnecessary, and the infinity resulting from this assumption is thus unreal.

A more natural assumption about the ground state is: for pure state $|\psi\rangle = \sum_k c(k) \left| \hbar \omega_k + \frac{1}{2}\hbar \omega_k \right\rangle$, the corresponding ground state is $|G\rangle = \sum_k c(k) \left| \frac{1}{2}\hbar \omega_k \right\rangle$, here $|c(k)|^2 = 1$.

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