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Particles Are Mutual Energy Flows and Waves Are Reactive Power without Collapse

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Abstract
In accordance with the Copenhagen interpretation, particles are created by the collapse of the wave caused by measurement. However, there is currently no mathematical description for the collapse of the wave. The transactional interpretation of quantum mechanics introduces advanced waves. The author successfully introduces advanced waves in classical electromagnetic theory. Retarded waves and advanced waves constitute mutual energy flow, and mutual energy flow possesses the properties of photons and can be considered as photons. Initially, the author believed that the self-energy flow of retarded waves and advanced waves collapsed in opposite directions. Recently, the author found that the reason for the need for reverse collapse is an error in the definition of the magnetic field in classical electromagnetic theory. After correcting the definition of the magnetic field, electromagnetic waves have reactive power, and thus, no collapse is needed. The author found that most quantum mechanics theories borrow patterns from classical electromagnetic theory. Thus, the probability flow in the Schrodinger equation and the Poynting energy flow in classical electromagnetic theory are very similar. Since the magnetic field in electromagnetic theory needs correction, the quantity corresponding to the magnetic field in the Schrodinger equation should also be corrected. The correction makes the self-energy flow obtained by the Schrodinger equation, i.e., the probability flow, have reactive power. The mutual energy flow obtained by the Schrodinger equation has active power. Thus, this mutual energy flow can express particles in quantum mechanics in a vacuum, such as electrons. Therefore, the collapse of the wave is entirely due to a problem with the definition of probability flow in quantum mechanics. After correcting this definition, the collapse of the wave is completely avoided. Once particles are represented by mutual energy flow, the wave-particle duality problem is completely resolved.

Keywords: Schrodinger Equation, Dirac Equation, Maxwell's Equations, Probability Flow, Mutual Energy Flow, Retarded Waves, Advanced Waves, Particles, Quantum Mechanics, Path Integral, Huygens' Principle, Magnetic Field

1. Introduction
The Schrodinger equation is the wave equation for particles such as electrons, and according to the Schrodinger equation, probability flow density can be constructed. This paper considers the motion of electrons in a vacuum. An electron moves from position $\boldsymbol{a}$ to another position $\boldsymbol{b}$. According to the Schrodinger equation, the particle's wave is emitted from $\boldsymbol{a}$, spreading in all directions, and then collapses onto $\boldsymbol{b}$. This is the interpretation of the Copenhagen school for the movement of electrons in a vacuum from $\boldsymbol{a}$ to $\boldsymbol{b}$. Quantum mechanics has other interpretations, and the one the author favors the most is John Cramer's quantum transactional interpretation in 1986 [1, 2]. This interpretation argues that a source $\boldsymbol{a}$ emits retarded waves, and a sink $\boldsymbol{b}$ emits advanced waves. Retarded waves and advanced waves interfere and reinforce along the line connecting $\boldsymbol{a}$ and $\boldsymbol{b}$. The transactional interpretation is built on the foundation of Wheeler and Feynman's absorber theory in 1945 [3, 4]. The Wheeler-Feynman absorber theory is based on the action-reaction theory and Dirac's self-force problem in 1938 [5-8]. Additionally, Stephenson's advanced wave theory is also intriguing [9].

The author found that if advanced waves are allowed to exist, emission and absorption are symmetric. If a point emits, it can be also a point of absorption, and energy flows from the emission point to the reception point. In this way, energy moves from one point to another. This type of energy flow is a point-to-point energy flow, rather than a diverging energy flow in all directions. This type of energy flow is closer to a particle.

The author initially studied electromagnetic field theory, and the introduction of advanced waves in the context of electromagnetic field theory was first mentioned by Welch in 1960 regarding the time-domain reciprocity theorem [10]. In 1987, the author proposed the electromagnetic mutual energy theorem, which is the Fourier transform of Welch's time-domain reciprocity theorem. Welch defined his theorem as a reciprocity theorem rather than an energy theorem, and the author believes it might be due to the involvement of advanced waves, which are not widely accepted in the engineering and scientific communities. Therefore, calling it a reciprocity theorem is more cautious. This theorem has been independently proposed multiple times, as seen in references [11-13]. However, they all position this theorem as a reciprocity theorem. Only the author defines it as an energy theorem.

In 2017, the author further argued that the mutual energy theorem (including Welch reciprocity theorem) is the law of energy conservation in electromagnetic field theory and introduced the mutual energy flow theorem (law) [14]. The author also proposed that the self-energy flow corresponding to the Poynting vector reversely collapses, so on average, the self-energy flow does not transfer energy. Energy in the vacuum space is only transferred by the mutual energy flow. The author considers the mutual energy flow as photons.

In 2020, the author further extended the concept of mutual energy flow from Maxwell's equations to the Schrodinger equation [15]. According to this theory, the retarded wave emitted by a source reversely collapses. The advanced wave emitted by a sink also reversely collapses. The mutual energy flow from the source to the sink is responsible for transmitting the particle's energy. The mutual energy flow can be regarded as particles. This way, the reverse collapse of two self-energy flows plus the mutual energy flow replaces the wave and wave collapse in the Copenhagen interpretation.

From 2020 to the present, the author has attempted to study various examples of electromagnetic waves, such as the energy flow between two parallel wires in a transformer, where one wire is the primary coil and the other is the secondary coil. Another example is the energy flow from a dipole emitting antenna to a dipole receiving antenna. In this process, the author found that Maxwell's electromagnetic theory's definition of the magnetic field is incorrect [16, 15, 17- 30]. Maxwell defined the magnetic field as the curl of the vector potential,

$$\boldsymbol{B}=\nabla\times\boldsymbol{A} \tag{1}$$

This is correct. However, further defining the magnetic field B as the curl of the retarded potential $\boldsymbol{A}^{(r)}$ is no longer correct. The formula,

$$\boldsymbol{B}=\nabla\times\boldsymbol{A}^{(r)} \tag{2}$$

is incorrect. For example, for a plane electromagnetic wave,

$$\boldsymbol{A}^{(r)} \sim \exp(-jkz)\hat{x} \tag{3}$$

The corresponding electric field is

$$\boldsymbol{E} = -\frac{\partial}{\partial t}\boldsymbol{A} = -j\omega\exp(-jkz)\hat{x} \tag{4}$$

$$\boldsymbol{H} = \frac{1}{\mu_0}\nabla\times\boldsymbol{A}^{(r)} = -jk\frac{1}{\mu_0}\hat{z}\exp(-jkz)\times\hat{x} = -jk\frac{1}{\mu_0}\exp(-jkz)\hat{y} \tag{5}$$

$$\frac{E}{H} = \frac{-j\omega}{-jk}\mu_0 = \frac{\omega}{k}\mu_0 = \frac{\omega}{\omega\sqrt{\mu_0\epsilon_0}}\mu_0 = \frac{1}{\sqrt{\mu_0\epsilon_0}}\mu_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} = \eta_0 \tag{6}$$

According to Maxwell's electromagnetic theory, the electric field and magnetic field are in phase. However, this is actually incorrect. According to the author's electromagnetic theory, the phase of the magnetic field is consistent with $\boldsymbol{A}^{(r)}$. For the far field, the magnetic field needs to be corrected to,

$$\boldsymbol{B}_{md} = (-j)\boldsymbol{B} \tag{7}$$

$\boldsymbol{B}_{md}$ is the corrected magnetic field according the author's electromagnetic theory, and this is the true magnetic field. After this correction, electromagnetic waves become reactive power, that means the electric and magnetic fields maintain a 90 degree phase difference. Thus, there is no need for wave collapse because, on average over time, waves do not carry energy. The carrier of energy is the mutual energy flow. Mutual energy flow transfers energy. Mutual energy flow is the energy flow from the light source ***a*** to the sink ***b*** and converges back to ***b***. Therefore, this mutual energy flow can be seen as photons.

$$\boldsymbol{H} = \frac{1}{\eta_0}E\hat{y} = \frac{1}{\eta_0}(-j\omega\exp(-jkz))\hat{y} \tag{8}$$

Hence,

$$\boldsymbol{H}_{md} = (-j)\frac{1}{\eta_0}(-j\omega\exp(-jkz))\hat{y}$$

$$= -\frac{\omega}{\eta_0}\exp(-jkz)\hat{y} \quad (9)$$

$\boldsymbol{H}$ is the magnetic field calculated according to Maxwell's electromagnetic theory formula (2). This magnetic field is incorrect. The correct magnetic field is the corrected magnetic field $\boldsymbol{H}_{md}$ given in the above equation. With the correction, electromagnetic waves are no longer active power. Electromagnetic waves become reactive power. For electromagnetic waves with reactive power, there is no need for wave collapse. This is because waves with reactive power consist of 4 quarter cycles in one period, two forward and two backward. Thus, within one period, both forward-propagating waves and backward-collapse waves are included. On average, these waves do not carry energy, and therefore, there is no need for wave collapse.

The author discovered that the theory of the Schrodinger equation borrows some ideas from classical electromagnetic theory. Therefore, when classical electromagnetic theory needs correction, it is likely that the theory of the Schrodinger equation also needs similar correction. Based on this idea, the author made further corrections to the energy flow theory of the Schrodinger equation. This correction is entirely consistent with the correction made to electromagnetic theory by the author. Such corrections may seem absurd within the scope of quantum mechanics. The significance of these corrections can only be understood in the context of electromagnetic field theory. In the realm of quantum mechanics, understanding the consistency of this correction with the correction to electromagnetic theory is sufficient.

2. Review of The Author's Electromagnetic Theory

2.1 Maxwell's Equations

The author has completed the revision of Maxwell's electromagnetic theory, mainly focusing on the modification of the far-field obtained from Maxwell's electromagnetic theory. The original Maxwell's equations are given by:

$$\nabla \cdot \boldsymbol{E} = \frac{\rho}{\epsilon} \quad (10)$$

$$\nabla \cdot \boldsymbol{H} = 0 \quad (11)$$

$$\nabla \times \boldsymbol{E} = -\frac{\partial}{\partial t}\mu\boldsymbol{H} \quad (12)$$

$$\nabla \times \boldsymbol{H} = \boldsymbol{J} + \frac{\partial}{\partial t}\epsilon\boldsymbol{E} \quad (13)$$

2.2 Plane Waves

Photons are considered as far-field, plane waves. Therefore,

$$\boldsymbol{E} = \exp(ikz)\hat{x} \quad (14)$$

In the frequency domain, the substitution can be made:

$$\frac{\partial}{\partial t} \to -i\omega \quad (15)$$

Thus, in the frequency domain, Maxwell's equations become:

$$\nabla \times \boldsymbol{E} = i\omega\mu\boldsymbol{H} \quad (16)$$

or

$$\boldsymbol{H} = \frac{1}{i\omega\mu}\nabla \times \boldsymbol{E} \quad (17)$$

$$\boldsymbol{H} = \frac{1}{i\omega\mu}\nabla \times \boldsymbol{E} \tag{17}$$

That is,

$$\boldsymbol{H} = \frac{1}{i\omega\mu}\nabla \times (\exp(ikz)\hat{x})$$

$$= \frac{1}{i\omega\mu}\nabla\exp(ikz) \times \hat{x}$$

$$= \frac{1}{i\omega\mu}(ik\hat{z})\exp(ikz) \times \hat{x}$$

$$= \frac{k}{\omega\mu}(\hat{z})\exp(ikz) \times \hat{x} \tag{18}$$

or

$$\boldsymbol{H} = \frac{k}{\omega\mu}\exp(ikz)\hat{y} \tag{19}$$

$$\frac{k}{\omega\mu} = \frac{\omega\sqrt{\mu\epsilon}}{\omega\mu} = \sqrt{\frac{\epsilon}{\mu}} = \frac{1}{\eta} \tag{20}$$

$$\boldsymbol{H} = \frac{1}{\eta}\exp(ikz)\hat{y} \tag{21}$$

2.3 Poynting Vector

The Poynting vector is given by:

$$\Re(\boldsymbol{E} \times \boldsymbol{H}^*) = \Re(\exp(ikz)\hat{x} \times (\frac{1}{\eta}\exp(ikz)\hat{y})^*)$$

$$= \Re(\exp(ikz)(\frac{1}{\eta}\exp(ikz))^*)\hat{z}$$

$$= \Re(\frac{1}{\eta})\hat{z}$$

$$= \frac{1}{\eta}\hat{z} \tag{22}$$

$\Re$ denotes the real part. The above equation shows that the energy flow density of the Poynting vector for the electromagnetic field (14, 21) is in the $\hat{z}$ direction, with a magnitude of the real number $\frac{1}{\eta}$.

2.4 Correction of the Magnetic Field

In Maxwell's electromagnetic theory, the Poynting vector is a real quantity, so taking the real part is non-zero. However, in the author's theory, the magnetic field needs to be corrected [23, 24, 25, 26, 27, 28]. Note that in the author's theory, when the wave function factor is exp(-*jkz*), the correction factor for the magnetic field is given by,

$$\boldsymbol{H}_{md} = (-j)\boldsymbol{H} \tag{23}$$

Transitioning from electromagnetic field theory to electrodynamics, the transformation

$$-j \rightarrow i \tag{24}$$

is performed. Therefore,

$$\boldsymbol{H}_{md} = (i)\boldsymbol{H} = i\frac{1}{\eta}\exp(ikz)\hat{y} \tag{25}$$

The above expression represents the correction for the far field, where md stands for modified.

$$\Re(\boldsymbol{E} \times \boldsymbol{H}_{md}^{*}) = \Re(\exp(ikz)\hat{x} \times (i\frac{1}{\eta}\exp(ikz)\hat{y})^{*})$$

$$= \Re(-i\frac{1}{\eta}\hat{z}) = 0 \tag{26}$$

Thus, according to the author's corrected magnetic field, the Poynting vector is imaginary, and its real part becomes zero. This indicates that electromagnetic waves have reactive power.

2.5 Mutual Energy Flow Density

In the author's electromagnetic theory, the Poynting vector has reactive power. The transfer of energy flow is carried out by the mutual energy flow, given by,

$$\boldsymbol{S}_{m\ md} = \Re(\boldsymbol{E}_1 \times \boldsymbol{H}_{md2}^{*})$$

$$= \Re(\boldsymbol{E}_2^{*} \times \boldsymbol{H}_{md1})$$

$$= \frac{1}{2}\Re(\boldsymbol{E}_1 \times \boldsymbol{H}_{md2}^{*} + \boldsymbol{E}_2^{*} \times \boldsymbol{H}_{md1}) \tag{27}$$

The factor 1/2 in the above expression is introduced based on the principle of half retarded waves and half advanced waves. The expression represents the mixed Poynting vector $\boldsymbol{S}_{m\ md}$, which is the mutual energy flow density. This mutual energy flow uses the corrected magnetic field, hence $\boldsymbol{S}_{m\ md}$ is the author's modified mutual energy flow density.

2.6 Energy Flow Law

In the author's electromagnetic theory, the electromagnetic field satisfies the following law of localized energy conservation,

$$-\int_{V_1} \boldsymbol{E}_2^{*} \cdot \boldsymbol{J}_1 dV = \iint_{\Gamma} \boldsymbol{S}_{m\ md} \cdot \hat{n}_{12} dV = \int_{V_2} \boldsymbol{E}_1 \cdot \boldsymbol{J}_2^{*} dV \tag{28}$$

This formula represents the localized law of energy conservation. Due to the author's correction to the magnetic field, electromagnetic waves (i.e., self-energy flow) have reactive power, and the transmitted energy is only carried by the mutual energy flow mentioned above. This mutual energy flow exhibits properties similar to photons. Therefore, the author considers it as a photon. In the author's electromagnetic theory, only photons transmit energy. Thus, waves have reactive power, which is very close to the idea that waves are probabilistic. The mutual energy flow is a real quantity, indicating that energy is transferred by mutual energy flow particles.

2.7 Synchronization

In the Cramer quantum mechanics interpretation, there is a handshake process between retarded waves and advanced waves. In the author's electromagnetic theory, this implies synchronization between retarded waves and advanced waves. This synchronization implies that,

$$\boldsymbol{H}_{md2} \sim \boldsymbol{E}_1 \tag{29}$$

meaning that the magnetic field $\boldsymbol{H}_{md2}$ has the same phase as $\boldsymbol{E}_1$,

$$\boldsymbol{E}_2 \sim \boldsymbol{H}_{md1} \tag{30}$$

The phase of $\boldsymbol{E}_2$ is the same as that of $\boldsymbol{H}_{\mathrm{md}1}$. However, the phase of $\boldsymbol{E}_2$ is different from that of $\boldsymbol{E}_1$. This is because $\boldsymbol{E}_1$ induces a current I_2. I_2 can maintain the same phase as the electric field $\boldsymbol{E}_1$. However, the electric field $\boldsymbol{E}_2$ and the current I_2 will maintain the same phase as the vector potential $\boldsymbol{A}_2^{(r)}$, determined by

$$\boldsymbol{E}_2 = -j\omega \boldsymbol{A}_2^{(r)} \tag{31}$$

Thus, the phase of $\boldsymbol{E}_2$ is the same as that of $\boldsymbol{H}_{\mathrm{md}1}$, but the phase of $\boldsymbol{E}_1$ lags 90 degrees behind $\boldsymbol{H}_{md1}$. Therefore, $\boldsymbol{E}_2$ is 90 degrees ahead of $\boldsymbol{E}_1$. We know that $\boldsymbol{E}_1 \times \boldsymbol{H}^*_{md2}$ represents action, and $\boldsymbol{E}^*_2 \times \boldsymbol{H}_{md1}$ represents reaction. This means that the reaction occurs before the action. This is understandable because the entire action is caused by the current I_1, and I_1 has the same phase as the magnetic field $\boldsymbol{H}_{md1}$. The electric field's phase is 90 degrees later than the current. The reaction needs to be realized in $\boldsymbol{H}_{md1}$, so its phase must be 90 degrees ahead of the electric field $\boldsymbol{E}_1$. In summary, in the author's electromagnetic theory, not all quantities $\boldsymbol{E}_1$, $\boldsymbol{H}_{md1}$, $\boldsymbol{E}_2$, and $\boldsymbol{H}_{md2}$ simply maintain the same phase. Instead, they are intricately combined.

3. Schrodinger Equation Theory

3.1 Schrodinger Equation

The probability density for the Schrodinger equation is given by

$$\rho = \Psi\Psi^* \tag{32}$$

where Ψ is the wave function, and the superscript "*" denotes complex conjugation. Taking the time derivative of this probability density yields

$$\frac{\partial}{\partial t}\rho = \frac{\partial}{\partial t}(\Psi\Psi^*) = \frac{\partial}{\partial t}(\Psi)\Psi^* + \Psi\frac{\partial}{\partial t}\Psi^* \tag{33}$$

The Schrodinger equation is given by

$$i\hbar\frac{\partial}{\partial t}\Psi = -\frac{\hbar^2}{2m}\nabla^2\Psi + U\Psi \tag{34}$$

where U is the potential function. Rewriting the equation, we get

$$\frac{\partial}{\partial t}\Psi = -\frac{\hbar^2}{i\hbar 2m}\nabla^2\Psi + \frac{1}{i\hbar}U\Psi \tag{35}$$

or,

$$\frac{\partial}{\partial t}\Psi = \frac{i\hbar}{2m}\nabla^2\Psi + \frac{1}{i\hbar}U\Psi \tag{36}$$

hence,

$$\frac{\partial}{\partial t}\Psi^* = -\frac{i\hbar}{2m}\nabla^2\Psi^* - \frac{1}{i\hbar}U\Psi^* \tag{37}$$

Hence, we have,

$$\frac{\partial}{\partial t}\rho = \frac{\partial}{\partial t}(\Psi)\Psi^* + \Psi\frac{\partial}{\partial t}\Psi^*$$

$$= (\frac{i\hbar}{2m}\nabla^2\Psi + \frac{1}{i\hbar}U\Psi)\Psi^* + \Psi(-\frac{i\hbar}{2m}\nabla^2\Psi^* - \frac{1}{i\hbar}U\Psi^*)$$

$$= (\frac{i\hbar}{2m}\nabla^2\Psi)\Psi^* + \Psi(-\frac{i\hbar}{2m}\nabla^2\Psi^*)$$

$$= \frac{i\hbar}{2m}(\nabla^2(\Psi)\Psi^* - \Psi\nabla^2(\Psi^*))$$

$$= -\frac{\hbar}{2im}(\nabla^2(\Psi)\Psi^* - \Psi\nabla^2(\Psi^*)) \tag{38}$$

Consider

$$\nabla \cdot (\Psi^* \nabla \Psi - \Psi \nabla \Psi^*) = (\nabla(\Psi^*) \cdot \nabla \Psi + \Psi^* \nabla^2 \Psi - \nabla(\Psi) \cdot \nabla \Psi^* - \Psi \nabla^2 \Psi^*)$$

$$= \Psi^* \nabla^2 \Psi - \Psi \nabla^2 \Psi^* \tag{39}$$

and

$$\frac{\partial}{\partial t}\rho = -\frac{\hbar}{2im}(\nabla^2(\Psi)\Psi^* - \Psi \nabla^2(\Psi^*))$$

$$= -\nabla \cdot \frac{\hbar}{2im}(\Psi^* \nabla \Psi - \Psi \nabla \Psi^*) \tag{40}$$

Define

$$\boldsymbol{J} = \frac{\hbar}{2im}(\Psi^* \nabla \Psi - \Psi \nabla \Psi^*) = \frac{\hbar}{m}\frac{1}{2i}(\Psi^* \nabla \Psi - \Psi \nabla \Psi^*)$$

$$= \frac{\hbar}{m}\frac{1}{2i}(\Psi^* \nabla \Psi - (\Psi \nabla \Psi)^*)$$

$$= \frac{\hbar}{m}\Im(\Psi^* \nabla \Psi) \tag{41}$$

where $\boldsymbol{J}$ is the quantum mechanical probability current density. The symbol "$\Im$" denotes the imaginary part.

$$\frac{\partial}{\partial t}\rho = -\nabla \cdot \boldsymbol{J} \tag{42}$$

3.2 Comparison with Electromagnetic Fields

The transformation from electromagnetic field theory to the Schrodinger equation is given by

$$\boldsymbol{E} \rightarrow \Psi \tag{43}$$

This means that Ψ corresponds to the electric field $\boldsymbol{E}$, and

$$\nabla \times \boldsymbol{E} = i\omega\mu \boldsymbol{H} \tag{44}$$

$$\boldsymbol{H} = \frac{1}{i\omega\mu}\nabla \times \boldsymbol{E} \sim \frac{1}{i}\nabla \times \boldsymbol{E} \tag{45}$$

where $\boldsymbol{H}$ is the magnetic field defined according to Maxwell's electromagnetic theory (not the magnetic field $\boldsymbol{H}_{md}$ defined in the author's electromagnetic theory).

$$\boldsymbol{H} \sim \frac{1}{i}\nabla \times \boldsymbol{E} \rightarrow \frac{1}{i}\nabla \Psi \tag{46}$$

This indicates that in quantum mechanics, 1/i $\nabla\Psi$ is analogous to the magnetic field $\boldsymbol{H}$.

$$2\Re(\boldsymbol{E} \times \boldsymbol{H}^*) = \boldsymbol{E} \times \boldsymbol{H}^* + \boldsymbol{E}^* \times \boldsymbol{H}$$

$$\rightarrow \Psi(\frac{1}{i}\nabla \Psi)^* + \Psi^*(\frac{1}{i}\nabla \Psi)$$

$$= \Psi(\frac{1}{i})^*\nabla\Psi^* + \Psi^*(\frac{1}{i}\nabla\Psi)$$

$$= -\Psi(\frac{1}{i})\nabla\Psi^* + \Psi^*(\frac{1}{i}\nabla\Psi)$$

$$= \Psi i\nabla\Psi^* - \Psi^* i\nabla\Psi)$$

$$= i(\Psi\nabla\Psi^* - \Psi^*\nabla\Psi)$$

$$= -2\frac{1}{2i}(\Psi\nabla\Psi^* - (\Psi\nabla\Psi^*)^*)$$

$$= -2\Im(\Psi\nabla\Psi^*)$$

$$= 2\Im(\Psi^*\nabla\Psi) \tag{47}$$

$$\Re(\boldsymbol{E} \times \boldsymbol{H}^*) \rightarrow \Im(\Psi^*\nabla\Psi) \tag{48}$$

Here, "→" means corresponds to. In this context, $\Im(\Psi^*\nabla\Psi)$ is equivalent to the real part $\Re(\boldsymbol{E} \times \boldsymbol{H}^*)$ of the Poynting vector.

3.3 Schrodinger Equation with Sources

While the electromagnetic field equations have sources, the Schrodinger equation does not. In order to establish a correspondence between the Schrodinger equation and the electromagnetic field equation, sources need to be added to the Schrodinger equation [15]. These sources include both emitters and absorbers.

$$\frac{\partial}{\partial t}\Psi = \frac{i\hbar}{2m}\nabla^2\Psi + \frac{1}{i\hbar}U\Psi \tag{49}$$

Alternatively,

$$\frac{i\hbar}{2m}\nabla^2\Psi + \frac{1}{i\hbar}U\Psi - \frac{\partial}{\partial t}\Psi = 0 \tag{50}$$

The equation can be written as

$$G\Psi = -\frac{\hbar}{2im}\nabla^2\Psi + \frac{1}{i\hbar}U\Psi - \frac{\partial}{\partial t}\Psi = 0 \tag{51}$$

The Schrodinger equation with sources is defined as

$$G\Psi = -\frac{\hbar}{2im}\nabla^2\Psi + \frac{1}{i\hbar}U\Psi - \frac{\partial}{\partial t}\Psi = S \tag{52}$$

where S is the source term for the Schrodinger equation. The operator is defined as

$$G \triangleq \left(-\frac{\hbar}{2im}\nabla^2 + \frac{1}{i\hbar}U - \frac{\partial}{\partial t}\right) \tag{53}$$

Thus,

$$G\Psi = S \tag{54}$$

represents the Schrodinger equation with added sources "S".

3.4 Mutual Energy Flow Theorem in Quantum Mechanics

The inner product of two wave functions is defined as

$$(\Psi_b,\Psi_a)_V \triangleq \int_V \Psi_b^*\Psi_a dV \tag{55}$$

where Ψ_a and Ψ_b are sources emitting waves, which can be either emitters or absorbers. The conditions are

$$G\Psi_a = S_a \tag{56}$$

$$G\Psi_b = S_b \tag{57}$$

Both retarded and advanced waves satisfy the same equations. It is important to note that this differs from the viewpoint of the author and Cramer. While the author believes that retarded and advanced waves satisfy the same equations, Cramer believes that advanced waves satisfy the complex conjugate of the Schrodinger equation. Thus,

$$(G\Psi_b,\Psi_a)_V = \int_V (G\Psi_b)^*\Psi_a dV$$

$$= \int_V \left(-\frac{\hbar}{2im}\nabla^2 + \frac{1}{i\hbar}U - \frac{\partial}{\partial t}\right)^* \Psi_b^*\Psi_a dV$$

$$= \int_V \left(\frac{\hbar}{2im}\nabla^2 - \frac{1}{i\hbar}U - \frac{\partial}{\partial t}\right) \Psi_b^*\Psi_a dV$$

$$= \int_V \left(\frac{\hbar}{2im}\nabla^2\Psi_b^* - \frac{1}{i\hbar}U\Psi_b^* - \frac{\partial}{\partial t}\Psi_b^*\right) \Psi_a dV \tag{58}$$

Similarly,

$$(\Psi_b, G\Psi_a)_V = \int_V \Psi_b^* G\Psi_a dV$$

$$= \int_V \Psi_b^* \left(-\frac{\hbar}{2im}\nabla^2\Psi_a + \frac{1}{i\hbar}U\Psi_a - \frac{\partial}{\partial t}\Psi_a\right) dV \tag{59}$$

Therefore,

$$(\Psi_b, G\Psi_a)_V + (G\Psi_b,\Psi_a)_V$$

$$= \int_V \Psi_b^* \left(-\frac{\hbar}{2im}\nabla^2\Psi_a + \frac{1}{i\hbar}U\Psi_a - \frac{\partial}{\partial t}\Psi_a\right) dV$$

$$+ \int_V \left(\frac{\hbar}{2im}\nabla^2\Psi_b^* - \frac{1}{i\hbar}U\Psi_b^* - \frac{\partial}{\partial t}\Psi_b^*\right) \Psi_a dV$$

$$= \int_V \left(-\frac{\hbar}{2im}\Psi_b^*\nabla^2\Psi_a - \Psi_b^*\frac{\partial}{\partial t}\Psi_a\right) dV$$

$$+ \int_V \left(\frac{\hbar}{2im}\nabla^2\Psi_b^*\Psi_a - \Psi_a\frac{\partial}{\partial t}\Psi_b^*\right) dV$$

$$= -\frac{\hbar}{2im}\int_V (\Psi_b^*\nabla^2\Psi_a - \nabla^2\Psi_b^*\Psi_a) - \left(\Psi_b^*\frac{\partial}{\partial t}\Psi_a + \Psi_a\frac{\partial}{\partial t}\Psi_b^*\right)$$

$$= -\frac{\hbar}{2im}\int_V (\Psi_b^*\nabla^2\Psi_a - \nabla^2\Psi_b^*\Psi_a) - \frac{\partial}{\partial t}(\Psi_b^*\Psi_a)dV \tag{60}$$

Consider,

$$\nabla\cdot(\Psi_b^*\nabla\Psi_a - \nabla\Psi_b^*\Psi_a)$$

$$= \nabla\Psi_b^*\cdot\nabla\Psi_a + \Psi_b^*\nabla^2\Psi_a - \nabla\Psi_b^*\cdot\nabla\Psi_a - \nabla^2\Psi_b^*\Psi_a$$

$$= \Psi_b^*\nabla^2\Psi_a - \nabla^2\Psi_b^*\Psi_a \tag{61}$$

Hence,

$$(\Psi_b, G\Psi_a)_V + (G\Psi_b, \Psi_a)_V$$

$$= -\int_V \nabla\cdot\frac{\hbar}{2im}(\Psi_b^*\nabla\Psi_a - \nabla\Psi_b^*\Psi_a)dV - \frac{\partial}{\partial t}\int_V (\Psi_b^*\Psi_a)dV$$

$$= -\int_V \nabla\cdot\boldsymbol{J}_{ab}dV - \frac{\partial}{\partial t}\int_V (\Psi_b^*\Psi_a)dV \tag{62}$$

where

$$\boldsymbol{J}_{ab} \triangleq \frac{\hbar}{2im}(\Psi_b^*\nabla\Psi_a - \nabla\Psi_b^*\Psi_a)dV \tag{63}$$

We have

$$(\Psi_b, G\Psi_a)_V + (G\Psi_b, \Psi_a)_V = -\int_V \nabla\cdot\boldsymbol{J}_{ab}dV - \frac{\partial}{\partial t}\int_V (\Psi_b^*\Psi_a)dV \tag{64}$$

Integrating both sides over time,

$$(\Psi_b, G\Psi_a)_{VT} + (G\Psi_b, \Psi_a)_{VT} = -\int_{VT} \nabla\cdot\boldsymbol{J}_{ab}dV - \int_{t=-\infty}^{\infty} dt\frac{\partial}{\partial t}\int_V (\Psi_b^*\Psi_a)dV \tag{65}$$

The subscripts $\boldsymbol{T}$ denote the time integral $\int_{t=-\infty}^{\infty} dt$. Considering,

$$\int_{t=-\infty}^{\infty} dt\frac{\partial}{\partial t}\int_V (\Psi_b^*\Psi_a)dV = U(\infty) - U(-\infty) = 0 \tag{66}$$

where

$$U = \int_V (\Psi_b^*\Psi_a)dV \tag{67}$$

Considering $\hbar U$ having the dimensions of energy, U can be seen as the system's energy. $U(\infty)$ is the energy at the end of the system, and this energy is 0. $U(-\infty)$ is the energy before the system starts, and this energy is also 0. Therefore, the above equation is 0. Thus, the energy term in equation (65) can be dropped after the time integration, resulting in

$$(\Psi_b, G\Psi_a)_{VT} + (G\Psi_b, \Psi_a)_{VT} = -\int_{VT} \nabla\cdot\boldsymbol{J}_{ab}dV \tag{68}$$

Considering equations (56) and (57), we have

$$(\Psi_b, S_a)_{VT} + (S_b, \Psi_a)_{VT} = -\oiint_{\Gamma T} \boldsymbol{J}_{ab} \cdot \hat{n} d\Gamma \tag{69}$$

If the surface Γ is taken as a spherical surface with an infinite radius, it is because $\boldsymbol{J}_{ab}$ consists of retarded waves emitted from source ***a*** and advanced waves emitted from sink ***b*** (62), on Γ, retarded and advanced waves cannot arrive simultaneously. One arrives in the future, and the other arrives in the past. Therefore, there always exists

$$\oiint_{\Gamma T} \boldsymbol{J}_{ab} \cdot \hat{n} d\Gamma = 0 \tag{70}$$

or

$$(\Psi_b, S_a)_{VT} + (S_b, \Psi_a)_{VT} = 0 \tag{71}$$

or

$$-(\Psi_b, S_a)_{VT} = (S_b, \Psi_a)_{VT} \tag{72}$$

Assuming that Γ contains only S_a, and such a Γ is denoted as Γ_a, enclosing the region V_a, equation (69) becomes

$$(\Psi_b, S_a)_{V_a T} = -\oiint_{\Gamma_a T} \boldsymbol{J}_{ab} \cdot \hat{n} d\Gamma \tag{73}$$

Considering

$$\hat{n} = \hat{n}_{ab} \tag{74}$$

we obtain

$$(\Psi_b, S_a)_{V_a T} = -\oiint_{\Gamma_a T} \boldsymbol{J}_{ab} \cdot \hat{n}_{ab} d\Gamma \tag{75}$$

Assuming that Γ contains only S_b, and such a Γ is denoted as Γ_b, enclosing the region V_b, equation (69) becomes

$$(S_b, \Psi_a)_{VT} = -\oiint_{\Gamma_b T} \boldsymbol{J}_{ab} \cdot \hat{n} d\Gamma \tag{76}$$

Considering

$$\hat{n} = -\hat{n}_{ab} \tag{77}$$

$$(S_b, \Psi_a)_{VT} = \oiint_{\Gamma_b T} \boldsymbol{J}_{ab} \cdot \hat{n}_{ab} d\Gamma \tag{78}$$

Considering equations (76), (78), and (72), we get

$$-(\Psi_b, S_a)_{V_a T} = \oiint_{\Gamma_a T} \boldsymbol{J}_{ab} \cdot \hat{n}_{ab} d\Gamma$$

$$= \oiint_{\Gamma_b T} \boldsymbol{J}_{ab} \cdot \hat{n}_{ab} d\Gamma = (S_b, \Psi_a)_{V_b T} \tag{79}$$

The above equation is the Mutual Energy Flow Theorem, or it can be rewritten as

$$-(\Psi_b, S_a)_{V_a T} = \oiint_{\Gamma T} \boldsymbol{J}_{ab} \cdot \hat{n}_{ab} d\Gamma = (S_b, \Psi_a)_{V_b T} \tag{80}$$

This equation is the Mutual Energy Flow Theorem, where Γ can be Γ_a, Γ_b, or any surface that separates sources S_a and S_b. $-\hbar(\Psi_b, S_a)_{V_a T}$ represents the energy emitted from source a. $\hbar \oiint_{\Gamma T} \boldsymbol{J}_{ab} \cdot \hat{n}_{ab} d\Gamma$ is the energy passing through the surface Γ. $\hbar(S_b, \Psi_a)_{VT}$ is the energy received at point b. The above theory is derived from [15].

3.5 Correction Corresponding to the Magnetic Field

In classical electromagnetic theory, it is known that corrections must be applied to the magnetic field. These corrections should also be reflected in the theory of the Schrodinger equation. In other words, corresponding corrections should be made to the theory of the Schrodinger equation. The magnetic field before correction is given by,

$$\boldsymbol{H} \to \frac{1}{i}\nabla\Psi$$

The correction is applied to the far field. Fortunately, in quantum mechanics, we are concerned with plane waves, which belong to the far field. In electromagnetic field theory, the correction for retarded waves (involving the factor exp(-*jkx*) is given by

$$\boldsymbol{H}_{md} = (-j)\boldsymbol{H} \tag{81}$$

Considering the convention from electromagnetic field theory to electrodynamics, when

$$\exp(-jkx) \to \exp(ikx) \tag{82}$$

we have,

$$-j = i \tag{83}$$

The corrected form is then,

$$\boldsymbol{H}_{md} \to (i)\boldsymbol{H}$$

$$\boldsymbol{H} \to \frac{1}{i}\nabla\Psi$$

The correction for $\boldsymbol{H} \to \frac{1}{i}\nabla\Psi$ is,

$$\boldsymbol{H}_{md} \to (i)(\frac{1}{i}\nabla\Psi) = \nabla\Psi \tag{84}$$

Here, $\boldsymbol{H}$ is the magnetic field before correction, calculated according to Maxwell's electromagnetic theory. This magnetic field is incorrect and corresponds to the far field. The truly correct magnetic field is $\boldsymbol{H}_{md}$. The subscript md denotes modified. The quantity corresponding to the Poynting vector is,

$$\boldsymbol{S}_{md} = \boldsymbol{E} \times \boldsymbol{H}_{md}^* \to \Psi(\nabla\Psi)^* \tag{85}$$

The symbol "→" signifies correspondence. Considering,

$$2\Re(\boldsymbol{E} \times \boldsymbol{H}_m^*) = \boldsymbol{E} \times \boldsymbol{H}_{md}^* + \boldsymbol{E}^* \times \boldsymbol{H}_{md}$$

$$\to \Psi(\nabla\Psi)^* + \Psi^*(\nabla\Psi)$$

$$= 2\frac{1}{2}(\Psi(\nabla\Psi)^* + \Psi^*(\nabla\Psi))$$

$$= 2\frac{1}{2}(\Psi(\nabla\Psi)^* + (\Psi(\nabla\Psi)^*)^*)$$

$$= 2\Re(\Psi(\nabla\Psi)^*) \tag{86}$$

That is,

$$\Re(\boldsymbol{E}\times\boldsymbol{H}_{md}^{*})\rightarrow\Re(\Psi(\nabla\Psi)^{*}) \tag{87}$$

$$\boldsymbol{S}_{md}\triangleq\boldsymbol{E}\times\boldsymbol{H}_{md}^{*}$$

$$\rightarrow\boldsymbol{J}_{self\ md}\sim(\Psi(\nabla\Psi)^{*}) \tag{88}$$

$\boldsymbol{J}_{self\,md}$ corresponds to the Poynting vector in the electromagnetic field. It is the modified self-energy flow. Comparing with formula (48),

$$\Re\boldsymbol{J}_{self\ md}=0 \tag{89}$$

This is because in quantum mechanics, $\Im(\Psi^{*}\nabla\Psi)$ is the probability flow, which is not zero. $\Re\boldsymbol{J}_{self\ md}$ is the probability flow after the author's correction, which is zero. This is similar to the author's theory that the self-energy flow does not overflow the universe. Note that the author does not consider $\Re\boldsymbol{J}_{self\ md}$ as a probability flow but regards it as an energy flow. Of course, $\rho=\Psi\Psi^{*}$ is not a probability either; it is energy or mass. The author's view is consistent with that of Schrodinger. Therefore, $\boldsymbol{J}_{self\ md}$ can be called the self-energy flow. The self-energy flow $\boldsymbol{J}_{self\ md}$ is imaginary, corresponding to reactive power.

$$\boldsymbol{J}_{self\ md}=\frac{\hbar}{m}\Psi(\nabla\Psi)^{*}$$

$\boldsymbol{J}_{self\ md}$ being reactive power indicates that it does not transfer energy.

3.6 Mutual Energy Flow Corresponding to the Schrodinger Equation

As obtained earlier,

$$\boldsymbol{J}_{ab}\triangleq\frac{\hbar}{2im}(\Psi_b^{*}\nabla\Psi_a-\nabla\Psi_b^{*}\Psi_a)$$

$$=\frac{\hbar}{2m}(\Psi_b^{*}(\frac{1}{i}\nabla\Psi_a)+(\frac{1}{i}\nabla\Psi_b)^{*}\Psi_a) \tag{90}$$

This is the mutual energy flow without correction. Considering the correction for the magnetic field, $J_{ab\,md}$, the quantity corresponding to the magnetic field is to be corrected as,

$$\frac{1}{i}\nabla\Psi_a\rightarrow(i)\frac{1}{i}\nabla\Psi_a$$

So we have,

$$\boldsymbol{J}_{ab\ md}=\frac{\hbar}{2m}(\Psi_b^{*}(i\frac{1}{i}\nabla\Psi_a)+(i\frac{1}{i}\nabla\Psi_b)^{*}\Psi_a)$$

$$=\frac{\hbar}{2m}(\Psi_b^{*}(\nabla\Psi_a)+(\nabla\Psi_b)^{*}\Psi_a) \tag{91}$$

$$\boldsymbol{J}_{ab\ md}\sim(\Psi_b^{*}(\nabla\Psi_a)+(\nabla\Psi_b)^{*}\Psi_a)$$

$$=(\Psi_a(\nabla\Psi_b)^{*}+\Psi_b^{*}(\nabla\Psi_a)) \tag{92}$$

$\boldsymbol{J}_{ab\ md}$ is the genuine energy flow of particles. In electromagnetic field theory, if the mutual energy flow density is given by,

$$\boldsymbol{S}_m=\boldsymbol{E}_a\times\boldsymbol{H}_b^{*}+\boldsymbol{E}_b^{*}\times\boldsymbol{H}_a$$

where $\boldsymbol{E}_a$ and $\boldsymbol{H}_b$ are synchronous, and $\boldsymbol{E}_b$ and $\boldsymbol{H}_a$ are synchronous, then there is synchrony here,

$$\Psi_a\sim\nabla\Psi_b \tag{93}$$

The symbol ~ indicates proportional. Equation (93) indicates that Ψ_a and $\nabla\Psi_b$ have the same phase. Similarly,

$$\Psi_b \sim \nabla\Psi_a \tag{94}$$

indicates that Ψ_b and $\nabla\Psi_a$ have the same phase.

3.7 Example

From the figure 1, it can be seen that assuming the electron is emitted from point a and annihilated at point ***b***. The green represents the energy flow (or mutual energy flow) of particles. The author considers this energy flow as the mutual energy flow $\boldsymbol{J}_{ab\,md}$ defined in the previous section. This mutual energy flow is the particle itself. Now, let's calculate this mutual energy flow with an example. The emission from point ***a*** is a retarded wave, spreading in all directions. We represent it with red dashed arrows. Dashed lines indicate that this wave is reactive power. The green line represents the mutual energy flow, which is the particle from ***a*** to ***b***.

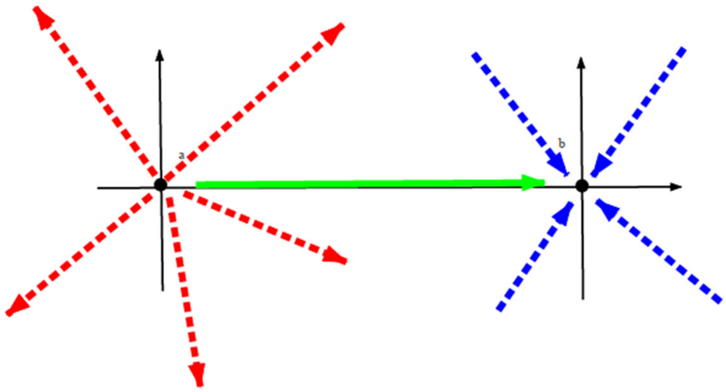

Figure 1: Red dashed lines represent retarded waves emitted from point ***a***, blue dashed lines are advanced waves emitted from point ***b***, both are reactive power waves. Green represents mutual energy flow. Mutual energy flow points from ***a*** to ***b***.

We consider the interference reinforcement of retarded waves and advanced waves on the line connecting ***a*** and ***b***. In this way, retarded waves and advanced waves become plane waves on the connecting line. So, we assume,

$$\Psi_a \sim \exp(ikz) \tag{95}$$

Ψ_a is the retarded wave emitted from point $z=a$.

$$\Psi_a \sim A\exp(ik(z-a)) \tag{96}$$

But A is an arbitrary constant, we take,

$$A\exp(-ika) = 1 \tag{97}$$

In this way, we have Eq. (95). Ψ_b is the advanced wave emitted from point ***b***, so it should be,

$$\Psi_b \sim B\exp(-ik|z-b|)$$

Considering

$$z < b$$

$$|z-b| = -(z-b)$$

$$\Psi_b = B\exp(ik(z-b)) \tag{98}$$

B is a complex constant including phase,

$$\nabla\Psi_b \sim ikB\exp(ik(z-b))\hat{z} \tag{99}$$

B can be arbitrarily chosen as long as $\nabla\Psi_b$ is synchronous with Ψ_a. Let's assume,

$$B = \frac{1}{ik\exp(ik(-b))} \tag{100}$$

$$\nabla\Psi_b \sim \exp(ikz)\hat{z} \tag{101}$$

This ensures the synchronicity of $\nabla\Psi_b$ and Ψ_a. About the phase of Ψ_b, we should refer to the phase of the electric field E_b. E_b is determined by the current I_b, as shown in figure 2.

$$\boldsymbol{E}_b = -j\omega I_b\hat{x} \tag{102}$$

Considering

$$-j \rightarrow i \tag{103}$$

The above formula is the transformation from electromagnetic field convention to electrodynamics convention,

$$\boldsymbol{E}_b = i\omega I_b\hat{x} \sim iI_b\hat{x} \tag{104}$$

I_b is determined by $\boldsymbol{E}_a$

$$I_b = \frac{\mathcal{E}_{a\rightarrow b}}{R_b + j\omega L_b} \tag{105}$$

R_b is the resistance at point b, L_b is the inductance at point b as shown in figure 2. We assume,

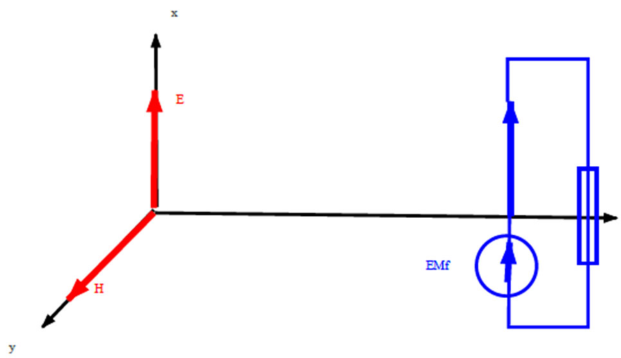

Figure 2: Assuming the circuit in the figure is connected to a large resistance. Since $R_b \gg \omega L_b$, ωL_b can be neglected.

$$R_b \gg \omega L_b$$

So we have,

$$I_b \simeq \frac{\mathcal{E}_{a\rightarrow b}}{R_b} \sim \mathcal{E}_{a\rightarrow b} \sim \boldsymbol{E}_a$$

$\varepsilon_{a\rightarrow b}$ is the induced electromotive force generated by the field at point a at point $\boldsymbol{b}$. For plane waves, this electromotive force is consistent with the phase of the electric field $\boldsymbol{E}_a$. So we have,

$$I_b\hat{x} \sim \boldsymbol{E}_a \tag{106}$$

$$\boldsymbol{E}_b \sim iI_b\hat{x} \sim i\boldsymbol{E}_a \tag{107}$$

Considering (95) ($\boldsymbol{E}_b \rightarrow \Psi_b$) determined by the above equation, ($\boldsymbol{E}_a \rightarrow \Psi_a$), Ψ_a given by formula (95),

$$\Psi_b \sim i\Psi_a \sim i\exp(ikz) \tag{108}$$

Next, consider making $\nabla\Psi_a$ and Ψ_b synchronous, that is (93,94), assume,

$$\Psi_a \sim di\exp(ikz)\hat{z} \tag{109}$$

d is a constant, can be arbitrarily chosen to ensure that $\nabla\Psi_a$ is synchronous with Ψ_b,

$$\nabla\Psi_a \sim iikd\exp(ikz)\hat{z} \tag{110}$$

Assume,

$$d = \frac{1}{ik} \tag{111}$$

$$\nabla\Psi_a \sim i\exp(ikz)\hat{z} \tag{112}$$

This ensures that $\nabla\Psi_a$ is synchronous with Ψ_b. The $\nabla\Psi_a$ obtained by the above formula is consistent with that obtained by taking the gradient from formula (95). Considering (95, 108, 101, 112),

$$\boldsymbol{J}_{ab\ md} \sim (\Psi_b^*(\nabla\Psi_a) + (\nabla\Psi_b)^*\Psi_a)$$

$$= (\Psi_a(\nabla\Psi_b)^* + \Psi_b^*(\nabla\Psi_a))$$

$$= (\exp(ikz)\exp(ikz)^* + (i\exp(ikz))^*(i\exp(ikz)))\hat{z}$$

$$= 2\hat{z} \sim \hat{z} \tag{113}$$

$J_{ab\ md}$ is the mutual energy flow after the author considers a similar correction to the magnetic field. The direction of $\boldsymbol{J}_{ab\ md}$ is in the direction of $\hat{z}$, and it is real. In this way, $\boldsymbol{J}_{ab\ md}$ is the energy flow of the particle,

$$\Re(\boldsymbol{J}_{ab\ md}) \sim \hat{z} \tag{114}$$

$\Re$ takes the real part. It indicates that $\boldsymbol{J}_{ab\ md}$ has active power. $\boldsymbol{J}_{ab\ md}$ transmits positive energy. The direction of energy transmission is $\hat{z}$. This indicates that $\boldsymbol{J}_{ab\ md}$, this mutual energy flow, is the particle itself.

3.8 Generation and Annihilation of Mutual Energy Flow

From the author's electromagnetic field theory, we know that waves emitted from the source ***a*** and the sink ***b*** both propagate in the right direction, as shown in Figure 3. Therefore,

$$\Psi_a \sim \exp(ik(z-a)) \tag{115}$$

$$\Psi_b \sim i\exp(ik(z-b)) \tag{116}$$

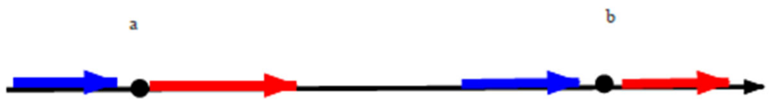

Figure 3: Wave propagating from point a to point b. The wave travels to the right.

$$\nabla\Psi_a \sim \begin{cases} -ik\exp(ik(z-a)) & z < a \\ ik\exp(ik(z-a)) & z \geq a \end{cases} \tag{117}$$

$$\nabla\Psi_b \sim \begin{cases} -iki\exp(ik(z-b)) & z \leq b \\ iki\exp(ik(z-b)) & z > b \end{cases} \tag{118}$$

In other words, the quantity corresponding to the magnetic field, $\nabla\Psi_a$ changes sign at $z=a$, and $\nabla\Psi_b$ changes sign at $z=b$. The sign change results in cancellation of the quantities that were originally added together. Therefore, within the range $a \leq z \leq b$, the mutual energy flow undergoes interference reinforcement. Fortunately, outside this range, interference cancellation occurs. Therefore,

$$\boldsymbol{J}_{ab\ md} \sim \hat{z}\begin{cases}0 & z < a\\ 1 & a \le z \le b\\ 0 & z > b\end{cases} \tag{119}$$

This formula tells us that the mutual energy flow $\boldsymbol{J}_{ab\ md}$ is generated at the source and annihilated at the sink. The quantum mechanics formula for mutual energy flow (80) can be rewritten as,

$$-(\Psi_b, S_a)_{V_aT} = \oiint_{\Gamma T} \boldsymbol{J}_{ab\ md} \cdot \hat{n}_{ab} d\Gamma = (S_b, \Psi_a)_{V_bT} \tag{120}$$

$-(\Psi_b, S_a)_{V_aT}$ is the input energy of the quantum mechanical system (transferring energy from one atom to space). $(S_b, \Psi_a)_{VT}$ is the output energy of the quantum mechanical system (transferring energy from space to the receiving atom). And $\oiint_{\Gamma T} \boldsymbol{J}_{ab\ md} \cdot \hat{n}_{ab} d\Gamma$ is the energy transferred by photons. Since $\oiint_{\Gamma T} \boldsymbol{J}_{ab\ md} \cdot \hat{n}_{ab} d\Gamma$ does not have the dimension of energy, we can also express the energy transferred by photons as $\hbar \oiint_{\Gamma T} \boldsymbol{J}_{ab\ md} \cdot \hat{n}_{ab} d\Gamma$. In this way, the energy transferred by photons is entirely due to the transfer of mutual energy flow.

3.9 Comparison between the Author's Theory and the Copenhagen Interpretation

3.9.1 First Scenario

The first scenario is the quantum mechanics interpretation of the Copenhagen school. The wave of the Schrodinger equation propagates in all directions from the source. Then, when measuring at the sink, it means the wave collapses to the sink.

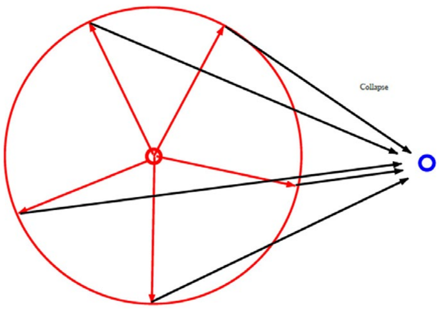

Figure 4: Copenhagen interpretation: the wave travels in all directions, then collapses to the position of the absorber.

The original Schrodinger equation only defined self-energy flow,

$$\boldsymbol{J}_{self} = \frac{\hbar}{2mi}(\Psi^* \nabla \Psi - \Psi \nabla \Psi^*) = \frac{\hbar}{m}\Im(\Psi^* \nabla \Psi) \tag{121}$$

This energy flow $\boldsymbol{J}_{self}$ moves from the source in all directions. Therefore, when we receive a particle at a certain point, we have to say that the wave collapsed onto the absorbing atom. See Figure 4.

3.9.2 Second Scenario

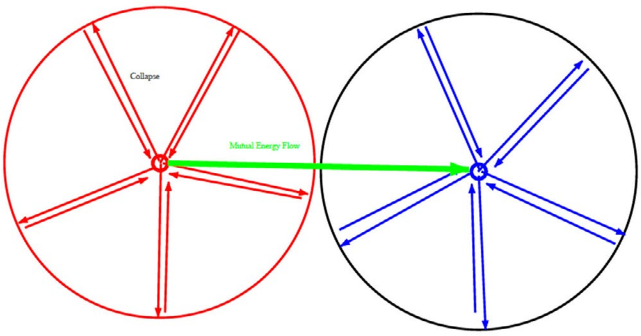

Figure 5: Author's proposal in 2017: self-energy flows collapse in reverse, and mutual energy flow transfers energy. Mutual energy flow is in green.

This scenario mainly comes from the author's previous paper [15]. The author believes that self-energy flow collapses in reverse, as shown in Figure 5. Thus, self-energy flow does not transfer energy. At this point, retarded waves emitted from the source and advanced waves emitted from the sink are synchronized. Note that this synchronization implies that Ψ_a and Ψ_b have exactly the same phase. Corresponding to electromagnetic field theory, this essentially requires $\boldsymbol{E}_a$ and $\boldsymbol{E}_b$ to have the same phase. Since the current $\boldsymbol{I}_b$ can have the same phase as $\boldsymbol{E}_b$, but $\boldsymbol{E}_b$ cannot have the same phase as $\boldsymbol{I}_b$, $\boldsymbol{E}_b$ cannot have the same phase as $\boldsymbol{E}_a$. Therefore, this kind of synchronization is problematic. However, this synchronization is still correct in numerical calculations of energy flow. In this case, there is self-energy flow,

$$\boldsymbol{J}_{a\ self} = \frac{\hbar}{2mi}(\Psi_a^*\nabla\Psi_a - \Psi_a\nabla\Psi_a^*) = \frac{\hbar}{m}\Im(\Psi_a^*\nabla\Psi_a) \tag{122}$$

$$\boldsymbol{J}_{b\ self} = \frac{\hbar}{2mi}(\Psi_b^*\nabla\Psi_b - \Psi_b\nabla\Psi_b^*) = \frac{\hbar}{m}\Im(\Psi_b^*\nabla\Psi_b) \tag{123}$$

The above two equations represent self-energy flow, which must collapse in reverse, as shown in Figure 5. Here is the mutual energy flow $\boldsymbol{J}_{ab}$,

$$\boldsymbol{J}_{ab} = \frac{\hbar}{2m2}(\Psi_b^*\nabla\Psi_a - \Psi_b\nabla\Psi_a^*) \tag{124}$$

Mutual energy flow $\boldsymbol{J}_{ab}$ transfers energy. Mutual energy flow $\boldsymbol{J}_{ab}$ can be regarded as the particle itself. This scenario is an improvement over the first scenario. Collapse is replaced by reverse collapse. The mutual energy flow can be seen as the particle itself.

3.9.3 Third Scenario

The third scenario is shown in Figure 6. This scenario corresponds to a correction to the magnetic field, making self-energy flow reactive power. Waves of reactive power are represented by dashed lines. Such waves do not carry energy. These waves alternately transmit energy forward and backward within one period. On average, they do not transmit energy. In electromagnetic field theory, this scenario is discussed in references [29, 30, 23, 24, 25, 26, 27, 28]. This paper generalizes these viewpoints to the quantum theory corresponding to the Schrodinger equation. Corrections have been made to mutual energy flow in quantum theory.

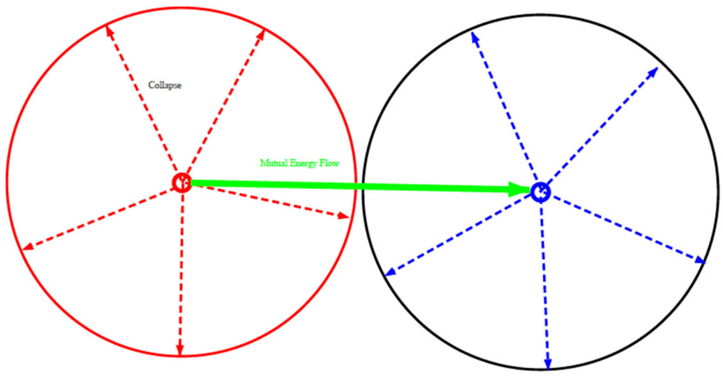

Figure 6: Scenario proposed by the author since 2022: retarded and advanced waves are both reactive power waves, represented by dashed lines, and mutual energy flow transfers energy. Mutual energy flow is in green.

$$\boldsymbol{J}_{a\ self} = \frac{\hbar}{m}\Psi_a(\nabla\Psi_a)^* \tag{125}$$

$$\boldsymbol{J}_{b\ self} = \frac{\hbar}{m}\Psi_b(\nabla\Psi_b)^* \tag{126}$$

$$\boldsymbol{J}_{ab\ md} = \frac{\hbar}{2m}(\Psi_b^*(\nabla\Psi_a) + (\nabla\Psi_b)^*\Psi_a) \tag{127}$$

For the energy flow defined above,

$$\Re(\boldsymbol{J}_{a\ self}) = 0 \tag{128}$$

$$\Re(\boldsymbol{J}_{b\ self}) = 0 \tag{129}$$

These two equations indicate that self-energy flow is reactive power. Since self-energy flow is reactive power, there is no need for collapse.

$$\Re(\boldsymbol{J}_{ab\ md}) \sim \hat{z} \tag{130}$$

The one transmitting energy is the mutual energy flow $\boldsymbol{J}_{ab\ md}$. The magnitude of the mutual energy flow obtained in the third scenario is consistent with that in the second scenario. It's just that in the second scenario, synchronization is between Ψ_a and Ψ_b. In electromagnetic field theory, we have already proven that this kind of synchronization is unrealistic. The synchronization in the third scenario is,

$$\Psi_a \sim \nabla\Psi_b \tag{131}$$

$$\Psi_b \sim \nabla\Psi_a \tag{132}$$

This kind of synchronization can be achieved in electromagnetic field theory. Therefore, when calculating mutual energy flow, the second scenario can be adopted. The third scenario is telling everyone that there is no wave collapse in real particle situations. The collapse of the wave is entirely due to the fact that the calculated wave has active power. In fact, these waves are all reactive power. This has been verified in electromagnetic theory [15, 31, 17, 23- 30]. Moreover, synchronization also needs to borrow conclusions from electromagnetic theory.

The third scenario comprehensively and effectively interprets the wave-particle duality problem in quantum mechanics. Waves have reactive power, so there is no need for collapse. Particles are mutual energy flows, which are composed of retarded and advanced waves. Since retarded waves can act as waveguides for advanced waves, and advanced waves can act as waveguides for retarded waves, the waves only interfere and strengthen along the line from ***a*** to ***b***, while interfering weakly in other directions. Therefore, retarded and advanced waves almost become plane waves, which is light ray. Inside the light ray, light is almost a plane wave.

4. Extension of the Concept of Mutual Energy Flow to Path Integrals

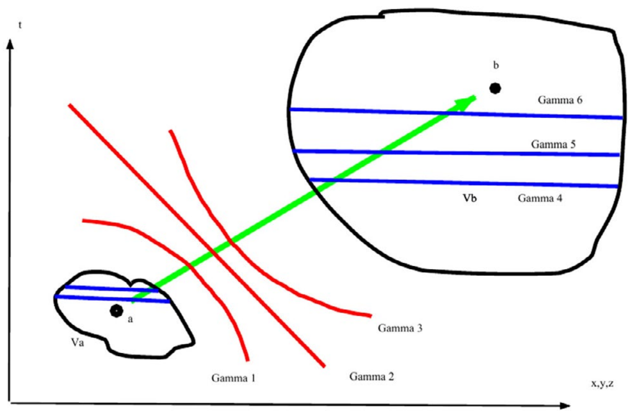

Figure 7: Three regions are depicted: V_a is the source region, V_b is the sink region, and between V_a and V_b is the mutual energy flow photon region.

In Equation (120), we can choose Γ to be any surface that separates the source S_a and the sink S_b. This surface can be a sphere enclosing a, ***a*** sphere enclosing ***b***, or any infinite plane between ***a*** and ***b***. In this case, we are considering spatial separation. If S_a and S_b are instantaneous events.

$$-(\Psi_b, S_a)_{V_aT} = \oiint_{\Gamma T} \boldsymbol{J}_{ab\ md} \cdot \hat{n}_{ab} d\Gamma = (S_b, \Psi_a)_{V_bT} \tag{133}$$

This equation can be rewritten as,

$$-(\Psi_b, S_a)_{V_a T} = \oiint_{\Gamma_T} \boldsymbol{J}_{ab\ md} \cdot \hat{n}_{ab} d\Gamma = (S_b, \Psi_a)_{V_b T} \tag{134}$$

The above two formulas are nearly same, the only difference is at the region of surface intergal, one is ΓT and another is Γ_T. ΓT is a 2D surface + 1D time, a 3D generalized surface. We can extend the definition of separation to any 3D surface Γ_T in 4D spacetime, as long as it separates events S_a and S_b.

From these generalized surfaces, we find a special surface that is divided in time, with time at an instant and including 3D space. With this division, the energy passing through the generalized surface is still the energy from event S_a to event S_b. We can not only separate the mutual energy flow $\boldsymbol{J}_{ab\ md}$ but also use it to separate V_a T or V_b T. For example, V_b T can be expressed as

$$(S_b, \Psi_a)_{V_b T} = \int_{t=-\infty}^{\infty} \int_{V_b} \Psi_a S_b^* dV dt \tag{135}$$

If our separation is in time, we can remove the time integral (or think that there is $\delta(t\text{-}t_b)$ inside the source S_b)

$$(S_b, \Psi_a)_{V_b} = \int_{V_b} \Psi_a S_b^* dV$$

$$= \int_{V_b} \Psi_a(t_b) S_b^* dV$$

$$= \langle \Psi_a(t_b) | S_b \rangle \tag{136}$$

The above equation actually considers that S_b implicitly contains the function $\delta(t\text{-}t_b)$, meaning that S_b is an event occurring at time t_b and at position $\boldsymbol{x}_b$,

$$\int_{V_b} \Psi_a(t_b) S_b^* dV = \langle S_b | \Psi_a(t_b) \rangle$$

$$= \langle x_b | \Psi_a(t_b) \rangle \tag{137}$$

Considering,

$$|\Psi_a(t_b)\rangle = \exp(-\frac{i}{\hbar}\hat{H}t)|\Psi_a(t_a)\rangle$$

$$= \exp(-\frac{i}{\hbar}\hat{H}t)|\Psi_a(0)\rangle \tag{138}$$

where considering t_a=0

$$\langle x_b | \Psi_a(t_b) \rangle = \langle x_b | \exp(-\frac{i}{\hbar}\hat{H}t) | \Psi_a(0) \rangle \tag{139}$$

Considering Equations (136), (137), (138), and (139), the right-hand side of Equation (134) can be written as,

$$(S_b, \Psi_a)_{V_b T} = \langle x_b | \exp(-\frac{i}{\hbar}\hat{H}t) | \Psi_a(0) \rangle \tag{140}$$

The right-hand side of Equation (134) represents the output of mutual energy flow, the left-hand side is the input of mutual energy flow, and the middle is mutual energy flow. This output of mutual energy flow can be divided in time, and this time division is the quantity often used to construct path integrals. In Figure 7, we can appropriately enlarge the region V_b. The division of mutual energy flow can be moved from region V_{ab} to region V_b, and within region V_b, the division can only be done in terms of time. With a time division like,

$$t_a = t_0 < t_1 < t_2 \cdots\cdots t_{N-1}, t_N = t_b$$

Now we can perform path integrals. The concept of path integrals can be found in textbooks on quantum mechanics or quantum field theory, and we won't go into details here. The key point is that this path integral is, in fact, the mutual energy flow defined by the author. It is essential to note that the middle part in Equation (134) and its right side are completely equivalent. The middle part is the expression of mutual energy flow, and the right side is the path integral.

This implies that path integrals are nothing else but mutual energy flow. The author believes that mutual energy flow is the particle. Thus, the path integral in quantum mechanics is, in essence, the particle itself. This is also the reason why Feynman's path integral is so effective in quantum mechanics. The path integral is the representation of the particle's energy flow, completely equivalent to mutual energy flow. Mutual energy flow is the particle itself.

When the author mentions mutual energy flow, the advanced wave, retarded wave, and their combination are discussed as contributors to mutual energy flow. However, in Feynman's path integral, the advanced wave is not explicitly mentioned. Feynman and his mentor Wheeler proposed the absorber theory[3, 4], which explicitly introduced the concept of advanced waves. The path integral theory also emerged around the same time as the absorber theory. Due to criticism of the causality violation inherent in the theory of advanced waves, Feynman had to heavily emphasize probabilities in his path integral theory to gain acceptance. However, in his path integral theory, Feynman introduced the famous Feynman propagator which is a propagator that is half retarded and half advanced [32].

In Feynman's path integral theory, he mentions Huygens' principle, stating that the idea of the path integral was inspired by Huygens' principle [32]. However, he did not derive the path integral from Huygens' principle. The author's proposed mutual energy flow and the mutual energy flow principle have always been closely associated with Huygens' principle[33-34, 17]. This way, the author has tightly linked path integrals with Huygens' principle and mutual energy flow.

5. Conclusion

The wave-particle duality is a result of the incorrect understanding of waves in classical electromagnetism and quantum theory. This misconception arises from classical electromagnetism, where waves have active power, and quantum mechanics, which borrows from classical electromagnetism, also considers waves with active power. Since waves have active power, they can transmit energy, but particles can also transmit energy. Thus, there are two entities capable of transmitting energy: (1) waves and (2) particles. This duality is the root cause of wave-particle duality. In 2017, the author proposed the reverse collapse of electromagnetic waves and that waves do not transmit energy. Consequently, only particles remain capable of transmitting energy. The author believes that particles are mutual energy flows. Recently (after 2022), the author found that electromagnetic waves have reactive power, and energy transfer is facilitated by mutual energy flow. Mutual energy flow is identified as photons. Photons are mutual energy flows. In this paper, the author applies this idea to particles, such as electrons. Electrons satisfy the Schrodinger equation or the Dirac equation. In the Schrodinger equation, the author identifies quantities corresponding to the electric field and magnetic field, and a correction is applied to the quantity corresponding to the magnetic field. After this correction, the self-energy flow corresponding to the Schrodinger equation becomes reactive power. The mutual energy flow corresponding to the Schrodinger equation can still have active power.

This renders the concept of wave collapse unnecessary. Instead, waves are considered to have reactive power. Particles are mutual energy flows, with the mutual energy flow of photons satisfying Maxwell's equations (with appropriate corrections to the magnetic field), and the mutual energy flow of electrons satisfying the Schrodinger equation (with appropriate corrections to the corresponding magnetic field quantity). Mutual energy flow involves point-to-point energy transfer. The phase of the quantity corresponding to the magnetic field in mutual energy flow needs correction. The author believes that the ideas presented in this paper are applicable to the Dirac equation as well, making them relevant to quantum field theory.

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