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ABSTRACT

In classical theory, phenomena are defined by the model of particles or waves, aiming to explain reality with certainty. In quantum theory, the phenomena are described by a quantum state |훼, 픑i, which explains the reality with uncertainty. Although in quantum theory, the reality is probabilistic, the quantum state |훼, 픑i can be determined with certainty due to the unitarity principle. The technology needs deterministic phenomena, and then quantum technology must be constructed based on this fundamental quantum state. The critical point in quantum technology is to build the deterministic phenomena from the quan- tum state |훼, 픑i: this is the main argument in the present article. The realization of quantum technology comprises three steps: constructing an appropriate quantum state, obtaining its time evolution, and detecting it deterministically.

Keywords: quantum technology, quantum states, deterministic, uncertainty.

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Conceptual Challenges of Quantum Field Theory in Technology

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ABSTRACT

In classical theory, phenomena are defined by the model of particles or waves, aiming to explain reality with certainty. In quantum theory, the phenomena are described by a quantum state $|\alpha, t\rangle$ *, which explains the reality with uncertainty. Although in quantum theory, the reality is probabilistic, the quantum state* $|\alpha, t\rangle$ *can be determined with certainty due to the unitarity principle. The technology needs deterministic phenomena, and then quantum technology must be constructed based on this fundamental quantum state. The critical point in quantum technology is to build the deterministic phenomena from the quan - tum state* $|\alpha, t\rangle$ *this is the main argument in the present article. The realization of quantum technology comprises three steps: constructing an appropriate quantum state, obtaining its time evolution, and detecting it deterministically.*

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I. INTRODUCTION

To explain a physical system, the physicist constructs a theoretical model, and when the model cannot explain the experimental results, older models are replaced with new ones. In classical paradigm, the physical systems are usually described by particles, $x_i^\mu(\lambda)$, and or waves (epitomised by electromagnetic 4-potential field $A_\mu(t,\vec{x})$), which are immersed in space-time (*i.e.* the gravitational field $g_{\mu\nu}(t,\vec{x})$). λ is the particle path parameter in space-time. An elementary particle has intrinsic properties such as mass (m), electrical charge (q), spin (s), flavour (f) and colour (c), where the numerical values can be determined experimentally. The last three properties can be measured at the atomic and subatomic levels. These intrinsic properties are associated with four fundamental interactions in nature and play an important role in technology.

The complete information concerning the motion of a particle in general relativity is encoded in $x^\mu(\lambda)$ which can be found from the following equation [1, 2, 3]:

$$\frac{d^2x^\mu}{d\lambda^2} + \Gamma^\mu{}_{\nu\rho}\frac{dx^\nu}{d\lambda}\frac{dx^\rho}{d\lambda} = F^\mu, \tag{1.1}$$

where $\Gamma^\mu{}_{\nu\rho}$ are Christoffel symbols and F^μ is the force acting on the particle. Knowing the initial conditions (which can be obtained from observation) allows us to determine $\vec{x}(t)$ with certainty. All the properties of the particle, its velocity, acceleration, momentum, energy, etc., can be explicitly derived from $\vec{x}(t)$.

A stationary charged particle will produce an electric field. In contrast, a moving charged particle will create an electric current and a magnetic field, and an accelerated charged particle will create an electromagnetic field. The latter can be determined from the electromagnetic 4-potential field $A_\mu(t,\vec{x})$ which satisfies the following field equation in the flat Minkowski space-time [4]:

$$\partial_\nu\partial^\nu A_\mu(x) - (1-l)\partial_\mu\partial\cdot A = j_\mu, \tag{1.2}$$

where l is the Lagrange multiplier and j_μ is the 4-current density. Suppose we know the initial conditions of the 4-potential field at any given time. In that case, we will be able to find $A_\mu(t, \vec{x})$ at any later or earlier time by explicit calculation, which in turn enables us to find the electric and magnetic fields with certainty, *i.e.* $\vec{E}(t, \vec{x})$ and $\vec{B}(t, \vec{x})$). Thus, we can also determine all electromagnetic field information with certainty, such as energy distribution, momentum, angular momentum, etc.

In the theory of Einstein's general relativity, space-time is equivalent to the gravitational field and represented by the tensor potential field $g_{\mu\nu}(t, \vec{x})$, which is the solution of the Einstein field equation [1, 2, 3]:

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}, \tag{1.3}$$

where $T_{\mu\nu}$ is the stress-energy tensor, $R_{\mu\nu}$ is the Ricci tensor, R is the scalar curvature, and Λ is the cosmological constant. If we have the initial conditions of the space-time, the metric $g_{\mu\nu}$ can be determined by the field equation (1.3). It is important to note that a tensor field describes space-time in general relativity. It can be imagined as a 4-dimensional curved hyper-surface immersed in a 5-dimensional flat Minkowski space-time.

According to the principles of classical theory, the solutions of the equation of motion, together with the boundary conditions (which can be obtained empirically), fully determine all natural phenomena or physical systems, and we can likewise understand them deterministically. The truth and reality of a physical system are equal, and both exist before the observation, which is the reality principle. The other important focus of the classical theory is that of locality, which forbids the simultaneous influence of one observer's observation on another's [5, 6].

II. THE QUANTUM PARADIGM

In quantum theory, the physical systems are described by a quantum state $|\alpha, t\rangle$, belonging to either the Hilbert space or the Fock space, depending on whether we are concerned with the first quantization or the second quantization (quantum field theory), respectively [6]. Therefore quantum technology must be constructed on the quantum state $|\alpha, t\rangle$.

In the flat Minkowski space-time, the quantum state $|\alpha, t\rangle$ is the solution of the following field equation:

$$i\hbar\frac{\partial}{\partial t}|\alpha, t\rangle = H|\alpha, t\rangle, \quad \text{or} \quad |\alpha, t\rangle = U(t, t_0; H)|\alpha, t_0\rangle, \tag{2.1}$$

where H is the Hamiltonian of the system and $U(t, t_0; H)$ is the time evolution operator. To obtain the explicit form of the quantum state $|\alpha, t\rangle$, we need to know the initial state $|\alpha, t_0\rangle$. Classically the initial state of the system is obtained from observations. Still, in quantum mechanics, the act of observation causes the state $|\alpha, t_0\rangle$ to collapse into the state $|\beta, t_0\rangle$. Evidently $|\beta, t_0\rangle$ is not the same as $|\alpha, t_0\rangle$ so that it is impossible for an observer to obtain and comprehend the quantum state $|\alpha, t\rangle$. Accordingly, how can we construct quantum technology? By choosing the quantum state $|\beta, t_0\rangle$ as the initial state after observation, quantum technology can be built, which will be clarified in this article.

Quantum technology has two different periods of progress. The first was constructed based on the probability amplitude and the second on the quantum state $|\alpha, t\rangle$, which will be discussed in the following sections.

2.1. The first quantum industrial revolution. The first quantum industrial revolution began with observing electrons' wave properties, which came from quantizing a particle. It is the so-called first quantization in which a wave function describes a particle, $\psi_\alpha(t, \vec{x})$, *i.e.* a classical field. However, the observed properties of the particle are explained with a probability density function in space $|\psi_\alpha(t, \vec{x})|^2 = |\langle\vec{x}|\alpha, t\rangle|^2$. Thus a phenomenon or a particle is described by the probability amplitude $\langle\vec{x}|\alpha, t\rangle$. From such a perspective, the quantum state $|\alpha, t\rangle$ is merely an auxiliary mathematical object immersed in Hilbert space. Despite the probability density function immersed in space-time, in this case, the Hilbert space is a purely mathematical subject.

Although the first quantization successfully explains the structure of atoms and predicts many fundamental particles, it suffers from many practical and philosophical problems, such as the creation and annihilation of particles and particle-wave duality. These problems are pretty solved in second quantization or quantum field theory.

The first quantization leads to the first quantum technology revolution. Technologies generated by the first quantization are electron microscope, nuclear power, Laser, transistors and semiconductor devices, and other devices such as MRI devices.

2.2. The second quantum industrial revolution. The second quantum industrial revolution was begun by observing the single photon (or particle properties of radiation field), and wave properties of the single-photon by Aspect et al. [7, 8]. Their observations were based on quantum field theory (QFT), also called second quantization. In the QFT model, a phenomenon or a physical system is described by a quantum state $|\alpha, t\rangle$, which is immersed in the Fock space. In this case, the Fock space is not a purely mathematical subject and it has observable physical properties.

The construction procedure of the quantum technology in this case may be performed in three steps: 1- the construction of a suitable quantum state $|\beta, t_0\rangle$, 2- obtaining its time evolution under the influence of the new interaction Hamiltonian H_n: $|\beta, t\rangle = U(t, t_0; H_n)|\beta, t_0\rangle$, and 3- its detection or observation, $|\beta, t\rangle \longrightarrow |\gamma\rangle$. This process will be briefly discussed in this article.

A class of devices actively create, manipulate, and read out quantum states of a system, often using the quantum effects of superposition and entanglement. The second quantum technologies revolution is constructed on the quantum state $|\alpha, t\rangle$ by applying its quantum properties such as entanglement and superposition. This model results in quantum technology such as quantum computing, sensors, cryptography, simulation, quantum metrology, quantum imaging, high-power fiber laser, etc.

III. NON-RELATIVISTIC CASE

In this section, we briefly recall the Hilbert space $\mathcal{H}^{(1)}$ and quantum state $|\alpha, t\rangle$ of a free particle and a simple harmonic oscillator in the non-relativistic quantum mechanics, which is essential for understanding the quantum field theory and then quantum technology. In quantum mechanics, an observable is presented by a hermitian operator, which is defined as a mapping from the Hilbert space on itself:

$$\text{Operators}: \ \mathcal{H}^{(1)} \longrightarrow \mathcal{H}^{(1)}, \quad and \ \ |\alpha, t\rangle \in \mathcal{H}^{(1)}.$$

In quantum mechanics, the Hilbert space plays the same role as the space-time in classical theory. Like space-time, the Hilbert space of a physical system is unique, but one can define the different basis for the Hilbert space similarly to the various coordinate systems in space-time.

3.1. **Free particle.** The Hamiltonian of a free particle is $H = \frac{p^2}{2m}$. Two important basis of the Hilbert space are $|\vec{k}\rangle$ and $|k, l, m_l\rangle$, which result in the plane wave ($\langle\vec{x}|\vec{k}\rangle \propto e^{-i\vec{k}\cdot\vec{x}}$) and spherical wave, respectively. The identity operator on these bases are:

$$I_{\vec{k}} = \int d^3k \ |\vec{k}\rangle\langle\vec{k}|, \quad I_{klm_l} = \int dk \sum_{l,m_l} |k, l, m_l\rangle\langle k, l, m_l| \,.$$

The quantum state can be written as:

$$|\alpha, t\rangle = \int d^3k \ |\vec{k}\rangle\langle\vec{k}|\alpha, t\rangle = \int dk \sum_{l,m_l} |k, l, m_l\rangle\langle k, l, m_l|\alpha, t\rangle = e^{-\frac{i}{\hbar}H(t-t_0)}|\alpha, t_0\rangle. \tag{3.1}$$

The sum or integral over the basis is a superposition. The outcome of a measurement depends on the initial state ($|\alpha, t_0\rangle$) and the Hamiltonian of the detector (H_d). If the initial state is one of the basis of Hilbert space, the time evolution only changes its phase, $|\alpha, t\rangle = e^{-i\frac{\vec{k}\cdot\vec{k}\hbar}{2m}t}|\vec{k}\rangle$ and if we have $[H, H_d] = 0$, the observed state is not a superposition of states.

3.2. **Simple harmonic oscillator.** The Hamiltonian of a simple harmonic oscillator is:

$$H = \frac{p^2}{2m} + \frac{1}{2}m\omega^2x^2 = \left(N + \frac{1}{2}\right)\hbar\omega, \quad N = a^\dagger a, \tag{3.2}$$

where a is the annihilation operator and N is the Number operator. In this case, three important bases for the Hilbert space, which we know them, are number states, coherent states, and squeezed states. The number states are the eigenstates of the number operator $N|n\rangle = n|n\rangle$. We have

$$a|0\rangle = 0, \quad a|n\rangle = \sqrt{n}|n-1\rangle, \quad a^\dagger|n\rangle = \sqrt{n+1}|n+1\rangle, \quad |n\rangle = \frac{\left(a^\dagger\right)^n}{\sqrt{n!}}|0\rangle. \tag{3.3}$$

$|n\rangle$ is a complete orthonormal basis:

$$I_n = \sum_{n=0}^{\infty} |n\rangle\langle n|, \quad n = 0, 1, 2, \cdots, \quad \langle n|m\rangle = \delta_{nm}. \tag{3.4}$$

The variance or the mean square deviation of x and p are:

$$\langle n|(\Delta x)^2|n\rangle = \left(n+\frac{1}{2}\right)\frac{\hbar m}{\omega}, \quad \langle n|(\Delta p)^2|n\rangle = \left(n+\frac{1}{2}\right)\frac{\hbar\omega}{m}. \tag{3.5}$$

They are minimum only for the ground state $n = 0$.

The coherent states are the eigenstates of the annihilation operator $a|z\rangle = z|z\rangle, \quad z \in C$ [9, 10]. We have

$$|z\rangle = D(z)|0\rangle = e^{za^\dagger - z^* a}|0\rangle = e^{-\frac{zz^*}{2}}\sum_n \frac{z^n}{\sqrt{n!}}|n\rangle, \quad D(z)|z'\rangle = e^{\frac{zz'^* - z'z^*}{2}}|z+z'\rangle, \tag{3.6}$$

where $D(z)$ is the displacement operator. The average of number operator and the time evolution of the coherent state are:

$$|z(t)\rangle = U(t)|z\rangle = e^{-i\frac{\omega t}{2}}e^{-i\frac{\omega t}{2}N}|z\rangle = e^{-i\frac{\omega t}{2}}|e^{-i\frac{\omega t}{2}}z\rangle, \quad \langle z|N|z\rangle = |z|^2. \tag{3.7}$$

Then in the time evolution, the mean square deviation of x and p are constant and minimum:

$$\langle z(t)|(\Delta x)^2|z(t)\rangle = \frac{\hbar m}{2\omega}, \quad \langle z(t)|(\Delta p)^2|z(t)\rangle = \frac{\hbar\omega}{2m}. \tag{3.8}$$

It is an exciting result, which is very important for quantum technology. The Laser produces the coherent state of electromagnetic field [11], and for signal and image processing, the coherent state may be used [12, 9, 10]. The coherent state may be used for signal, and image processing in MRI instead of Fourier transformation for minimum error [13].

If we define an annihilation operator, which is rotated in plane $(a, a^\dagger)$, such as:

$$a_s \equiv \cos\beta\; a + \sin\beta\; a^\dagger, \tag{3.9}$$

the variance of x and p are the functions of β as:

$$\begin{cases} \Delta x_s = \Delta x\cos\beta + \Delta p\sin\beta, \\ \Delta p_s = -\Delta x\sin\beta + \Delta p\cos\beta. \end{cases} \tag{3.10}$$

The variance or the mean square deviation of x_s or p_s can become less than the coherent state for some value of β. This property of the squeezed states is used to detect the gravitational wave in the LIGO experiment [14]. The squeezed state is defined as the eigenstates of the annihilation operator a_s:

$$a_s|\nu, z\rangle = f(\nu, z)|\nu, z\rangle, \quad \nu \equiv e^{i\beta}. \tag{3.11}$$

It can be written as:

$$|\nu, z\rangle = S(\nu)D(z)|0\rangle, \quad S(\nu) = e^{\frac{1}{2}(\nu^* a^2 - \nu a^{\dagger 2})}. \tag{3.12}$$

Squeezed states can be experimentally produced by forcing coherent states to propagate through a non-linear medium, which reproduces the effect of the non-linearity of the Hamiltonian [15],

$$|\nu, z\rangle \equiv e^{-iH_I t/\hbar}|z\rangle, \quad H_I = \frac{i\hbar}{2t}\left(\nu^* a^2 - \nu a^{\dagger 2}\right), \tag{3.13}$$

This property is essential for quantum tomography and has many applications in Lithography and medicine. Nano-lithography or advanced lithography is vastly used in producing nanoelectronic devices [16, 17]. Squeezed states have much application in detecting and photographing [14] and making electronic components [18, 19]. Squeezed states can also be used in MRI for best imaging resolution [20].

Different bases of Hilbert space can be used in quantum technology, such as quantum computation, quantum tomography, high-power fiber Laser, etc. [21, 22]. The construction of solid-state Lasers and high-power fiber lasers has many applications in industry, military, oil industry, etc. Lasers also have a wide range of medical applications, from imaging and diagnosis to treatment and surgery [11, 23].

If we assume that the Hamiltonian is time-independent and the initial state is one of the Hamiltonian eigenstates $|\alpha, t_0\rangle = |m\rangle$ $(H|m\rangle = E_m|m\rangle)$, during the time evolution only the phase of the quantum state is changed:

$$|\alpha, t\rangle = e^{-iE_m(t-t_0)/\hbar}|m\rangle,$$

whereas if the initial state is a superposition of different Hamiltonian eigenstates, $|\alpha, t_0\rangle = \sum_n c_n|n\rangle$, then the quantum state of the physical system is a complex superposition of states:

$$|\alpha, t\rangle = \sum_n e^{-iE_n(t-t_0)/\hbar}c_n|n\rangle.$$

A measurement of the physical system can be interpreted as an interaction with the system, and then one can define a new system that includes the measuring apparatus. We do this by introducing the perturbed Hamiltonian $H_T = H + H_d$. If $[H, H_d] = 0$ and the initial state is a single state, then the quantum state of the physical system is also a single state, which may be interpreted as a particle in quantum field theory. In all other cases, the quantum state of the physical system would be a superposition of states, which may also be interpreted as the wave function. Through this short presentation, one can better understand the quantum field theory.

IV. QUANTUM FIELD THEORY

In quantum field theory, H in equation (2.1) is the Hamiltonian of the relativistic fields, and the quantum state $|\alpha, t\rangle$ is immersed in Fock space. The classical Hamiltonian of the free field can be extracted from the field equation (Klein-Gordon equation, Dirac equation, Maxwell's equations, etc.). For the interaction fields, the Hamiltonian can be calculated from the gauge theory [24]. One of the essential parts of quantum technology is constructing the interaction Hamiltonian.

4.1. **Fock space.** Fock space is constructed by the relativistic one-particle Hilbert space as:

$$\mathscr{F}(\mathscr{H}) = \left\{C, \mathscr{H}^{(1)}, \mathscr{H}^{(2)}, \cdots, \mathscr{H}^{(n)}, \cdots\right\}, \quad |\alpha, t\rangle \in \mathscr{F}, \tag{4.1}$$

where C is vacuum state, $\mathscr{H}^{(1)}$ is one-particle states and $\mathscr{H}^{(n)}$ is n-particles states. n-particles states is constructed by tensor product of one-particle ststes (for bosons a symmetry product, $\mathscr{H}^{(2)} = S\mathscr{H}^{(1)} \otimes \mathscr{H}^{(1)}$ and for fermions an anti-symmetric products, $\mathscr{H}^{(2)} = A\mathscr{H}^{(1)} \otimes \mathscr{H}^{(1)}$).

The kinematical group of the Minkowski space-time is the Poincare group. By using the Lie algebra of this group, the one-particle states and unitary irreducible representation of this group can be constructed as [25]:

$$U^{(m,s)}(\Lambda,a)\,|k^{\mu},m_s;s,m\rangle = e^{-ia\cdot\Lambda k}\sqrt{\frac{(\Lambda k)^0}{k^0}}\sum_{m'_s} D^{(s)}_{m'_s m_s}(\Lambda,k)|(\Lambda k)^{\mu},m'_s;s,m\rangle, \tag{4.2}$$

where $\Lambda \in SO(1,3)$, $a^{\mu} \in R^4$ and $D^{(s)}_{m'_s m_s}(\Lambda,k)$ is a group representation of $SU(2)$. $k^{\mu} = (k^0,\vec{k})$ is the four-vector of energy-momentum. m is mass, s is spin, and the one-particle state is:

$$|k^{\mu},m_s;s,m\rangle \equiv |1_k\rangle \in \mathcal{H}^{(s,m)}_{k,m_s} \equiv \mathcal{H}^{(1)}, \quad (k^0)^2-(\vec{k}\cdot\vec{k}) = m^2c^4/\hbar^2, \quad -s \leq m_s \leq s. \tag{4.3}$$

The identity operator on the Fock space is:

$$I_F = \left(|0\rangle\langle 0| \oplus \int \tilde{dk}|1_k\rangle\langle 1_k| \oplus \int \tilde{dk}_1\tilde{dk}_2|1_{k_1},1_{k_2}\rangle\langle 1_{k_1},1_{k_2}| \oplus \cdots\right), \tag{4.4}$$

where $\oplus$ is tensorial sum, $|0\rangle$ is vacuum state, $\tilde{dk}$ is Lorentz invariant measure and $|1_k\rangle$ is the one-particle states. The field operator is defined as a mapping from the Fock space on itself:

$$\text{Field Operators}: \ \mathcal{F}(\mathcal{H}) \longrightarrow \mathcal{F}(\mathcal{H}).$$

In quantum field theory, from the equations (4.2) and (4.4), one can see that there is two sum or integral, one overall possibility states in one-particle Hilbert space similar to the first quantization and the other general possibility states in Fock space. Therefore, the creation and annihilation of a particle can be explicitly explained, which is the most crucial problem of the first quantization. In this model, the physical systems are equivalent with the quantum state $|\alpha,t\rangle \in \mathcal{F}$, and we have two statistics over observations: one over Hilbert space and the other on Fock space, which is complexly intertwined [26, 27]. This complexity must be well manipulated in quantum technology, an important theoretical and experimental research goal.

In quantum field theory, the particle-wave duality is meaningless. The observer can observe different aspects of the physical system from the particle and classical waves, which will be discussed in the following subsection for the electromagnetic field (for simplicity).

4.2. **Electromagnetic field.** For quantization of the electromagnetic field, we must begin with the Hamiltonian of this field. The Hamiltonian of the electromagnetic free field with two physical polarization states is [28]:

$$H = \int d^3x\,\frac{1}{2}\left(E^2-B^2\right) = \int \tilde{dk}\sum_{m_s=1,2}\hbar\omega_k\left[a^{(m_s)\dagger}(k)a^{(m_s)}(k)+\frac{1}{2}\right], \tag{4.5}$$

where m_s is the polarization of the electromagnetic field or photon's spin direction, this Hamiltonian is constructed from an infinite number of the simple harmonic oscillator (3.2). Like a harmonic oscillator, one can define the number state as the number of photons. The particle number operator is defined as: $N(k,m_s) = a^{(m_s)\dagger}(k)a^{m_s}(k)$, which commute with the Hamiltonian (4.5), $[H,N(k,m_s)] = 0$. The electromagnetic field's coherent and squeezed states can be introduced, similar to the harmonic oscillator. In this case, the Laser produces coherent states. Squeezed states can be experimentally produced by forcing coherent states to propagate through a non-linear medium.

Hence, within quantum field theory, the observation of what we usually call particles (in this case photons) or waves depends on the initial state $|\alpha, t_0\rangle$ and the Hamiltonian of the detector H_d as well. If the initial state is one of the number operator's eigenstates, then the physical system's quantum state contains a definite number of particles or quanta. In this case, we can observe the photon if $[H, H_d] = 0$. With a single photon, if $[H, H_d] \neq 0$, the interference is observed or the wave properties of the photon. It is interesting to note that in the number states, the concept of particles or quanta exists but the number of the particles is dependent on the detector energy, which manifests the fluctuation in the Fock space.

If the initial state is a superposition of the particle number operator's eigenstates, the physical system's quantum state ($|\alpha, t\rangle$) is a superposition of states, and the particles picture is inappropriate. One can only speak of the average number of photons or particles. We see that the particle-wave duality conundrum, well-known in ordinary quantum mechanics [5], disappears in the framework of the quantum field theory as the fundamental concept in quantum field theory is the quantum state $|\alpha, t\rangle$. Expressing this concept in entangled states shatters classical physics' naive realism and locality. When a quantum field exists (for example, electron field, electromagnetic field, etc.), the corresponding quantum state $|\alpha, t\rangle$ also exists.

The reality observed by the observer depends on the apparatus of the observer, and reality observation is probabilistic, but the quantum state $|\alpha, t\rangle$ is deterministic due to the unitarity principle ($UU^\dagger = 1$):

$$|\alpha, t\rangle = U(t, t_0)|\alpha, t_0\rangle \implies \text{Observations} \implies |\beta, t_0\rangle \equiv \begin{cases} \text{Particles,} \\ \text{Classical waves,} \\ \text{Number state,} \\ \text{Coherent states,} \\ \text{Squeezed states,} \\ \cdots . \end{cases} \tag{4.6}$$

In the model of quantum theory, the quantum state $|\alpha, t\rangle$ may be considered the truth of the physical system, which is inaccessible to the observer, and the quantum state $|\beta, t_0\rangle$ as its reality. t_0 is the time of the observation. From the principles of quantum theory, one cannot obtain and comprehend the quantum state $|\alpha, t\rangle$ because we need the initial state for calculating $|\alpha, t\rangle$ and the observation for perceiving the physical system. However, after the observation, due to the collapse of the quantum state $|\alpha, t\rangle$, we obtained a new quantum state, and also the act of observation caused the state $|\alpha, t_0\rangle$ to collapse into the state $|\beta, t_0\rangle$. This new quantum state $|\beta, t_0\rangle$ is understandable for the observer because of observation.

Under the evolution of the new interaction H_n on the quantum states $|\beta, t_0\rangle$, due to the unitarity principle, one can obtain the time evolution of this quantum states $|\beta, t\rangle$ exactly or deterministically:

$$|\beta, t\rangle = U(t, t_0; H_n)|\beta, t_0\rangle, \quad UU^\dagger = 1 = U^\dagger U. \tag{4.7}$$

The critical point in quantum engineering or technology lies here. For the construction of the technology, we need a deterministic physical state, which now exists, $|\beta, t\rangle$. Therefore the process of quantum technology can be divided into three steps. The first step is constructing the quantum states $|\beta, t_0\rangle$, which requires high precision. Then we must obtain the best interaction Hamiltonian H_n in the atomic and subatomic levels. This step is the most complicated part of quantum engineering, which requires collaboration between the different branches of engineering and physics. The final step is to detect the quantum state $|\beta, t\rangle$, which is also a complex problem. The final stage is also a probabilistic process. Using the entangled state, one can manipulate the other part of the entangling state for use in the quantum computer, which is an art of the experimentalist. The quantum computation (quantum algorithm), quantum information processing, quantum cryptography, quantum radar, quantum tomography, and quantum teleportation are based on quantum entanglement [29, 30, 31, 32, 33]. The IC programming must be done at the quantum level.

V. QUANTUM TECHNOLOGY

The classical technology is based on the intrinsic properties of electrical charge, and mass of the particles [34]. In quantum technology, the other inherent properties such as spin, flavor, and color may play a similar role. Still, due to the limitations of contemporary technology, spin only appears in quantum technology.

Before constructing quantum technology, we must accept that a physical system is equivalent to a quantum state, physical system $\equiv |\alpha, t\rangle$, which can be calculated deterministically using the quantum theory principles, unitarity principle. In the last decade, considerable advances have been achieved concerning the theoretical understanding, technical fabrication, and experimental characterization of the quantum state, $|\alpha, t\rangle$.

From the principles of quantum theory, we know that observation causes the collapse of the quantum state to a new quantum state, $|\beta, t_0\rangle$, which is a probabilistic process. The construction of quantum state $|\beta, t_0\rangle$, its time evolutions, and finally, its detection is an essential procedure of quantum technology. Therefore these procedures can be divided into three steps, briefly discussed in the following subsections.

5.1. **Quantum-state reconstruction.** Quantum technology is based on the construction of the quantum state, which generally uses the magnetic or spin properties of matter and electromagnetic field [35, 36, 37, 38]. The construction of quantum states of photons, phonons, and electric charge particles are vastly studied in the different disciplines of quantum engineering, such as photonics, solid-state physics, and plasma physics. We briefly recall two important experiments, which have been extensively used in technology for the reconstruction of the quantum states for charge spin $= \frac{\hbar}{2}$ particles and photons (spin $= 1\hbar$). The first one is the Stern-Gerlach experiment. In the original investigation, silver atoms were sent through a spatially varying magnetic field in the z direction, and the particles with non-zero magnetic moments were deflected in two branches. The spin quantum state of the particles is a superposition of the spin up and down in the z direction:

$$|\alpha, t\rangle = c_1\, |z, +\rangle + c_2\, |z, -\rangle. \tag{5.1}$$

The meaning of this superposition is not clear to our perception. After blocking $-z$ direction, which is equivalent with an observation or interaction, the quantum state collapse to the new quantum state $|\beta, t_0\rangle = |z, +\rangle$. Now, this quantum state can be undergone with a new interaction Hamiltonian, which will be discussed in the following subsection, and is obtained as its time evolution:

$$|\beta, t\rangle = U(t, t_0; H_n)|\beta, t_0\rangle = U(t, t_0; H_n)|z, +\rangle. \tag{5.2}$$

Because of the unitarity principle, we have explicitly the quantum state $|\beta, t\rangle$.

The second one is the Aspect et al. experiment [7, 8]. They produce polarization entangled photon-pair source, where the quantum state is:

$$|\alpha, t\rangle = \frac{1}{\sqrt{2}} \left[\, |H_1, H_2\rangle - |V_1, V_2\rangle \right]. \tag{5.3}$$

$H(V)$ is horizontal (vertical) polarization. After observing one photon, a single photon (another photon) generate with the specific polarization:

$$|\beta, t_0\rangle = |H\rangle, \quad \text{or} \quad |\beta, t_0\rangle = |V\rangle. \tag{5.4}$$

It is interesting to note that with the single-photon, the observer can observe the wave properties of the single-photon if the Hamiltonian of the detector cannot commute with the photon number operator, $[H_d, N] \neq 0$.

The production of quantum states is an experimental art and is precious in quantum technology. The Laser produces a coherent state. The squeezed states may be generated by forcing coherent states to propagate through a non-linear medium. The production of squeezed states can be extended to the case of condensed matter physics by replacing photons with phonons. Applying coherent and squeezed states in quantum engineering is vast and needs careful study.

5.2. **Interaction Hamiltonian.** The interactions used in technology may be divided into three types: charge particles-charge particles, charge particles-photons, and photons-photons. The first two interactions exist in classical theory, and they can also be explained in the first quantization and formulated by the gauge theory, following classical field Lagrangian density:

$$\mathcal{L}_c = -\frac{1}{2}\partial_\mu A_\nu \left(\partial^\mu A^\nu - \partial^\nu A^\mu\right) + \frac{1}{2} l \left(\partial \cdot A\right)^2 + \sum_n \bar{\psi}_n \left(i\gamma^\mu D^n_\mu - m_n\right)\psi_n, \tag{5.5}$$

where $D_\mu = \partial_\mu + iq_n A_\mu$ is the gauge covariant derivative, ψ_n is the particle-wave function, and n is defined as the type of the particles. $l \neq 0$ is an arbitrary constant. In this matter, n is a huge number, and it is also necessary to use the statistical mechanics [26, 27]. The photons-photons interactions can only be explained in the quantum field theory, where the effective Lagrangian density (effective potential) can be obtained by the loop-expansion approximation [24]:

$$\mathcal{L} = \mathcal{L}_c + \hbar \mathcal{L}^{(1)} + \hbar^2 \mathcal{L}^{(2)} + \cdots. \tag{5.6}$$

Then the interaction Hamiltonian can be calculated theoretically by the equation (5.6).

Since calculating the effective potential is difficult for experimental researchers, the interaction Hamiltonian is usually obtained by trial and error. Therefore the most challenging problem in quantum engineering is to design the interaction Hamiltonian between the quantum state and matter or quantum field experimentally, which needs cooperation between the various discipline of physics and engineering. The interactions are generally based on field-matter properties: electric charge, spin, magnetic moment, and electric moment. In the interaction between the photons-photons and photons-matter, the non-linear optics and quantum optics play an essential role. In the magnetic properties of matter, matter's superconductivity and semiconductor properties are pretty important. If other materials are provided to it to form interfaces, remarkable devices can be made to control quantum states.

Researchers have coupled the monolayer form of carbon known as graphene with thin layers of magnetic materials like cobalt and nickel, producing the sort of exotic behaviors in electrons that could be useful for next-generation computing applications. The interaction of graphene with magnetic materials affects the spin property of electrons. It has been studied as a route for driving low-energy, high-speed computer memory, and logic. The use of graphene may represent a revolutionary advance. Graphene is ultra-thin and lightweight, with very high electrical conductivity. Researchers are now working to form the graphene-magnetic multilayer material on an insulator or semiconductor to bring it closer to potential applications.

The nanoscale crystals, photonic crystals, and growing anisotropic crystals at the nanoscale have much application in nanoelectronic devices [39, 40]. The revolution has been taking place in the field of electronics with the development of nano transistors, quantum dots, quantum wires, and quantum wells [41, 19, 18]. The subjects such as nano-meter CMOS IC, circuit design IC and circuit design CPU are considered in this domain [42, 43]. Recently the researchers tried to use Plasmons [44, 45] and microwave circulator [44], which are based on quantum anomalous Hall effect [46, 47, 48], since they may support electrical currents that flow without resistance [44].

5.3. **Observation or detection.** In quantum theory, observation causes the collapse of the quantum state, which is probabilistic. However, for engineering technology, we need a deterministic result. This goal is achieved by using the entangled states. Entanglement will be used extensively as a powerful computational resource in quantum information processing and quantum computation. In the entangled two qubits state, the measurement of the first qubit affects the outcome of the measurement on the second qubit, which shows that the initial state is entangled. In other words, there exists a strong correlation between the two qubits. This correlation may be used for information processing. Suppose the register is set to an initial fiducial state, for example, $|\beta, t_0\rangle$. A unitary matrix $U(t, t_0)$ is designed to represent an algorithm we want to execute. Operation of U on $|\beta, t_0\rangle$ yields the output state $|\beta, t\rangle = U(t, t_0)|\beta, t_0\rangle$. Information is extracted from $|\beta, t\rangle$ by appropriate measurements [29]. For the homodyne detection and quantum state reconstruction, see [49] and references in it.

Some important entangled states are the Bell state, Greenberger-Horne-Zeilinger state (GHZ), W state (three-qubit state), and EPR state. An eight-qubit entangled state has been realized with an ion trap. The ion trap is one of the candidates for a scalable quantum computer [50]. Jaksch et al. proposed a method to prepare neutral-atom entangled states and Bell-like states, to be more specific, by controlling atom-atom collision time [51].

VI. CONCLUTION

The most important concept in the quantum theory is the quantum state $|\alpha, t\rangle$, which is modelled a phenomenon, *i.e.* physical system $\equiv |\alpha, t\rangle$. The reality, which is an observer-dependent quantity, is the collapse of a quantum state. From the general covariance, all observers are equivalence. Therefore, no one can claim that he has come to the truth because they have come to reality, and the truth is an illusion for the observer. In quantum theory, the truth of a natural phenomenon is a quantum state $|\alpha, t\rangle$, which is not accessible to the observer, and the reality is a specific collapse of the quantum state, *i.e.* $|\beta, t_0\rangle$, which is perceivable for the observer.

On the other part, technology needs deterministic phenomena. In this paper, we discussed how one could construct a quantum state, obtain its time evolutions, and finally detect it with certainty in Minkowski space-time. The critical step in quantum technology

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