Understanding the “spooky action at a distance”

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Quantum entanglement (QE), or in many cases, the nonlocality of quantum states, is the basis of modern quantum information researches, but is counter-intuitive and puzzles even the greatest minds in the physics community. We investigated the previous interpretation of quantum entanglement, and found some questionable hidden assumptions and inconsistencies with current theories. By clarifying the concepts and definitions, we found QE is actually a trivial phenomenon easily understandable in the current framework of quantum theory, i.e., the Copenhagen interpretation. Moreover, the understanding suggest a limit to QE and is supported by historical QE experiments, which means Einstein’s local realism still works, and no weirdness is involved.

The “spooky action at a distance”, as stated by Einstein, or quantum entanglement (QE), is a fundamental physical phenomenon of multiple interacting particles, that each particle depends on the other(s), even when they are separated afar, and the change or measurement of one party will immediately affect the other(s). This spooky action could happen much faster than the speed of light, which violates the local realism suggested by Einstein. Einstein was very upset by the concept, and wrote a famous paper[1] with B. Podolsky and N. Rosen (EPR), to show that quantum mechanical description of quantum states was incomplete. Schrödinger[2] shared the uneasiness of Einstein, and first used the term “entanglement”.

In 1964, John Bell[3] noticed there is a way to tell the difference between the quantum theory and the hidden variable theory supporting EPR. Even since 1972, S. Freedman and J. Clauser[4], and A. Aspect[5] in 1982, till B. Hensen et al.,[6] in 2015, numerous experiments eventually ruled out many local realism theories. Questioning of the nonlocality of quantum states fades away, and researches and applications based on quantum nonlocality, such as quantum communication and quantum computing, thrive.

Furthermore, there are many public claims like "instantaneous entanglement no matter how far away separated" (or universal entanglement, UE), although many physicists find it puzzling, they are not challenged. Experimentally, the claim is verified at a distance of about 1200 km[7], which is still far from "billions of light years" or "at the other end of the universe". Will QE transverse over the distance of galaxies, or equivalently, last forever?

We found there are a few hidden assumptions in the theoretical foundation of QE. Clarifying these assumptions can lead to better understanding of QE.

Formulation of QE and its hidden assumption

In the context of QE, the mathematic form for QE is the superposition of two or more eigenstates, such as the Bell states:

$$|\phi\pm\rangle = \frac{1}{\sqrt{2}}\left(|00\rangle \pm |11\rangle\right), \qquad |\psi\pm\rangle = \frac{1}{\sqrt{2}}\left(|01\rangle \pm |10\rangle\right) \tag{1}$$

and GHZ state:

$$|\mathrm{GHZ}\rangle = \frac{1}{\sqrt{2}}\left(|000\rangle \pm |111\rangle\right) \tag{2}$$

The exact meanings of the symbols are well known and are irrelevant in our discussion here. The key fact is that they are purely mathematic symbols, and every one of them is a constant. The definition alone assumes that every entity involved in QE is a constant. Any relationship defined in these formula will for sure last forever, or to infinity in space.

This is a huge hidden assumption, introduced in without any awareness of its implications, and will lead to the conclusion of universal entanglement, hence the above claims.

Are the definitions Eq. (1) and (2) physical and complete? If yes, any theory based on the definitions is well-founded, or the derivative claims are questionable.

In real life, or in experiment, QE is a transient process, which changes over time, no matter where changes come from (or QE would not happen at the first place). Therefore, we believe the above definition is neither physical nor complete, but an over simplified mathematical notation, which deprived of many important physical properties. We should not go to far with such a definition.

The definition of a photon

As photons are involved in all existing QE experiments (as the particle, or as the interaction carrier), the nature or physical properties of the photon is essential in understanding the experimental results. However, even though the definition of a photon is fundamental in our physics knowledge system, it is not so clear.

In quantum electromagnetic field theory (QED), by definition, a photon is a stable massless elementary particle, with its spin being 1 (circular polarization), a fixed energy proportional to its frequency, and acts as the carrier of electromagnetic interaction. However, this definition only has its mathematic significance, because for any fixed single energy photon, the wave function is a plane wave expanding over the entire universe, and last forever. With this definition, UE statement is certainly plausible.

However, this is another problematic hidden assumption, because in real life, or in experiment, a photon is created by atomic electron energy level transition with an internal linewidth, or energy uncertainty. It has a limited spatial extension, or limited existing time locally. A real photon can be polarized in many ways, or be a superposition of many different frequencies.

We believe we should discuss QE in the context of physical photons, not mathematical ones as in QED, because this is exactly what physics or sciences are about. In this case, the understanding of the internal linewidth of the atomic energy transition is essential.

Internal linewidth and Heisenberg uncertainty principle

In the real world, every photon has an internal linewidth (aside from various broadening mechanisms), which is connected to the lifetime of the excited energy level by Heisenberg uncertainty principle,

$$\Delta E \cdot \Delta t \geq \hbar/2 \tag{3}$$

There might be a misconception about the energy uncertainty ΔE. One might think ΔE is a statistic distribution, while for each specific photon, the energy is a fixed single value. This is not what recognized in Copenhagen interpretation. Both uncertainties ΔE and Δt are the internal properties for every single photon. Δt can be also interpreted as the lifetime of the energy level, a. k. a., the local lifetime of the photon produced by the energy level transition. Please note that, from measurement point of view, the misconception actually looks to be correct.

According to Eq. (3), mathematically, by simply assuming there is an energy transition between two electron energy levels, and leaving out the uncertainties, we are in fact implying the transition energy is a fixed single number, i.e., $\Delta E = 0$ and transition time is forever, or $\Delta t \sim \infty$, which leads to UE.

However, as in real life, the energy transition happens in a limited time Δt, and with an internal energy uncertainty ΔE. Therefore, we believe that the transition time Δt, or the local lifetime of the photon produced, should put a limit to the time or distance to a QE event. If this photon is then used to make a pair of entangled photons, as in spontaneous parametric down-conversion (SPDC), though there could be some change to the lifetime of the produced pair, $\Delta t'$, the QE of the pair can only last in a time duration in the order of $\Delta t'$, and the maximum distance of QE should be in the order of

$$L_{\max} \sim c\Delta t', \tag{4}$$

with c being the speed of light. The quantum state of a photon has certain time span Δt, and a photon can only travel at the speed of light, so the influence of the photon is limited to $L_{\max}$. This is local realism, but with the consideration of the property of a physical photon. Here, this is only an assumption, which can only be verified by experiment, as shown below.

Unfortunately, the uncertainty principle (3) can not determine $L_{\max}$, but give a lower limit, because of the $\geq$ symbol in Eq. (3).

Copenhagen interpretation and time uncertainty

In addition to Heisenberg's uncertainty principle, the definition and the interpretation of wave function $\Psi(x,t)$ are also essential, for $\Psi(x,t)$ has all information of a quantum state.

What does time uncertainty Δt of a quantum state mean? In the theoretical framework of quantum physics including quantum field theory, time t is just another dimension similar to space x, because formally x and t are equal in $\Psi(x,t)$. We can interpret time in analogy with the space dimension. As a quantum state has a distribution in a range of the space dimension, the exact same state also has a distribution in time dimension. There is no classic correspondence of this concept, just like the other internal uncertainties, such as momentum Δp, spatial distribution Δx, and energy ΔE.

In Copenhagen interpretation, the wave function of a quantum state is a virtual amplitude of the probability distribution in space, the same is true for the time dimension. The wave function of the quantum state is an overall solution to the basic equations, with the consideration of all in-region and boundary conditions in both space and time dimension. The equations should be solved in 4-dimensional space, not 3-dimensional as in classic world, thus the solution (photon wave function) is also 4-dimensional. In another word, the photon knows everything about its environment in its Δt and Δx space-time block, because its wave function is the solution based on these conditions, including how it is (and will be as long as not over exceeding Δt) measured. The correlation or entanglement of the photon established in this space-time block is the exact solution to the basic equations with all the spatial and temporal boundary conditions (including measurement apparatuses). The photon, or equivalently, its wave function, is the manifestation of these conditions. Or, the photon just passively reacts to what you decide to measure, with a Δt margin.

In this picture, many of the counter-intuitivity and weirdness of quantum physics are gone.

Here we have to extend the 3 dimension wave function to 4 dimension is due to the fact that photon is not a legit concept in unrelativistic quantum theory, which is ignored previously.

Experimental proof of local realism

Experimenting the "the spooky action" has been a long time effort in quantum physics researches. We studied some of the historical experiments[6–21] and found a tantalizing proof to local realism in QE, i.e., the entanglement does decrease as the distance between both ends of the measurements grows.

Table 1 shows the compiled experimental results of the entanglement of formation. The quantified measurement of the entanglement is denoted by Bell-CHSH inequality, with the maximum value being $2\sqrt{2}$, and should be greater than 2. The smaller the value is, the less the two particles are entangled, or less particles are fully entangled.

As the experiments had been carried out by different scientists over long time in different settings, the table is not a consistent systematic one, so meticulous quantified analysis may not be well grounded. However, we can still have the following observations:

1. The CHSH inequality is low if ions were used as the entangled particles.
2. Only photons were used in long distance experiments over 2 kilometers, and ion entanglement was achieved only in a few meters.
3. Generally speaking, for photon entanglement results, CHSH inequality decreases as the distance grows.
4. One group (W. Tittel and J. Brendel[12,18]) did two consequent experiments. As the distance goes from 35 meters to about 11 kilometers, CHSH inequality drop from 2.698 to 2.41.

Discussions

1. For ion involved entanglement experiments, the CHSH inequality is low[8–10]. The reason is, a standing-alone ion's excited electron energy level has a short life-time of a few nanoseconds, $\Delta t \sim 1$ ns. As the interaction carrier, the corresponding photon has a short correlation (entanglement) length of about $L \sim 1$ m.

2. In the case of photon entanglements, photons are usually originally produced by a laser source. For commonly used 1046 nm YAG laser, the lifetime of the transition between the energy levels $4F_{3/2} \rightarrow 4I_{11/2}$ of Nd^{3+} ion is 230 μs, and for ruby laser, the corresponding transition lifetime of Cr^{3+} ion is 3 ms, both are far longer than ordinary atomic transitions, which can sustain a correlation or entanglement far more distant, up to thousands of kilometers. Please note, Δt is not a rigid limit. For a specific atomic energy transition life time Δt, there are still a considerate amount of photons exist even after the exponentially decreasing of multiple lifetimes. For ruby laser, there are still $e^{-5} \approx 1\%$ photons left after $5\Delta t$ = 15 ms, corresponding to a distance of 4500 km.

3. In quantum field theory, the above understanding is also valid in Lorentz covariant solutions, i.e., the photon must obey Einstein's special relativity theory. In the case of QE, if we observe a QE event from a different frame of reference, classically, the causality relation of the two measurements may change, but this will not happen if we take into account time uncertainty Δt. In another word, our understanding agrees naturally with Einstein's special relativity theory.

4. The common claim of "if you measure one party of the entangled particles, the other party simultaneously changes its state no matter how far away" does not consider the fact that a photon can span over long distance as long as its Δt is large enough, which can be tens of microseconds if the photon is produced by a laser source, or thousands of kilometers apart.

5. From the above principles, we can have the picture of BBO crystal entanglement as follows: when the entanglement mode in BBO crystal is excited by the incoming laser, the

measurement is involved in the excitation and determines the polarization direction in both directions. All happen simultaneously if the detecting slits are close enough. The further the slits are away from the crystal, the less the correlation will be, or less entanglement of formation one can get. The limit is the life or coherence time of the original laser photon.

6. Time uncertainty understanding also naturally explains well post-selection double-slit experiment[24,25] and delayed choice quantum eraser[26] experiment.

7. We do not rule out the possibility of very long range QE, but realistically, as the internal uncertainty Δt or Δx grows, more and more environment entities are involved, and the field and the boundary conditions becomes more and more complex, a pure entangled solution (photon wave function) will be less and less likely to achieve.

8. Local realism has profound implications to our physical world. The violation of local realism in quantum states is not true if the time uncertainty of quantum states is considered.

Conclusions

In Copenhagen Interpretation of quantum physics, the definition of wave function $\Psi(x, t)$ and Heisenberg's uncertainty principle are the most important principles. The claim of faster than light action comes from questionable assumptions and definitions. By suggesting that we should use the physical picture of a photon, and the measurement participates the entanglement, we found QE is easily understandable, and a limit to QE is natural, which is supported by historical QE experiments. Einstein's local realism still works.

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Contributions

Yian Lei contributed to the original idea and concepts, wrote the final manuscript.

Yiwen Liu did background research, collected reference data, prepared the table and figures, wrote the early manuscripts.

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Table 1: Collected experimental results of quantum entanglement by distance

Scientists	year	particles	distance	CHSH inequality
M. Rowe[8]	2001	Be^+ ions	3 μm	2.25
D.N. Matsukevich[9]	2008	Yb^+ ions	1 m	2.22
D. L. Moehring[10]	2004	Cd^+ ion and photon	1.1 m	2.203
A. Aspect[11]	1982	photons	13 m	2.697
W. Tittel[12]	1997	photons	35 m	2.698
G. Weihs[13]	1998	photons	400 m	2.73
M. Aspelmeyer[14]	2003	photons	600 m	2.41
B. Hensen[6]	2015	electrons	1.3 km	2.42
J. Handsteiner[15]	2016	photons	1.6 km	2.49
P.R. Tapster[16]	1994	photons	4.3 km	2.46
H. Zbinden[17]	2000	photons	10.6 km	2.35
W. Tittel[18]	1998	photons	10.9 km	2.41
C.Z. Peng[19]	2005	photons	13 km	2.45
D. Salart[20]	2008	photons	17.55 km	2.47
T. Herbst[21]	2012	photons	143 km	2.43
J. Yin[7]	2017	photons	1203 km	2.37