Emerging Applications of Quantum Entanglement: Quantum Lidar and Unhackable Communication over Large Distances

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ABSTRACT

The phenomenon of quantum entanglement has applications leading to devices and systems having capabilities unperceived till recently. Quantum lidar is one such system, which has been demonstrated that it can detect even the stealth targets like aircraft, ships etc. located at far off distances. Quantum lidar capabilities have recently been demonstrated by China and then followed by Canada. In this paper we introduce the fundamentals of quantum entanglement and show how it can be applied in designing the quantum lidar systems which have far better capabilities than the classical lidar systems. . In addition to quantum lidar, with is limited range, we shall also discuss how the phenomenon of entanglement among photons, separated by over 1200 km from each other, could help in secure and unhackable communication between the ground station and the satellite.

Keywords: Quantum Lidar, Quantum Entanglement, Stealth Technology.

1. Introduction

There have been recent reports [1-3] that China is planning to create a globe-spanning constellation of satellites that constitute a super-secure quantum internet. This will help China catch up with, and perhaps overtake, the US in building powerful quantum computers. The fundamental units of computation in these machines are qubits, which, unlike bits, can occupy a quantum state of 1 and 0 simultaneously. Unlike conventional bits, qubits can have indeterminate states, neither 1 nor 0, but a possibility of both—and become oddly connected or entangled, so that the behavior of one bit directly impacts the other. By linking qubits through a phenomenon known as entanglement, quantum computers can generate exponential increases in the processing power. Chinese scientists have been able to pack 18 qubits into just six weirdly connected photons. That is an unprecedented three qubits per photon, and a record for the number of qubits linked to one another via quantum entanglement.

According to another Report [4] released in April 2018, the Canadian Department of National Defense was investing $2.7 million in research at the University of Waterloo to investigate quantum radar technology. This brings Canada into a technological race in which China apparently has taken the lead. The report further says that the quantum radar might eventually provide a capable means of detecting stealth fighters and bypassing electronic warfare capabilities. While Canada has opted out from acquiring F-35 stealth fighters, the North American Aerospace Defense Command (NORAD) operates jointly with the United States and must contend with potential intrusions by new Chinese and Russian stealth aircraft. This system would not be susceptible to many of the techniques designed to circumvent the radio wave reflection that is, a reduced radar cross section and radar-absorbent materials, and also would not be affected by jamming and other electronic warfare ploys, which play an important role in defeating air military radars.

One of the applications of Quantum entanglement phenomenon is that it can lead to ‘Quantum Lidar’, which has a resolution of more than ten times that of classical Lidars. A Quantumly-entangled Lidar can also detect stealth military objects like aircrafts, ships, submarines etc. Stealth objects are designed to reflect signals away from the radar/lidar, typically by using rounded surfaces and avoiding anything that might form a partial corner reflector. The stealth property can also be achieved to a large extent by coating the object with the Radar Absorbing Material (RAM). This so reduces the amount of signal returned to the radar's receiver that the target is (ideally) lost in the thermal background noise.

In this paper we shall discuss about the ‘Quantum Lidar’, its advantages over classical lidar, and the phenomenon of ‘Quantum Entanglement’, the technology this Lidar is based upon.

2. Quantum Lidar

A quantum lidar functions by using a device to split a photon into two entangled photons. Then the radar beams one half of the entangled pair outwards, and monitors the corresponding effects on their entangled partners. If the beamed particles bump into, say, a stealth fighter, the effect on the beamed photon would be visible on the un-beamed partner photon as well. Then the photons which register a ‘ping’ are sorted out from the unaffected photons to form a sort of radar image.

The basic concept of Chinese Quantum Lidar is to create a stream of entangled visible-frequency photons and split it in half. One half, the "signal beam", goes through a conversion to microwave frequencies in a way that preserves the original quantum state. The microwave signal is then sent and received as in a normal radar system. When the reflected signal is received it is converted back into photons and compared with the other half of the original entangled beam, the "idler beam". This scheme is represented in Fig. 1 below:

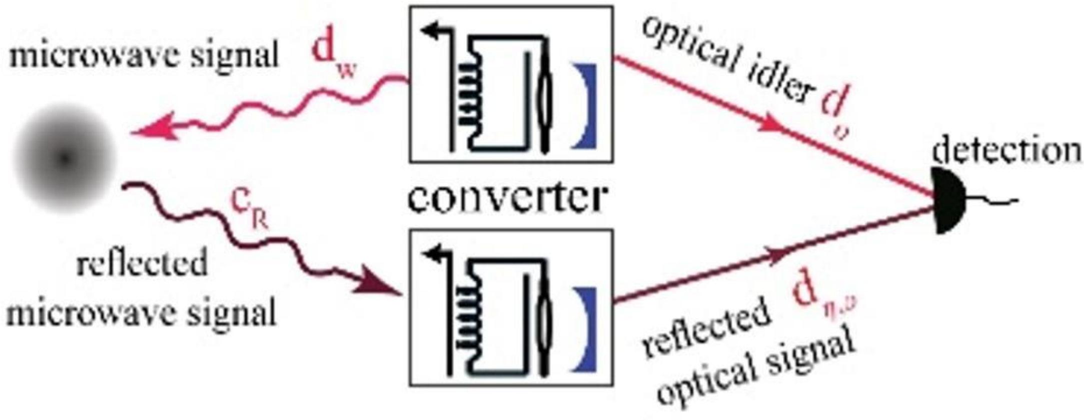

Fig. 1 : Schematic of Chinese Quantum Lidar

Although most of the original entanglement will be lost due to quantum decoherence as the microwaves travel to the target objects and back, enough quantum correlations will still remain between the reflected-signal and the idler beams. Using a suitable quantum detection scheme, the system can pick out just those photons that were originally sent by the radar, completely filtering out any other sources.

While conventional radars just measure the reflection of radio waves, quantum radar uses entangled photons, which result when a microwave signal beam is entangled with an optical idler beam. The microwave beam's entangled photons bounce off of the target object and back to the quantum radar. The system compares them with the entangled photons of the optical idler beam. As a result, it can identify the position, radar cross section, speed, direction and other properties of detected objects. Importantly, attempts to spoof the quantum radar would be easily noticed since any attempt to alter or duplicate the entangled photons would be detected by the radar. In this system, it will allow the radar system to pick out its own signal even when swamped by background noise.

Future implementations of quantum illumination at the microwave regime could also be achieved by using other quantum sources, for instance based on Josephson parametric amplifiers, which are able to generate entangled microwave modes of high quality. These amplifiers might become a very good choice once that suitable high-performance microwave photo-detectors are made available.

Quantum radar systems could be small and would be able to evade enemy countermeasures such anti-radar missiles because the ghostly quantum entanglement could not be traced, it said.

However, quantum radars have their limitations; like traditional radars, they degrade in resolution over longer distances. This is because the entangled particles do eventually lose the coherence of their quantum state over long distances, a phenomenon which can worsen in adverse weather.

3. Photon Entanglement at Large Distances Apart

According to report [5], a team of Chinese scientists using an experimental satellite has tested quantum entanglement over unprecedented distances, beaming entangled pairs of photons to three ground stations across China—each separated by more than 1,200 kilometers. The test verifies a mysterious and long-held tenet of quantum theory, and firmly establishes China as the front-runner in a burgeoning "quantum space race" to create a secure, quantum-based global communications network—that is, a potentially unhackable "quantum internet" that would be of immense geopolitical importance.

The concept of quantum communications is considered the gold standard for security, in part because any compromising surveillance leaves its imprint on the transmission. Conventional encrypted messages require secret keys to decrypt, but those keys are vulnerable to eavesdropping as they are sent out into the ether. In quantum communications, however, these keys can be encoded in various quantum states of entangled photons—such as their polarization—and these states will be unavoidably altered if a message is intercepted by eavesdroppers. Ground-based quantum communications typically send entangled photon pairs via fiber-optic cables or open air. But collisions with ordinary atoms along the way disrupt the photons' delicate quantum states, limiting transmission distances to a few hundred kilometers. Sophisticated devices called "quantum repeaters"—equipped with "quantum memory" modules—could in principle be daisy-chained together to receive, store and retransmit the quantum keys across longer distances, but this task is so complex and difficult that such systems remain largely theoretical.

A quantum repeater has to receive photons from two different places, then store them in quantum memory, then interfere them directly with each other before sending further signals along a network. But in order to do all that, you have to know that you have stored them without actually measuring them. The situation is a bit like knowing what you have received in the mail without looking in your mailbox or opening the package inside. You can shake the package—but that's difficult to do if what you are receiving is just photons. You want to make sure that you have received them but you don't want to absorb them.

To form a globe-girdling secure quantum communications network, then, the only available solution is to beam quantum keys through the vacuum of space then distribute them across tens to hundreds of kilometers using ground-based nodes. Launched into low Earth orbit in 2016 and named after an ancient Chinese philosopher, the 600-kilogram "Micius" satellite is China's premiere effort to do just that, and is only the first of a fleet the nation plans as part of its $100-million Quantum Experiments at Space Scale (QUESS) program.

Micius carries in its heart an assemblage of crystals and lasers that generates entangled photon pairs then splits and transmits them on separate beams to ground stations in its line-of-sight on Earth. For the latest test, the three receiving stations were located in the cities of Delingha and Ürümqi—both on the Tibetan Plateau—as well as in the city of Lijiang in China's far southwest. At 1,203 kilometers, the geographical distance between Delingha and Lijiang is the record-setting stretch over which the entangled photon pairs were transmitted.

4. Einstein's mistaken notion of 'Spooky Action at a Distance'

Einstein (along with two other scientists, Podolsky and Rosen, called together as EPR) famously derided this entanglement between particles at large distances as "spooky action at a distance". According to EPR (called the EPR paradox, that this was one of the most bizarre elements of quantum theory—the way that measuring one member of an entangled pair of particles seems to instantaneously change the state of its counterpart, even if that counterpart particle is on the other side of the galaxy. This was abhorrent to Einstein and his colleagues, because it suggests that information might be transmitted between the particles faster than light, breaking the universal speed limit set by his theory of special relativity. Instead, he and others posited, perhaps the entangled particles somehow shared "hidden variables" that are inaccessible to experiment but would determine the particles' subsequent behavior when measured. In 1964 the physicist John Bell devised a way to test Einstein's idea, calculating a limit that physicists could statistically measure for how much hidden variables could possibly correlate with the behavior of entangled particles. If experiments showed this limit to be exceeded, then Einstein's idea of hidden variables would be incorrect.

Ever since the 1970s "Bell tests" by physicists across ever-larger swaths of space-time have shown that Einstein was indeed mistaken, and that entangled particles do in fact surpass Bell's strict limits. The most definitive test arguably occurred in the Netherlands in 2015, when a team at Delft University of Technology closed several potential "loopholes" that had plagued past experiments and offered slim-but-significant opportunities for the influence of hidden variables to slip through. That test, though, involved separating entangled particles by scarcely more than a kilometer. With Micius's transmission of entangled photons between widely separated ground stations, Chinese team performed a Bell test at distances a thousand times greater. Just as before, their results confirm that Einstein was wrong. The quantum realm remains a spooky place—although no one yet understands why.

Jennewein and his collaborators are pursuing a space-based approach from the ground up, partnering with the Canadian Space Agency to plan a smaller, simpler satellite that could launch as soon as five years from now to act as a "universal receiver" and redistribute entangled photons beamed up from ground stations. At the National University of Singapore, an international collaboration led by the physicist Alexander Ling has already launched cheap shoe box–size CubeSats to create, study and perhaps even transmit photon pairs that are "correlated"—a situation just shy of full entanglement. And in the U.S., Kwiat at the University of Illinois is using NASA funding to develop a device that could someday test quantum communications using "hyper-entanglement" (the simultaneous entanglement of photon pairs in multiple ways) onboard the International Space Station.

5. Quantum Entanglement

A multi-particle system is described as being in an ***entangled state*** if its wave function cannot be factorized into a product of the wave functions of the individual particles. **Quantum entanglement** represents the set of collective correlations between the quantum observables of different subsystems that offers full information on the ensemble system state, but no information on the states of the subsystems regardless of the distance between them [6]. In a maximally entangled state, all information is encoded in joint properties of the individual systems while the individuals themselves carry no information whatsoever. The first measurement on any subsystem will collapse all subsystems into their entanglement-induced states, and the ensemble state will behave classically from that point onward.

Quantum mechanics allows "entangled states" of two distant systems. Measuring the properties of one system can instantly change the properties of the other system. Einstein did not believe this was true. He referred to it as "spooky action at a distance". He advocated hidden-variable theories that would eliminate the randomness of quantum mechanics. Experiments have ruled out hidden-variable theories.

6. Illustration of 'Quantum Entanglement' by a Thought Experiment

Let us imagine that we are able to fabricate a really, really small currency coin of a size comparable to that of an atom [7]. Then this coin would be subject to the laws of quantum physics, and the Copenhagen interpretation applies (wave-particle duality). Let us imagine that we flip this quantum coin — what happens?

After the flip, but before looking at it, the quantum coin is in a wave state, that is, simultaneously 50% heads and 50% tails. When we look at the coin, that is, when we measure it, the coin "chooses" one of the outcomes for itself, and becomes either definitely heads or definitely tails.

The key difference between this quantum coin flip and an ordinary coin flip is in the first part of this description. When we flip an ordinary coin, we may not know the outcome — we covered the coin with our hand, for instance — but it is definitely either heads or tails under our hand. With the quantum coin, it is heads and tails until we look at it and "collapse" the wavefunction of the coin.

At this point, it will be helpful to introduce a little mathematical notation. First of all, let us represent the state of the coin, *after* being flipped but *before* being looked at, as follows.

$$| \text{Coin} > = a_{\text{heads}} \, | \text{heads} > + a_{\text{tails}} \, | \text{tails} > \qquad (1)$$

The symbol: '| ⟩' symbolizes the quantum state of an object; by |Coin⟩ we mean "the general quantum state of the Coin." a_{heads} represents the amplitude of that part of the wave which represents the coin landing on heads, and a_{tails} represents the amplitude of that part of the wave which represents the coin landing on tails. The objects |heads⟩ and |tails⟩ represent the coin being either heads up or tails up.

Our equation written above, then, states that "the quantum state of the coin (before measurement) is a combination of the Coin being in the state heads up and the state tails up."

If it is a normal coin, we expect that the probabilities of heads or tails are equal, that is, ½ (or 50%) for each. (we use 1 = 100% and ½ = 50%.) Our quantum state of the quarter may then be written as:

$$| \text{Coin} > = 1/\sqrt{2} \ | \text{heads} > + 1/\sqrt{2} \ | \text{tails} > \qquad (2)$$

Whenever we describe the state of a particle as being some sum of distinct outcomes, we refer to it as a *superposition*.

Why is it that we have written 1/√2 , instead of ½ ? It is because of Max Born's rule for relating the quantum wave of the system to the probability of a particular measurement; it turns out that the relation between the probability p of a particular outcome and the amplitude a of that outcome in the wave is:

$$p = |a|^2. \qquad (3)$$

So what happens to the quantum state of the coin after measurement? We cannot predict with certainty what happens: the Copenhagen interpretation of quantum mechanics implies that the outcome is truly a random one. Let us suppose we find that the coin is heads up; this means that the quantum state of the coin has "collapsed" to the form

$$| \text{Coin} > = | \text{heads} > \qquad (4)$$

The part of the state that was |tails⟩ has disappeared, leaving us with a quantum coin that is definitely, 100% heads up. And we say that that the wave function has collapsed (because it has transformed from a 'probabilistic' state to a 'certain' state.

Now we are ready to introduce **entanglement**. Let us do so by sticking with our quantum coin example; however, we now consider the situation where we glue two coins together, tail to tail. This means that the heads of the two coins are facing outwards. In what is a subtly important point, we scratch a number "1" on one of the outward faces of our double coin and a number "2" on the other, so that the two faces are *distinguishable*.

Let us think about the outcomes of a non-quantum version of this first. If we flip the coin and it lands with heads 1 up, that means that tails 2 is up; similarly, if heads 2 lands facing up, that means that tails 1 is up. These are the only two possibilities from the flip of this double coin: the two coins, by nature of their gluing, always land with opposite faces up.

Similar to our earlier argument, the flip of this non-quantum double coin lands with "heads 1, tails 2" or "tails 1, heads 2". If we were to make a quantum version of this coin, then, before it is measured, it is in the state "heads 1, tails 2" and "tails 1, heads 2". In terms of our quantum physics notation, we may write:

$$|\text{Double Coin} > = 1/\sqrt{2} \ | \text{heads} >_1 \ | \text{tails} >_2 + 1/\sqrt{2} \ | \text{tails} >_1 \ | \text{heads} >_2 \qquad (5)$$

This is our first example of quantum entanglement. It should be noted that it is not possible to talk about the quantum state of coin-1 without taking into account the behavior of coin-2, because the behaviours of the two coins have a definite relationship with each other: their fates are "***entangled***".

Our idea of a "quantum coin" and "quantum double coin" may seem quite artificial, but it turns out that electrons and other elementary particles such as protons, neutrons and photons possess a property somewhat analogous to it, known as spin. The spin of each of electron, proton and neutron is ħ /2 (called spin-half particles), and that of photon , graviton and gluon is ħ (called the integral-spin particle), 2 ħ, and ħ, respectively. Further, the spin of a spin-1/2 particle, like an electron, will always be measured as either +1/2 or -1/2. That is, the spin of the particle is 1/2 but it can be measured as spinning in a clockwise sense or a counterclockwise sense, which we refer to as "spin-up" or "spin-down."

One may see where we are going with this now: a spin-1/2 particle acts very much like a quantum coin! The mathematical formula for such a state can be written as:

$$| \text{Spin-1/2} > = a_{up} \, | \text{up} > + a_{down} \, | \text{down} > \tag{6}$$

This can be read as "the general quantum state of a spin-1/2 particle is a superposition of a spin-up state and a spin-down state."

7. Application of Quantum-Coin Example to Entanglement between Photons

Let us now apply this explanation to the phenomenon of 'quantum entanglement between photons', which are the particles relevant to the quantum lidar, mentioned earlier. Photons, are spin-1 particles, which can be described by a superposition of two states: horizontal and vertical polarization.

$$| \text{Spin-1}> = a_v \, | V > + a_H \, | H > \tag{7}$$

Here "V" and "H" stand for vertical and horizontal polarizations, respectively.

Similar to the 'double-coin sytem described above, we can entangle a pair of photons in such a way that if one is found to be horizontal, then the other is definitely vertical, with a quantum state that appears as follows:

$$| \text{Two photons}> = 1/\sqrt{2} \; | H >_1 \; | V >_2 \; + \; 1/\sqrt{2} \; | V >_1 \; | H>_2 \tag{8}$$

One thing is worth mentioning about beams of light under ordinary circumstances: they don't interact with one another. If we send two beams of light on a collision course, they pass right through each other without effect. On a quantum level, we can say that the photons don't interact with each other. This is only true, however, in vacuum. When light propagates in matter, the matter can "mediate" an interaction between two or more photons, causing photons to combine, split apart, or do even more unusual things. In order for these interactions to happen, however, photons have to be relatively densely packed or, equivalently, the beam of light itself has to be very intense. Such high-intensity beams only became possible with the invention of the laser and the field of *nonlinear optics.*

In the scheme of quantum lidar, describe earlier in this paper, the visible photons are converted to the microwave photons through the p*arametric* processes, which means that the net energy and momentum of the input and output photons are the same; no momentum or energy gets transferred to the nonlinear medium. Thereafter the phenomenon of quantum entanglement between the 'idler photon' and the received photon can be applied to determine the requisite information about the target.

8. Maximum Range of the Quantum Lidar

Chinese researchers, in the quantum lidar design, assumed nearly 100% quantum efficiency for the optical part of their quantum receiver [8]. This is not far from the current experimental conditions: photon collection efficiencies from optical cavities can be very high (over 74%), loss at the beam splitter can be extremely low, and photodetection can be extremely efficient at optical wavelengths. Thus the main source of loss may come from the optical storage of the idler mode, to be preserved during the signal roundtrip time. This is not an issue for short-range applications but, for long-range tasks, the idler loss must remain below 3 dB, otherwise the advantage of the phase-conjugating quantum receiver is lost. While using a good quantum memory (e.g., a rare-earth doped-crystal) would solve the problem, the practical solution of storing the idler into an optical-fiber delay line would restrict the maximum range of the quantum radar to about 11.25 km in free-space (assuming a fiber loss of 0.2 dB/km and fiber propagation speed equal to 2c/3, where c is vacuum light-speed).

9. Conclusion

Quantum entanglement phenomenon has a large number of applications leading to systems with extraordinary capabilities. One such system is the quantum lidar. It has been discussed in this paper as to how the technology based on the quantum entanglement leads to the quantum lidar which can defeat the design of the adversary claiming to having stealth aircraft, missiles, ships etc. In addition to quantum lidar, with is limited range, we have also discussed how the phenomenon of entanglement among photons, separated by over 1200 km from each other, could help in secure and unhackable communication between the ground station and the satellite.

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