Physics for the 21^{st} Century

Unit 7: Manipulating Light

Paul Kwiat and Lene Hau

The computer is able to calculate billions upon billions of bits of information. A simply elegant reduction to ones and zeros enables humans to encode and move information, to simulate and examine the world around them in amazing detail.

But now physicists world-wide are changing the landscape of computation and transmission of information by exploiting the probabilistic nature of quantum mechanics.

> PAUL KWIAT: *Quantum information is a field that came up roughly 20 years ago and the idea is to use really weird, bizarre features of quantum mechanics to do things in information processing that would be difficult or impossible otherwise.*

In Paul Kwiat's quantum optics lab, his team is manipulating pairs of entangled photons to investigate the foundations of quantum computing logic, trying to create a reliable source of quantum bits from laser light.

And at Harvard University, physicist Lene Hau takes advantage of the rules of quantum mechanics to stop light, the fastest moving thing in the universe. The light she traps can be used to store, compute and send information in unique ways that were thought to be impossible.

> LENE HAU: *There are non-intuitive phenomena in quantum mechanics that are just like weird. It's like, does nature really behave like this?*

Both scientists are manipulating light experimentally working on the very foundations of quantum information. If they can harness the uncertainty of the quantum world it could lead to a new generation of light-based quantum computing that will change the way humans think about and flow information around the globe.

Part I: Photon Entanglement

Paul Kwiat

At the University of Illinois, Paul Kwiat's research is focused on the strange quantum behavior of particles of light: photons. He uses properties of these photons to encode information and to create quantum-bits, or qubits,

the basic building block of quantum computation.

> PAUL KWIAT: *So in my research we study light in particular single particles of light that we call photons. They have properties, just like this car has properties. So light is the fastest particle in the universe. Photons have a direction just like a car can have a direction when it is moving, color, just like the car has a color. And there's another property, a third property that we really care about in my research, which is the polarization of light. It's a little bit harder to see with our naked eye, but we can look at that using a pair of polarizing sunglasses. So if I take a pair of polarizing sunglasses and I look up at the sky, these are going to block out all of the horizontally polarized photons. They will only let through vertically polarized photons. Any photons that get through are then vertically polarized if I use a second pair of sunglasses I can use those to block out those photons as well and I can block out all the rest of the photons that are getting through. I can use the polarization of the light to encode information on the photon just like I can use the color of the light to encode information, or I can use the direction. And the fun thing is, in my lab we use all of these properties to encode information on single particles of light, single photons.*

Kwiat's experimental group is trying to create and control single particles of light so they can use the particle's properties of energy, direction, and polarization as information holders. If they can produce a reliable, repeatable source of information-holding photons, they will take a huge step towards quantum computation.

> PK: *So, light is all around us -- every day when we're outside -- we're being hit by millions and billions and billions of photons. What we do is in a very controlled setting -- produce very, very special pairs of photons. And I'm interested in just how those one or two photons behave. And they can behave in really strange ways that are almost inconceivable using classical physics.*

The photons created by Kwiat's team in the lab are entangled pairs. Each photon in the pair contains information that is totally random yet perfectly correlated with that of its partner. The fact that the information exists in a random state is referred to as a superposition state. This is what allows them to be used as qubits.

> PK: *Quantum information can be understood by comparing it to classical information -- classical information is based on bits. Bits stands for binary digits, so things that can be zero or one. In any computer there's lots of these bits and anyone of them is a zero or*

a one. In the quantum case we have the extra possibility that we can have superpositions of zero and one at the same time. So the bit acts like it's not really zero and it's not really one. It's somehow both of those at the same time. And that enables you to have a great parallelism in order to solve certain problems.

Each photon produced in Kwiat's experiment is in a superposition state, and thus could be used as a qubit. But that's not the end of the story. These photons are also created as correlated quantum mechanically entangled pairs.

PK: *Imagine, for example, that we each had a coin, and we each are flipping our coin -- if they're classical coins, I'm likely to get heads or tails -- you're likely to get heads or tails. There's no connection between the two of them. On the other hand, if these were quantum mechanically entangled coins, then it could be the case that when I flip my coin, I'm equally like to get heads or tails. You're equally likely to get heads or tails. But whenever I get heads, you always get heads; whenever I get tails, you always get tails. And that's a correlation -- that's a connection that exists no matter how far apart those coins are -- and in that sense, it's a non-local connection. And it's that connection that enables us to do really interesting things. When you have a quantum computer that's working, all of the internal states are these extremely complicated entangled states of all the different particles interacting.*

A quantum computer could take advantage of superposition to hold and compute many variables simultaneously, and use entanglement to coerce multiple qubits into working together. In the end, a quantum computer will solve complicated mathematical problems exponentially faster than its classical counterpart.

PK: *Your typical computer has millions of registers, a classical computer, but if I have just 300 quantum registers. 300 quantum bits means that you simultaneously encode 2 to the 300 and that's more than the number of particles in the universe. So if you take every electron and you label it, here's number one here's number two here's number three, you run out of electrons in the whole universe before you get to the number of numbers that you encode in those 300 quantum bits, which is amazing. That's what you can't get classically. That's the quantum parallelism that you gain by using superposition and by using entanglement.*

For a calculation involving a trillion variables, a classical computer must take trillions of steps while a quantum computer could require only a few

hundred. Computer models of weather systems or complex chemical reactions require solving millions of equations with millions of variables. Quantum computers could revolutionize our ability to predict devastating hurricanes and potentially deadly drug interactions.

The key idea to unlock this extreme quantum computational power is to understand and take advantage of the entangled superposition state like those of the paired photons that Kwiat's team is creating.

Over a period of months Kwiat's group painstakingly aligns a maze of laser light and optics to gain control over these exquisitely sensitive quantum systems. They start with a blue laser beam.

> RADHIKA RANGARAJAN: *So in order to generate entanglement we have about ten million billion photons in the blue that are incident on this crystal and out of the ten million billion photons we have only about ten million pairs that are generated, that are entangled, that are coming out. And in the crystal where the main experiment happens, you have a blue photon that comes in and splits into two red photons. Blue light is actually higher in energy than red. So you have blue light that comes out, one blue photon produces 2 red photons. And the sum of these two red photons equals one blue photon.*

When the down-conversion crystal splits the high-energy blue parent photon into two lower energy daughter photons, these photons become entangled in energy. The two daughter photons can have the same energy or one can be stronger than the other, or any other combination. But because they are entangled the combined energy of the 2 daughter photons always exactly equals the energy of the parent photon.

These photons are also in a superposition state. Although the total energy of the two daughters must add up to the energy of the parent, the energies of each photon is undefined. They do not have individual values. Instead, they are simultaneously every possible combination that makes up the energy of the parent photon.

> PAUL KWIAT: *The weird thing about entangled states is that neither of the things has a definite value. It's not like you were a parent that had two children and you were bequeathing them in your will and you're saying this person is getting 60% and this person is getting 40%. It's not like the lawyer is sitting there with the will in the envelope and you know that there's a definite amount written on that piece of paper and it's just that you don't know what it is. The piece of paper is in some ways is really blank or it's blurry. It doesn't have a definite amount until the envelope is*

opened and then you see the result. And that's where quantum mechanics is weird because in classical physics you can talk about things having definite values without measuring them. Whereas in quantum mechanics, because we have the superposition, it doesn't have a definite value of either of those two states.

The entangled superposition state photons can be used as qubits that aren't limited to a single input value like the bits in classic computers. But Kwiat's work goes one step further. Kwiat can create photons that can encode up to three qubits each.

In the lab, they entangle multiple properties of the photons, creating hyper-entangled superposition states. They not only entangle the photons' energies, but also their directions and polarizations. By accessing multiple properties of a single photon, they turn it from one qubit into three.

A single down-conversion crystal automatically births photons that are entangled in energy and direction. To entangle polarization as well, Kwiat's team adds a second down-conversion crystal to the experiment. They orient the first crystal to produce vertically polarized photons and the second to produce horizontally polarized photons.

RADHIKA RANGARAJAN: *The magic happens when you put both these crystals together and they are thin enough that you don't know which photons were born in which crystal. When the photons come out of this crystal here, you have no idea which way each one is polarized.*

The two photons always have the same polarization, but they could be any polarization. The only condition is that they are both exactly the same.

PAUL KWIAT: *You could think of it as the polarization direction is like the angle of a clock and so each photon could be anywhere around that clock but as soon as you find this one is at 2 PM the other one is at 2 PM.*

RADHIKA RANGARAJAN: *It's not that we don't know what the polarization of a single photon is. It's just that the photons themselves don't know. They don't have. It doesn't make sense to even ask what is the polarization of a single photon.*

Here we use polarizers to actually measure the polarization. And all the measurement happens here, the generation happens here, and in between is the weird unknown.

Kwiat's team has had great success creating the hyper-entangled photons

in the lab. Determining their success, however, is a tricky business. When the photons are measured, the act of measuring collapses the superposition state and the photons are no longer qubits. The only way to test if their experiments are successful is to destroy what they have created. To do so, they pass the photons through a carefully designed train of optical elements ending in a photo detector.

> PAUL KWIAT: *And so we pass them through polarizers to say what is the polarization and we can pass them through other sorts of filters to ask what direction they are going in and then that measurement at the end we get a click at our detector and that collapses all of these different properties at once. And in some sense it's the detector that causes those properties to have definite values. The measurement is changing the system.*

Their results have shown robust correlations between the daughter photons in energy, direction, and polarization.

The next step is to scale the experiments up to get multiple qubits interacting together in logic calculations. This is an engineering challenge as well as an intellectual challenge. Using superposition in computation is still a counter-intuitive concept, even to Kwiat himself.

> PK: *You know I've done this for a long time and that one simple experiment is still kind of incomprehensible in some ways, I mean, its not that I don't understand what's happening and I can predict what happens and I can predict patterns exactly. You know I won't ever get the wrong answer. But in terms of actually trying to put a model to, well what's actually happening. What are the photons actually doing in terms of really getting a deep intuitive understanding of quantum mechanics and what it means for something to be in a superposition. You can't really get there. Because we think with classical concepts and this is not a classical thing. It's beyond that.*

Kwiat and his team will continue to push their understanding of superposition states of photons. They are one of many groups worldwide that are using the counter-intuitive power of the quantum world to go beyond the everyday world.

Part II: Ultra-Cold Superposition

Lene Hau

At Harvard University, Lene Vestergaard Hau, who is known internationally as "the woman who stopped light," changed the physics world forever when she decided to use a Bose-Einstein Condensate, the coldest material on earth, to try to slow down the fastest moving particles in the universe,

photons.

> LENE HAU: *Well the idea was we had gotten our hands on this really cold atom clouds called Bose-Einstein condensates and we wanted to probe them with light, really poke at them see how they behaved. And then people thought we were crazy because if you send laser beams into a condensate, these really cold atoms, everything should just blow apart.*

Conventional physicists believed that shooting resonant laser light into a super-cold medium was at best a fool's errand. But Hau was undeterred. She believed she could create a system that would slow down the fastest moving particles in the universe.

> LH: *Nothing goes faster than light. Light is like in free space moves at 186,000 miles a second. And if we could somehow use this system to tame light to get it down to you know bicycle speed, I thought, "Gee that's fascinating." So that's what we went after.*

Hau quickly moved her theory of slowed light into an experiment and pushed tirelessly for a year in the lab. And after many failed attempts, she stunned her peers by successfully slowing light down by a factor of 20 million, to only 38 miles an hour.

> LH: *So it took a full year, non-stop work where you're just thinking about this. You know just working on it all the time non-stop. And we eventually managed to get light speed down a little bit and then eventually we got it down to bicycle speed and that was really really fantastic. So the people who thought we were crazy initially, they sort of had to revise their view and thought we might not be so crazy after all.*

Light is known to travel through the universe at a constant speed. But light can be slowed down, and is everyday, in as simple a material as glass. As light moves through glass, some reflects off the glass, and some interacts with the atoms that make up the glass. This slows down the speed of the light a little. This slowing down is the glass' refractive index.

> LH: *If you send light through a window, that will tend to slow light down just a little bit, just by like 30% or so. In our lab we are slowing it down by factors of 10 to hundred million. You know we're not talking about 30% in a window. It's a factor of 10 to a hundred million. So from 200,000 miles a second we go down to like 15 miles an hour.*

To slow light down in this dramatic fashion, it may seem logical to simply

create a material with a much higher refractive index than glass, causing the light to move slower and slower.

> LH: *Oh no no no, that's not a good idea because if you start cranking this refractive index up more and more to stop light down in the medium, what will happen is you will reflect all the light off the medium before it even enters. So in that way you would just create the world's best mirror. That's a classical effect, an effect we can get out of classical physics. But what we are using, we are really playing with quantum mechanics, to get this enormous light slow down.*

Professor Hau's research centers on slowing light completely without losing any of the information in the light pulse due to reflection. To do so, she creates a Bose-Einstein Condensate, or BEC, a super-cold state of matter that is unlike any other on the Earth. The BEC she creates is a cloud of trapped sodium atoms that have been carefully manipulated with laser light and magnetic traps so that they are all in the same quantum state. The atoms in the BEC act as a coherent, single quantum system. The BEC will interact with light in ways standard materials like glass never could.

> JON WELCH: *When we come down in the chamber, if we want to make a BEC, it has to be really really cold, a billionth of a degree above absolute zero. We do that by slowing the atoms and eventually get to a point where the energy, and actually hence the temperature of this system, is so cold that these atoms will then undergo the phase transition into Bose-Einstein Condensation. The atoms become indistinguishable from each other. So atoms in one part of the condensate are kind of in a harmony if you will with the rest of the atoms. You know they all behave as a single quantum system and that's really where our experiments begin.*

Electrons in any material occupy quantized energy levels and can move between these discrete energy levels by absorbing and emitting photons. In the BEC, all of the outermost electrons of the atoms are in the lowest energy level: the ground state. Typically if resonant light, light of the correct frequency to interact with the ground state, were introduced into the BEC, it would excite the electrons, promoting them into a higher energy level. Very strong interactions between the light and atoms would take place and the BEC would simply be destroyed. But Hau's team introduces a 'coupling' laser that, in a sense, blurs the energy levels and prepares the condensate to store light.

> LENE HAU: *We started realizing, "Gee what if you have not one, but if you have 2 precisely tuned laser beams sort of with the exact right properties coming in at the right angles and with the right wave*

lengths and all of that. If you have 2 of those, those 2 can kind of together do the right things to the atom such that you actually might be able to slow light down to bicycle speed."

The team carefully sends in the coupling laser. The coupling laser is tuned to the energy difference between states 2 and 3 so it doesn't interact at all with the electrons in the ground state. Nothing happens. Then a second laser, called the probe laser, that contains the information they want to capture is sent into the condensate. The probe laser is tuned to the energy difference between energy level 1 and 3. In the absence of the coupling laser beam, the 'probe' laser pulse would be completely absorbed by the electrons in the ground state, destroying the condensate. All information would be lost. But instead, the coupling laser prevents this absorption. The two laser beams shift the electrons into a quantum superposition of states 1 and 2, meaning that each individual electron is in both states at once. The two laser beams, in a way, cancel each other out, like evenly matched competitors in a tug of war. This superposition state allows the light pulse to be imprinted in the atoms.

LH: *The internal state of the atoms in the condensate is changed. So the atoms are brought into superposition states where the atoms are at the same time a little bit in one state and at the same time a little bit in the other state. So the light pulse is really effectively transferring its photons into atomic amplitude or atoms in a particular superposition state.*

LH: *Basically we come in with a light pulse from the other side of the vacuum chamber. We send this light pulse into the condensate in the middle of the vacuum chamber. And now this light pulse will slow down from its initial extremely high speeds all the way down to 15 miles an hour in our most recent experiments. At the same time as this light pulse is slowing down, it's compressing enormously. So eventually even though the light pulse starts out being a mile long in free space it will compress to only 0.02 mm, which is less than half the thickness of a hair. So that little light pulse will actually snugly fit inside the condensate and at that point we can snap our fingers and stop the light pulse. The light pulse comes to a stop and turns itself off, but the information that was in the light pulse is not lost because that's imprinted by the light pulse as a little hologram in the atom cloud. And then when we feel like it we can turn the light pulse back on and send it back on its way. And we can measure that we stopped the light pulse in our atom cloud by just measuring the arrival time of that light pulse with our light detector over here.*

Measuring the results of this complicated experiment is surprisingly quite

simple. The probe laser light is sent through the vacuum with no BEC and measured by a photo detector. Then a second probe laser pulse is sent through the experiment, this time with a BEC in place, and its speed is measured. The speeds of the two pulses are compared and the difference is the amount the BEC has slowed light.

> ANNE GOODSELL: *It's amazing that light and atoms can handle the same kind of information. So information that's being carried by light gets transferred to the atoms, then the atoms give that information back in the form of light. But light is something that is completely different from atoms when you think about it.*
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> *Light has no mass and an atom you think of as being something that's made of material. It's something that has mass. It has weight. And the idea that you can have information that light carries and transfer that information in this way to atoms is something that you wouldn't expect when you first think about these two things for the very first time.*

Because the atoms that make up the condensate are storing the light as a matter imprint, it opens up the door for computation and quantum computation. Not only is all of the information in the light pulse slowed and converted, but it is stored in a quantum superposition state. The superposition state is what allows quantum processing to occur.

> LENE HAU: *So what we are trying to do is you could say we are trying to make a computer. What does a computer consist of? A computer consists of two main ingredients. It has a memory and it has a processor. So, we have to be able to store and hold onto the optical information without destroying any of the quantum information in the light pulses. We preserve them into its matter form and then process that matter form and then turn it back into light.*

Hau has demonstrated exquisite control over light and matter in several experiments, but her experiment with 2 condensates is one of the most compelling. First a light pulse is sent into the first condensate where, as expected, the light slows down. Then the coupling laser is turned off completely. The information is stored in the condensate and then strangely, a matter wave containing all of the light's information moves out of the first condensate into free space. It moves slowly to the second condensate. Then the control laser illuminates and the original light pulse is emitted from the second condensate. This magic trick of light allows Hau to manipulate, or in another word process, the matter wave before it enters the second condensate.

LH: *Once you have information in matter form you have extremely powerful processing methods. I mean we can start talking quantum networks and sending quantum states around the networks and use that to controllably process information, and use it for quantum computing. So this is a totally new system where we have some absolutely new paradigms that we can pursue and we are just at the beginning of that, I think, very exciting set of possibilities and this whole new area.*

NARR: If Hau can refine her two processes of slowing light and processing its matter copy then practical future technologies will be close behind, but what exact technologies emerge is the next unknown.

LH: *I see our experiments in a broader light than quantum computing. Quantum computing is certainly one very very possible application, but I do like to see it in a broader light. That we have some new abilities here that are just unique and what comes of that in the future. That's what I think is exciting that you can't quite predict it. I don't like things to be too predictable. But allowing researchers to play around, giving them the resources, giving them the freedom to push into new territories is super important because it's from new territory that we will eventually get new applications that we can't even imagine today.*