Letting Schrödinger's Cat out of Pandora's Box - Exploiting Quantum Mechanics for Defense

Good morning.
As Albert Einstein once said, "We can't solve problems by using the same kind of thinking we used when we created them."
The Defense Sciences Office has a long history of turning extraordinary science into imaginative technology, and I hope to motivate you to help us continue that tradition.
I also hope to convince you that we are indeed taking a different approach to develop an entirely new set of materials and concepts - we are exploiting quantum mechanics to induce dramatically new behavior in materials to solve DoD problems

You have heard John Main describe some unique opportunities for new materials and structures.
Though imaginative, the macroscopic behavior of those materials is quite predictable.
But what if we consider their behavior at a microscopic scale, where quantum effects become important?
At that scale, we enter a world where behavior becomes counter-intuitive; in fact, so much so that it disturbed even Einstein himself.

That is the world I want to discuss today - a world where particles are waves, light acts like a particle, and optics seem to work backwards.
This is precisely the kind of world that DSO loves to exploit, and I want to talk today about how we will control and exploit the strangeness of quantum mechanics.
To quote Richard Feynman, another great scientist, "when we look at any question deeply enough...we turn over each new stone to find unimagined strangeness leading on to more wonderful questions and mysteries."
Come and join me as we turn over a few stones.

I'd like to start with some work that is already underway, the Quantum Information Science and Technology program, or QUIST.
This effort is exploiting quantum mechanics both for communications and computation.
By DSO standards, this work is fairly mature, but it still offers an excellent introduction into the counter-intuitive nature I am describing, and shows how we can exploit this behavior to produce dramatic new opportunities - in this case, the opportunity to provide new methods for secure communication.

One of the keys to understanding the quantum world is to realize that there is a fundamental limit that prevents us from precisely measuring the state of quantum particles, known as Heisenberg's Uncertainty Principle.
We cannot eliminate this measurement uncertainty; yet we can use it to our advantage in interesting ways.

One way to do this is by utilizing one of the building blocks of quantum computers: the entanglement of two or more quantum particles.
Entanglement has a specific meaning in quantum mechanics, referring to the creation of a specific collective relationship between particles.

To help you think about this, imagine a pair of dice such that the sum of the two die rolls would always equal seven - those two dice are entangled.

There is (as always) a subtlety that makes this effect especially intriguing: the entanglement of particles is preserved as the dice are separated from each other.

Why is this intriguing? Well, we could use entangled particles (such as the dice) to securely distribute information as in the cartoon playing on the screen - I can use one die's roll to encrypt a message and effectively teleport the measurement result to the other die to allow someone at the destination to immediately decrypt the message.
Researchers have already successfully demonstrated the teleportation of information in a laboratory setting.

As an added benefit, using this scheme, you can detect if someone has intercepted your message and attempted to decrypt it, as the entanglement of the dice is destroyed with any attempt at measurement!

So quantum information research is trying to take advantage of the unusual phenomena of physics to develop new capabilities - working where physical intuition fails you and trying to bring theory closer to concrete, everyday reality.
How this teleportation process works is still an open question of physics, but we can still use the results for practical purposes, like instantaneous information exchange and ultra-secure encryption.

Now let's look at a future area of interest that also exploits non-intuitive physics - we want to dramatically alter the interactions between light and matter by re-examining optics principles that have their origins in the 1700's.
Using 21st century engineering, we are combining the material properties of two systems to change their interaction in ways never imagined.
We think these Negative Index Materials will produce dramatically different optical devices such as telescopes.

Let me back up a little and explain what I mean.
For the most part, interactions between light and bulk matter are governed by Snell's Law, which tells us how light bends as it passes through materials with different indices of refraction.
This is how we are able to make lenses for cameras, glasses, and radar.
It even explains why a road seems to shimmer on a hot sunny day.

However, Snell's Law relies on several assumptions about the physical characteristics of the bulk materials involved, namely that they have a positive index of refraction.
With that in mind, we have been working on ways to turn that familiar interaction around such that it behaves counter-intuitively, by producing materials with a negative index of refraction.

We have developed such materials that work at radio frequencies by creating a lightweight composite made by carefully matching two microscopic structures, and the results have been intriguing.
First, as you can see, the light bends opposite the direction it would in normal materials!

Because of that, we can make RF structures that seem to work backwards!
We should be able to make lenses and antennas with different shapes, and lighter weight, than any that have been made before.
This work is well underway, and the results have been tremendous.

Now your challenge is to extend this principle to infrared and visible wavelengths.
Since light travels through negative index materials differently, you could create lenses that can resolve objects smaller than with conventional optics. Meaning, for example, you could produce higher resolution microscopes.
And more importantly, negative index lenses should have virtually no reflection from their surfaces, implying that they would avoid many of the heating problems encountered in optics for intense lasers - and these properties are just the tip of the iceberg!

Now let's look at two further examples of ideas that probe this juncture between quantum mechanics and practical engineering.

One of the underlying tenets of quantum mechanics is that things are neither particles nor waves, but have characteristics of each that are manifested under certain conditions.
There are two ways we can exploit this wave-particle duality, and I will give you an example of each to finish my talk today:

We can treat particles like waves,

Or

We can treat waves like particles.

As a first example let me describe some ways we are developing technologies that force atoms to act more like light waves.
In the Precision Inertial Navigation Systems program, we are measuring how individual atoms interfere with themselves - an effect normally thought of as occurring with waves, not particles. We plan on using these atom interferometers to measure forces--a seemingly mundane task that turns out to have significant military utility.

It is not particularly obvious how to make atoms act like light and interfere with themselves, so let me explain a little bit about how this is accomplished.
First we use the momentum of laser light to slow down individual atoms, effectively cooling them to very low temperatures.
This procedure is analogous to slowing down an Abrams tank with a ping pong ball - it takes a lot of ping-pong balls, but every one slows the tank down a little bit!
Note that by using lasers to cool these atoms, we are exploiting a particle-like property of the light.

As you can see, we then send the atoms into a volume where we again use laser light to push on the atoms and split a portion of the wave to move in a different direction (like sending a light wave through a partially silvered mirror, so that part of the wave travels in one direction, the other part in a different one).
Further laser pulses act as mirrors and redirect the atomic waves back towards each other.
At the end of this process, we use an additional laser pulse to measure how the two waves have interfered with each other.

Now I know what many of you must be thinking by now, because this is long past the point where my wife has picked up a magazine and said "That's nice dear, but who really cares?"

We care because atom interferometers are proving to be incredibly precise measurement tools for sensing inertial forces - that is, accelerations and rotations.
When these sensors are put together into an inertial navigation system, we expect the drift in our measured position to be less than five meters per hour, over 200 times better than current aircraft inertial navigation systems!
Put another way, the limiting factor for improving the system beyond this point is NOT the sensitivity of the individual sensors, it is the precision with which we can measure and maintain alignment of the navigation system platform to minute changes in the gravitational field around the sensor.
And we already expect to measure this deviation precisely enough that we could register the change in the gravitational field produced by a HMMWV sitting 18 feet from the sensor!

Our challenge in DSO is to push this technology out of the laboratory and into the hands of operational forces.
This requires advances in low-power portable ultrahigh vacuum systems, miniaturized narrow-linewidth lasers, rugged laser-cooled atomic beams, and multi-function optoelectronics to precisely control the laser pulses.
We need your ideas to achieve each of these advances.

I've shown how we are treating particles like waves; now I want to talk about future area of interest-looking at new technologies that allow us to localize, control, and even store light pulses as if they were particles by slowing (or stopping) light.
How is this done, you ask?
Well, we create a situation where a pulse of light has a very specific relationship with a collection of atoms and light from another laser.

In fancy techno-speak, we produce incredibly large non-linear interactions between the light pulse and the atomic system, creating a situation where a narrow transmission window appears in the material.
In other words, the light passes through a medium that should be opaque.
This is called Electromagnetically Induced Transparency

When this happens in the right way, the light pulse can be slowed down - or even stored if we so desire - as it passes through the atoms, as you can see on the screen.

The light pulse has some unusual properties when we do this.
For instance, the physical length of the pulse is contracted by many orders of magnitude, so that pulses that are kilometers long in air are compressed to fractions of a millimeter.
One way to think about this process is that we have made a holographic imprint of the compressed light pulse into the quantum mechanical states of the material.
Since a hologram coherently stores both amplitude and phase information about the light pulse, we can actually think about controlling what happens to that light pulse in unique ways.

Why is this important? This could lead to entirely new approaches to processing optical signals.
As a simple example, look at a problem in routing optical signals in a communications network.
A router basically switches packets of information from one port to another.
The problem occurs when two packets try to vie for the same output port at the same time.

This results in one of the packets being lost, and the entire network pays the huge penalty of re-transferring the information later.
If one can slow light controllably, the router could delay one pulse sufficiently long so that both pulses would reach their destinations, resulting in dramatic improvements in network efficiency.
Currently this process is done by converting the optical signals to electrical pulses, a process that limits the speed at which this may be accomplished.
We expect that using a slow-light, all-optical technique will remove those speed limitations, and reduce power consumption at the same time.

There are many other promising applications, but to be honest, we don't know most of the possibilities that could result from this new capability.

Our challenge in DSO is to understand how to utilize slowed and stopped light pulses in a controllable way, meaning we can read, process, and write information into and out of these systems in devices compatible with current and future information technology.
This will require you to develop advanced technology for controlling the laser pulses, to search for newly engineered materials with the quantum mechanical structure needed for producing this effect, and to develop advanced mathematics for exploiting highly nonlinear interactions to perform information processing.
So we imagine single-photon optical switches, continuously tunable optical delay lines, and many other enabling device components - all that came about from work on how to stop light!

I will leave you today by asking questions that point to some other areas of potential future interest - the next set of stones to turn over.
We ask: Is it possible to create materials that switch back and forth between two stable structural configurations with dramatically different physical properties?
In other words, can we make materials that can switch from being a conductor to an insulator or from transparent to opaque?
We think there are answers in the quantum world waiting to be found.

We also wonder if it is possible apply pulse-shaping techniques to recent developments in stable laser oscillators, or optical frequency combs.
Each oscillator has over 1 million frequency channels and appears capable of carrying over 500 TerraBits/second of information (over 1000 times current systems).
Such a system could produce arbitrary optical waveforms with unprecedented sub-fs precision, and would have applications ranging from radar systems to telecommunications.
We hope to explore these and many other intriguing questions.

I have given you but a glimpse of the future of physics research in DSO.
If I leave you with one message today, it is this: We are exploiting quantum mechanics to induce dramatically new behavior in materials to solve DoD problems.

I hope I have motivated you to help us solve these mysteries, determine the next set of problems, and develop the radically new capabilities that will blur the interface between physics theory and real-life engineering.

Thank you for your time.

Now I would like to take the opportunity to introduce Dr. Carey Schwartz, who will talk about DSO's vision for the future of mathematics -- a future that underlies many, if not all, of the efforts you will hear discussed today.