UMBC

# QUANTUM ENTANGLEMENT
## -EINSTEIN'S "SPOOKY ACTION AT A DISTANCE"


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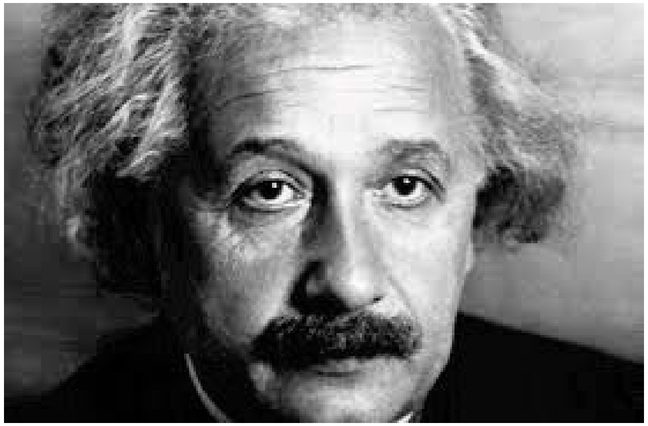
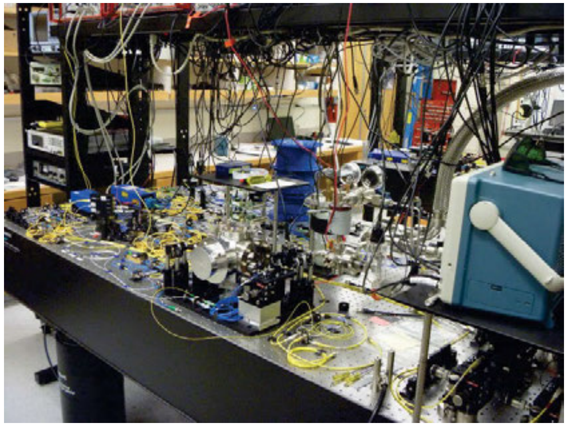
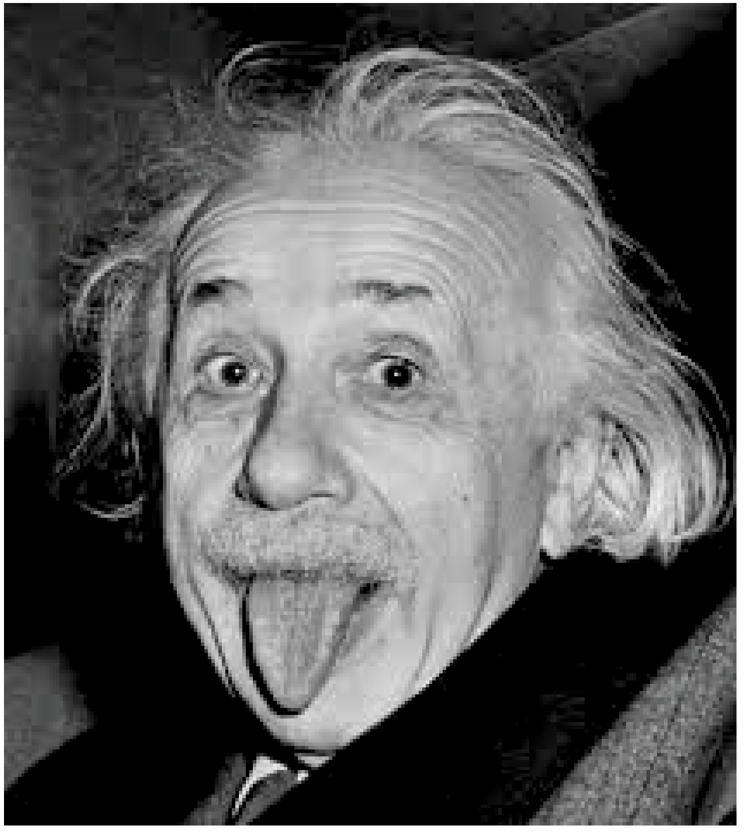


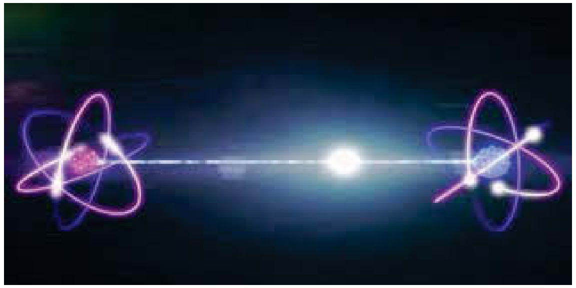




Einstein discussing quantum mechanics
with Neil Bohr

# "SPOOKY ACTION AT A DISTANCE"

- 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".
- Recent experiments have verified the properties of entanglement.
  - Entanglement is beginning to have practical applications as well.

# OUTLINE

Basic properties of quantum mechanics.

Entanglement or classical correlations?

Quantum interference between distant objects.

Einstein-Podolsky-Rosen paradox (1935).

“Hidden-variable theories”.

Bell’s inequality (1964).

Quantum mechanics differs from Einstein’s ideas.

Recent experiments.

Possible applications (quantum cryptography and computers.)

# BASIC PROPERTIES OF QUANTUM MECHANICS

# QUANTIZATION – DISCRETE VALUES

In classical physics, the energy in a beam of light can take on a continuous range of values.

For example, a 100 W light bulb.

In quantum mechanics, the energy in a beam of light is quantized:

$$E = nh\nu$$

n is an integer

$h$ = Planck's constant

$\nu$ = the frequency

Individual particles of light are known as photons.

This laser pointer emits approximately $10^{18}$ photons per second.

We can detect single photons with a high probability.

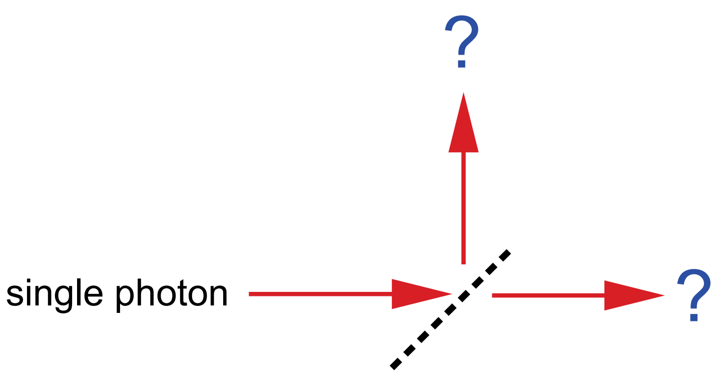
# RANDOMNESS

Quantum mechanics is inherently random.

We cannot predict the outcome of certain experiments, even in principle.

Einstein didn't believe this: "God does not play dice with the universe".

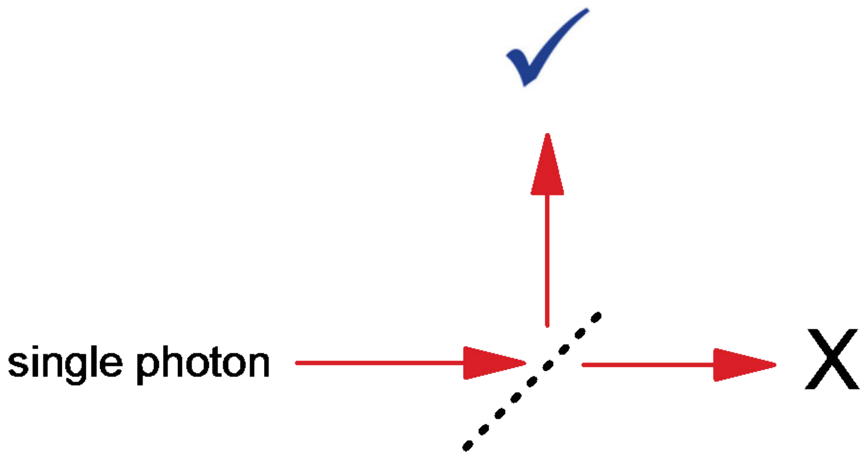
Simple example: A single photon incident on a beam splitter (half-silvered mirror):



# HIDDEN-VARIABLE THEORIES

Einstein felt that there must be a more complete theory that would predict the outcome of all experiments.

We just don't know what that theory is.




The photon is assumed to carry enough information with it to determine the outcome.

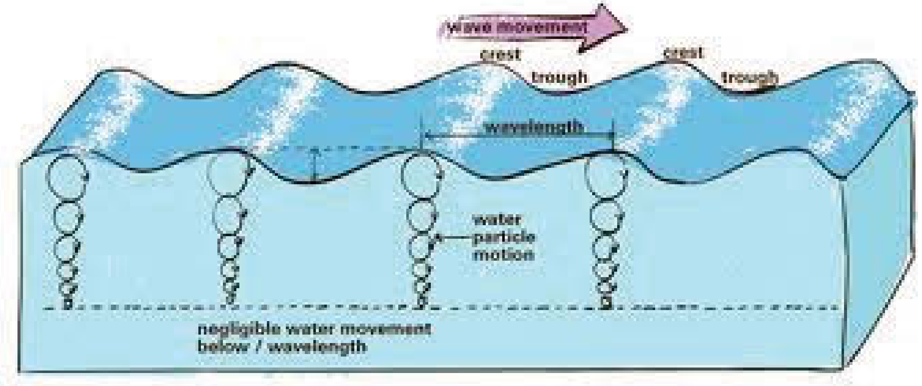
Theories of this kind are called hidden-variable theories.

We will consider them in more detail later.

# PARTICLES AND WAVES

In classical physics, waves are very different from particles:

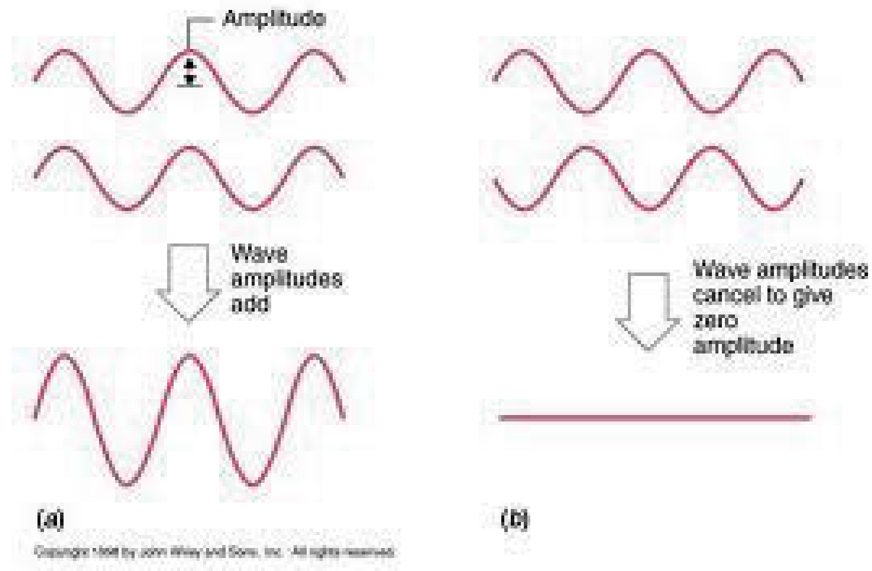
Wave patterns oscillate as they move along:



# INTERFERENCE OF WAVES

Two different waves can add to become stronger.

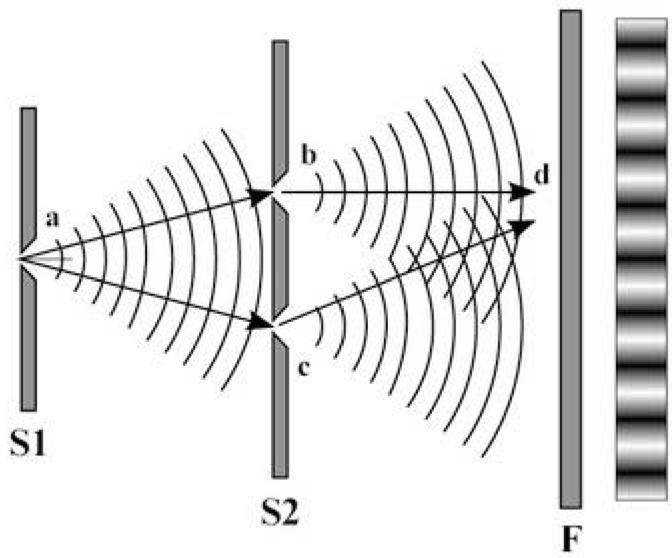
Or subtract to become weaker.

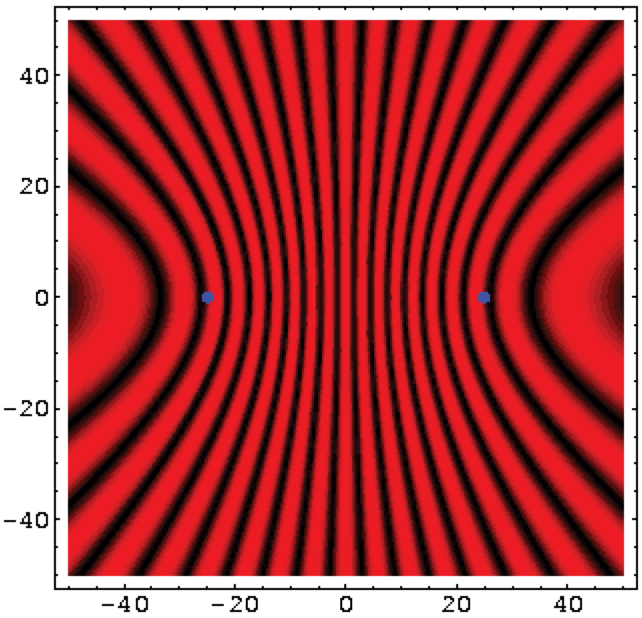



"in phase"    "out of phase"

# INTERFERENCE OF LIGHT

Because light is a wave, two light waves can interfere to produce a stronger or weaker wave:



# PARTICLES AND WAVES

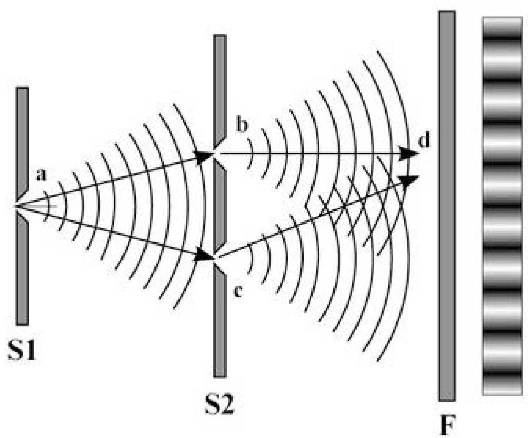
In quantum mechanics, particles are described by a wave function $\psi(x)$ .

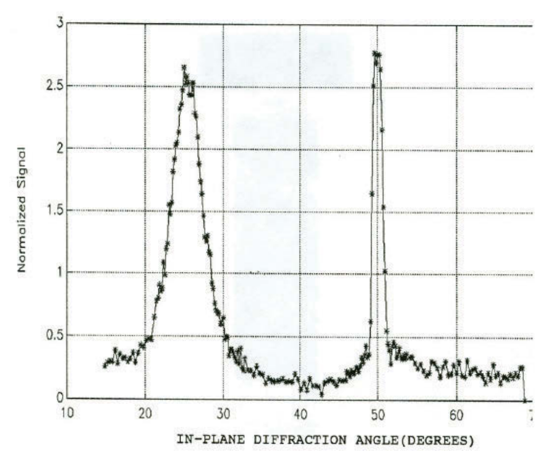
The probability of find the particle at position x is given by the square of the wave function:

$$P = |\psi(x)|^2$$

As a result, a beam of atoms can give all the same interference effects of a wave:

atoms



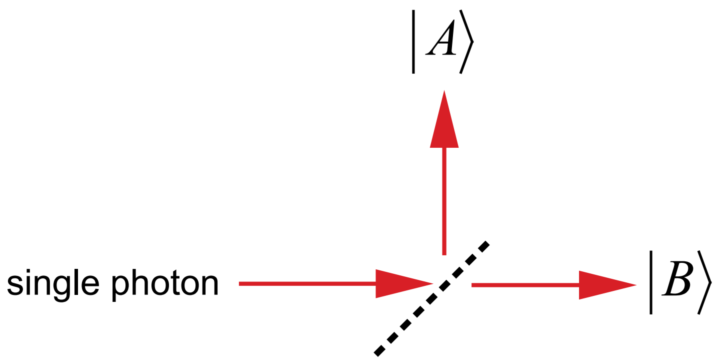




Helium diffraction pattern.

# SUPERPOSITION STATES

In quantum mechanics, we can have a "superposition" of two states that are incompatible with each other.

For example, consider a single photon after it has passed through a beam splitter:




$$|\psi\rangle = |A\rangle + |B\rangle$$

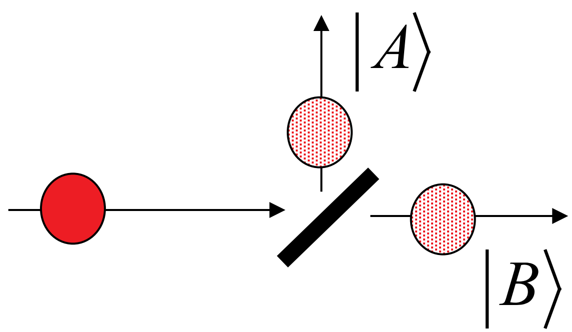
$|\psi\rangle$ is the "state" of the system

**The photon is assumed to be in both states <u>simultaneously</u>.**

# SINGLE-PHOTON INTERFERENCE

How do we know the photon is really in both states at the same time?

Put mirrors in each path to produce interference between the two states $|A\rangle$ and $|B\rangle$ :



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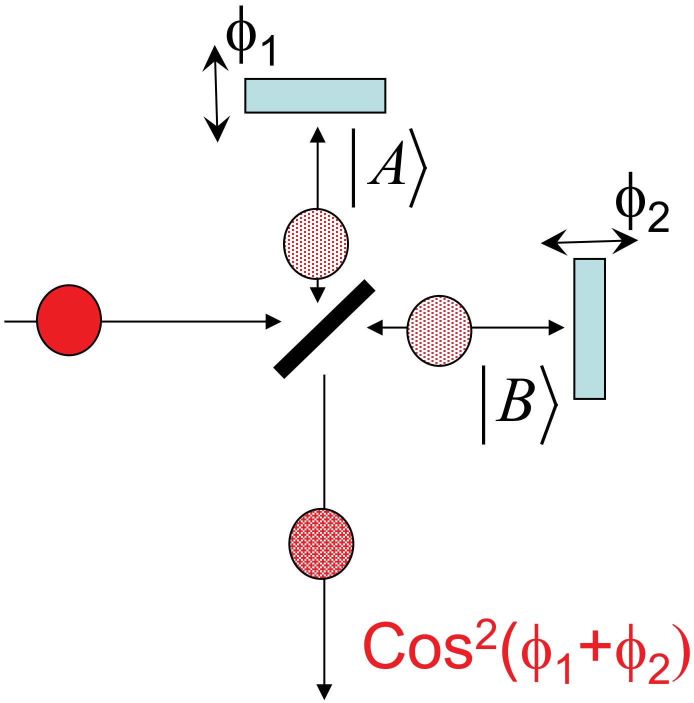
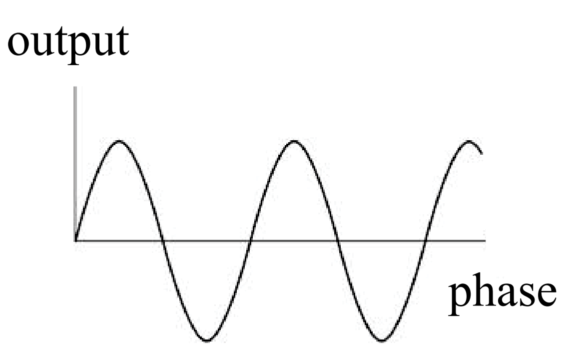


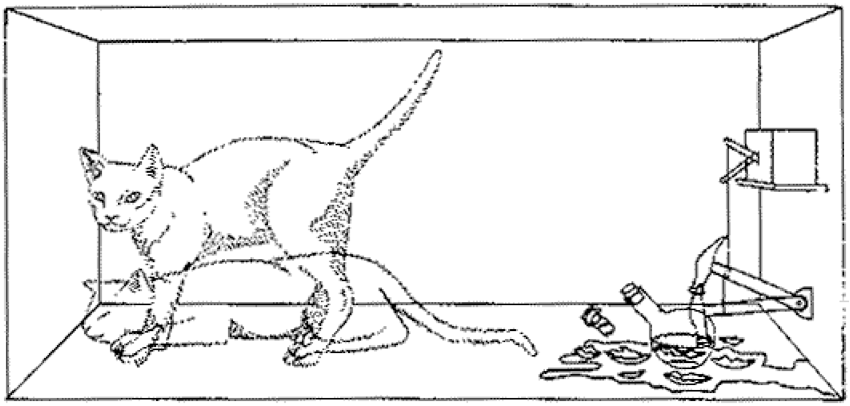
# SCHRODINGER CATS

Schrodinger considered a random quantum process such as the decay of a radioactive particle.

- At intermediate times, the quantum system is in a superposition of the original state and the final state.

A detection of the decay particle sets off a mechanism that kills a cat.

- Is the system left in a superposition of a live and dead cat?



$$\left|\psi\right\rangle = \left|alive\right\rangle + \left|dead\right\rangle ?$$

# SCHRODINGER CATS

This topic has received a great deal of interest:

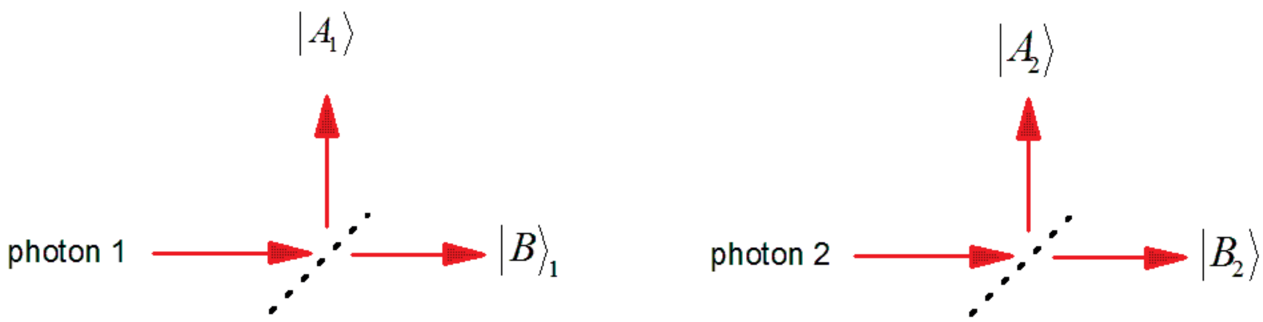

“Don’t let the cat out of the box”

# ENTANGLEMENT AND THE COLLAPSE OF THE WAVE FUNCTION

# ENTANGLEMENT

Schrodinger also considered a situation where two distant systems are in a correlated superposition state.

For example, consider two photons and two beam splitters:



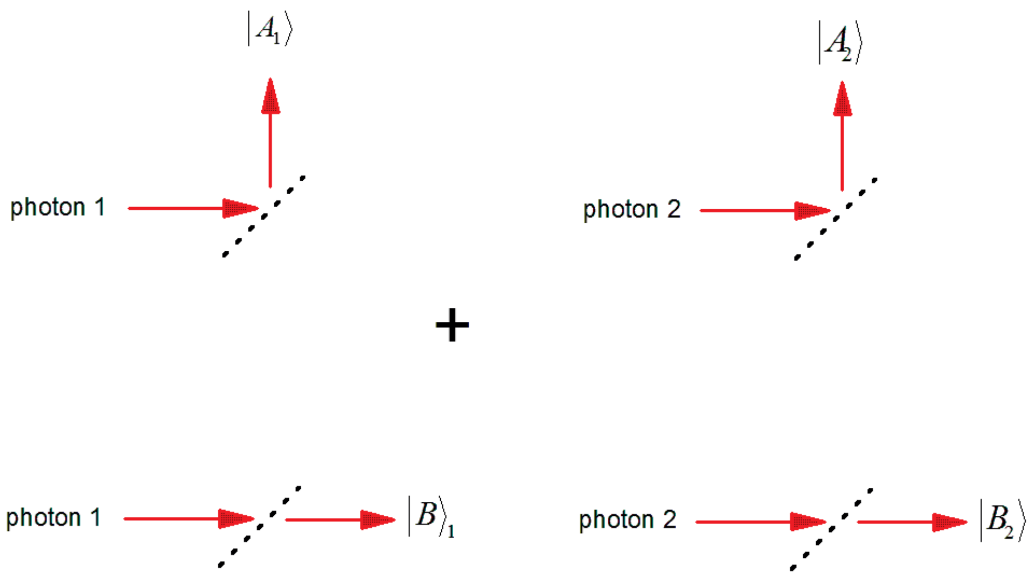

We can create an "entangled" state where

$$|\psi\rangle = |A_1\rangle|A_2\rangle + |B_1\rangle|B_2\rangle$$

The paths are totally correlated.

# ENTANGLED STATE OF TWO PHOTONS

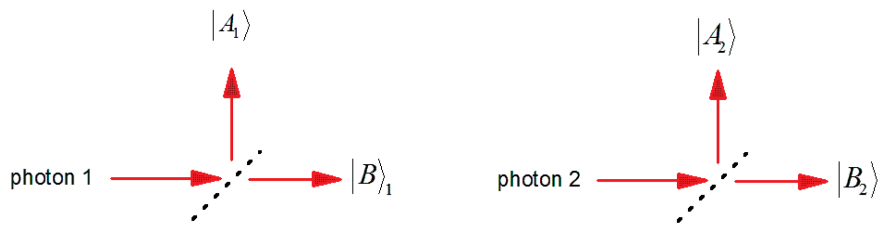
The entangled state $|\psi\rangle = |A_1\rangle|A_2\rangle + |B_1\rangle|B_2\rangle$ can be viewed as:




Both of these states exist <u>simultaneously</u>.

# COLLAPSE OF THE WAVE FUNCTION

Consider an entangled state where the paths of two photons are correlated:




$$|\psi\rangle = |A_1\rangle|A_2\rangle + |B_1\rangle|B_2\rangle$$

Suppose we use a single-photon detector to measure which path photon 1 is in.

And find that it is in path $A_1$ .

Then photon 2 must be in path $A_2$ and the state instantly "collapses" to

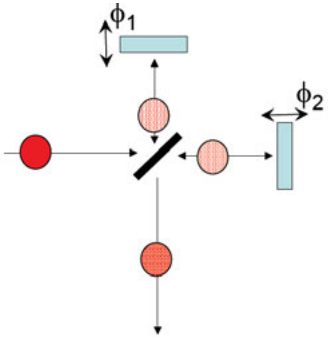
$$|\psi\rangle = |A_1\rangle|A_2\rangle$$

This has physical effects at location 2.

# NONLOCAL INTERFERENCE

How do we know that both states in an entangled state really exist at the same time?

Recall that, for a single photon and a beam splitter, quantum interference shows that both states must exist:




For two entangled photons, we can use "nonlocal interference" to show the same thing.

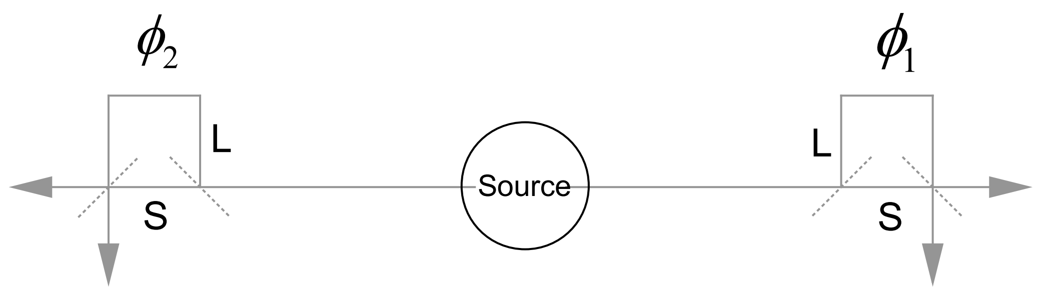
# NONLOCAL INTERFERENCE

We can generate an entangled state in which two photons were created at exactly the same time.

But we have a coherent superposition of what time that was.

$$|\psi\rangle = \int f(t)\hat{E}_1^{(-)}(r_s,t)\hat{E}_2^{(-)}(r_s,t)dt$$

Suppose the two photons travel in opposite directions to two single-photon interferometers:

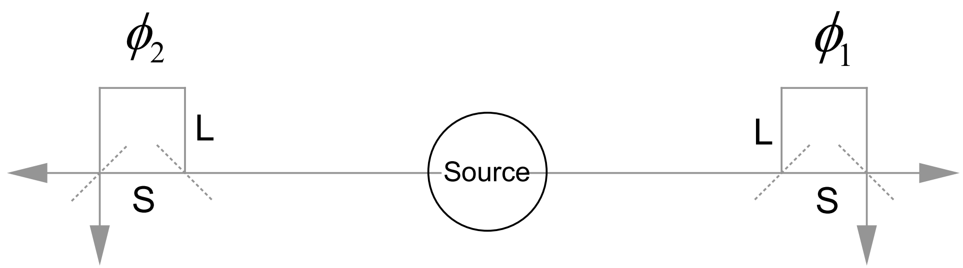



A "Franson interferometer"

The two photons will interfere with each other regardless of how far apart they are.

# "SPOOKY ACTION AT A DISTANCE"

The probability that a photon will take the upper path on the right is not determined by the phase setting in that interferometer.



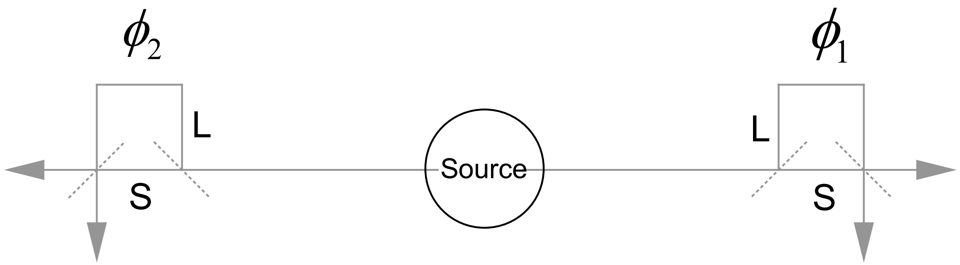

Instead, the path taken by the photon on the right depends on the phase settings in the distant interferometer as well.

Any <u>classical</u> interpretation would require that information be transmitted faster than the speed of light.

Roughly speaking, the photons must communicate with each other.

# NONLOCAL INTERFEROMETRY[1]

We know that the two photons are emitted at the same time.[1]:




If we only accept events in which the photons arrive at the same time, there are two possibilities.

They both took the long path ( $L_1L_2$ ) or the short paths ( $S_1S_2$ )

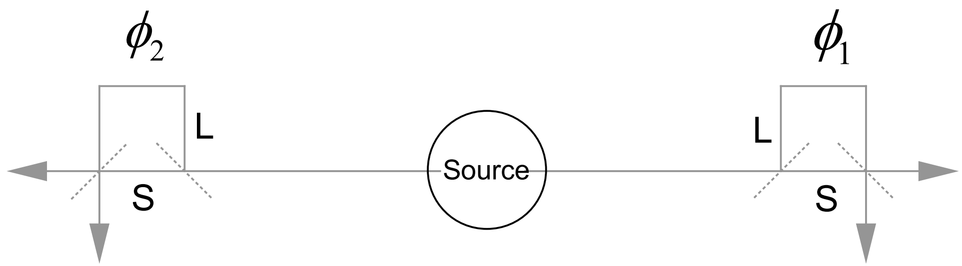
There is no contribution from $L_1S_2$ or $S_1L_2$ .

Interference between $L_1L_2$ and $S_1S_2$ gives a coincidence rate proportional to $\cos^2[(\phi_1+\phi_2)/2]$.

This violates Bell's inequality.


1. J. D. Franson, Phys. Rev. Lett. **62**, 2205-2208 (1989).

# A CONTROVERSIAL PREDICTION




This predicted effect was initially very controversial:

- Classically, the output of interferometer 1 cannot depend on the setting of the distant phase shift $\phi_2$ .
- The difference in the path lengths is much larger than the (first-order) coherence length.
  - The second-order coherence length is much longer.

This interferometer is now widely used for quantum cryptography.

# OTHER FORMS OF ENTANGLEMENT

Entangled states can be created in many different ways:

Polarization states of photons:

$$|\psi\rangle = \left(|x_1\rangle|x_2\rangle + |y_1\rangle|y_2\rangle\right)/\sqrt{2}$$

Path entanglement of photons.

Energy-time entanglement (nonlocal interferometer).

Energy levels of atoms or ions.

"Hyper-entanglement" – several degrees of freedom at once.

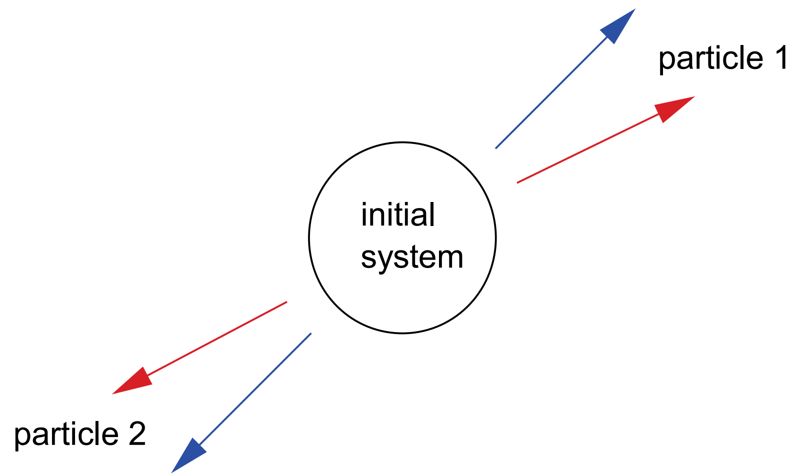
# EINSTEIN-PODOLSKY-ROSEN PARADOX

# HIDDEN-VARIABLE THEORIES

# EINSTEIN-PODOLSKY-ROSEN PARADOX[1]

Einstein and his colleagues considered an example in which a particle decays into two particles.

The two remaining particles travel in opposite directions:




In quantum mechanics, this corresponds to an entangled state.

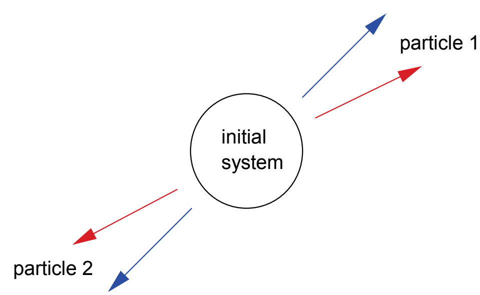
How is this different from a classical correlation?

1. A. Einstein, B. Podolsky, and N. Rosen, Phys. Rev. 47, 777 (1935).

# EINSTEIN-PODOLSKY-ROSEN PARADOX

EPR argued that quantum mechanics is an incomplete theory.

- Element of reality – "If, without in any way disturbing a system, we can predict with certainty the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity."
- Complete theory - For a theory to be complete, "every element of the physical reality must have a counter-part in the physical theory.




We can predict the momentum of particle 1 by measuring the momentum of particle 2.

Quantum mechanics does not predict the momentum of particle 2 – therefore it is "incomplete".

# HIDDEN-VARIABLE THEORIES

How do we know that the state of the particles wasn't determined all along?

More generally, each particle could carry a set of information with it that determines the results of any measurements.

Theories of that kind are known as hidden-variable theories.

"Realism" – Nature has certain properties that exist regardless of whether or not we measure them.

Einstein: "Does the moon really exist if no one is looking at it?"

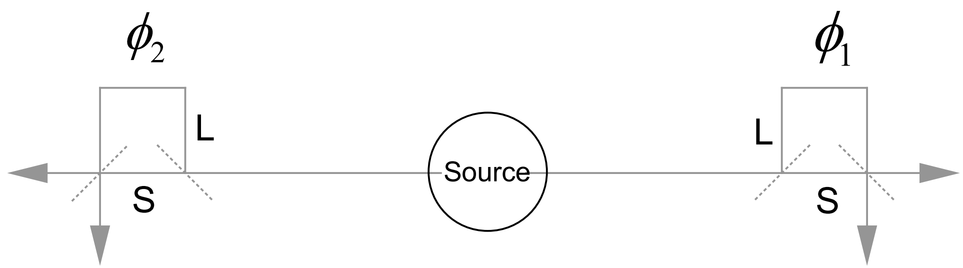
"Locality" – What happens at one location can have no immediate effect on a system at a distant location.

"Local realistic theories"

# BELL'S INEQUALITY (1964)

John Bell considered the most general local realistic theory of this kind.

In the case of a nonlocal interferometer, the phases of the two interferometers are set to one of three settings, $\phi_A$ , $\phi_B$ , or $\phi_C$ .




Bell showed that $|P(\phi_A,\phi_B) - P(\phi_A,\phi_C)| \leq 1 + P(\phi_B,\phi_C)$ for any local realistic hidden-variable theory.

Quantum mechanics violates this.

There is no classical explanation of the results, unless we give up locality or realism.

# EXPERIMENTAL TESTS OF LOCAL REALISM

# EXPERIMENTS BASED ON BELL'S INEQUALITY

Bell's inequality shows that Einstein's objections to quantum mechanics were not just a matter of interpretation.

- The predictions of quantum mechanics are different from any hidden-variable (local realistic) theory.

These experiments also generated renewed interest in entanglement.

This eventually led to possible practical applications based on entanglement.

# EARLY EXPERIMENTS ON BELL'S INEQUALITIES

Holt and Pipkin – Harvard -1973.

- The results agreed with classical physics – never published.
- Due to a distortion in the vacuum chamber windows?

E. Fry – U. Texas – 1973.

- Agreed with quantum mechanics, but not statistically significant.

J. Clauser – U.C. Berkeley – 1976.

- Gave the first convincing violation of Bell's inequality.

A. Aspect – France – 1981.

- First experiment with large spatial separation.
- Rules out ordinary interactions between the devices.

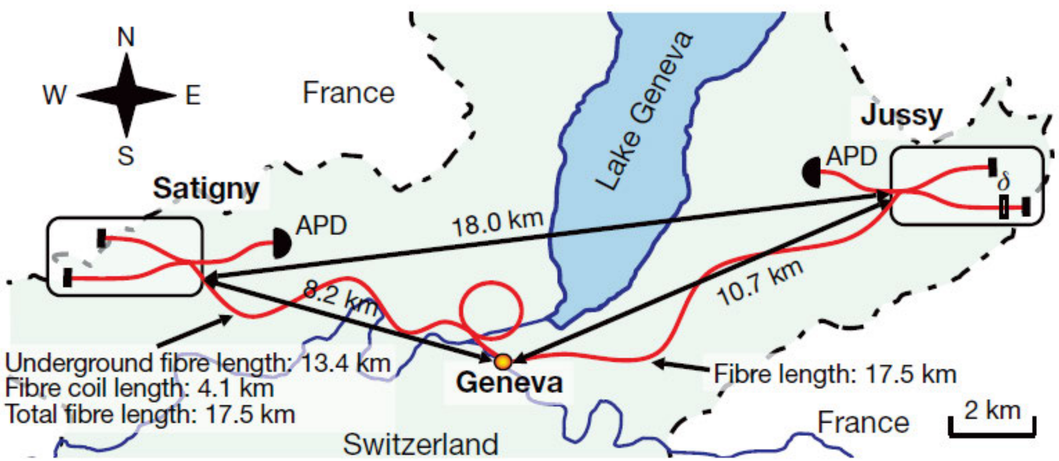
Y. Shih – University of Maryland - 1986.

- First experiment using parametric down-conversion.
- Gives very high counting rates and statistics.

# LONG-DISTANCE EXPERIMENTS

Gisin's group in Switzerland performed a nonlocal interferometer experiment[1] over a distance of 10 km.

They subsequently showed[2] that the collapse of the wave function occurs at least 10,000 faster than the speed of light.





1. W. Tittel, J. Brendel, H. Zbinden, and N. Gisin, Phys. Rev. Lett. **81**, 3563 (1998).
2. D. Salart, A. Baas, C. Branciard, N. Gisin, and H. Zbinden, Nature **454**, 861 (2008).

# PRACTICAL APPLICATIONS

# QUANTUM KEY DISTRIBUTION

Most conventional secure communications systems are based on public-key encryption.

It is very easy to multiply two large integers $N_1$ and $N_2$ to obtain a larger integer $N$.

$$N = N_1 N_2$$

Factoring $N$ to find $N_1$ and $N_2$ would take longer than the age of the universe on a supercomputer for ~ 400 digits.

Public key encryption is based on the difficulty in factoring.

But quantum computers may be able to factor very quickly.

# QUANTUM CRYPTOGRAPHY USING ENTANGLED PHOTONS

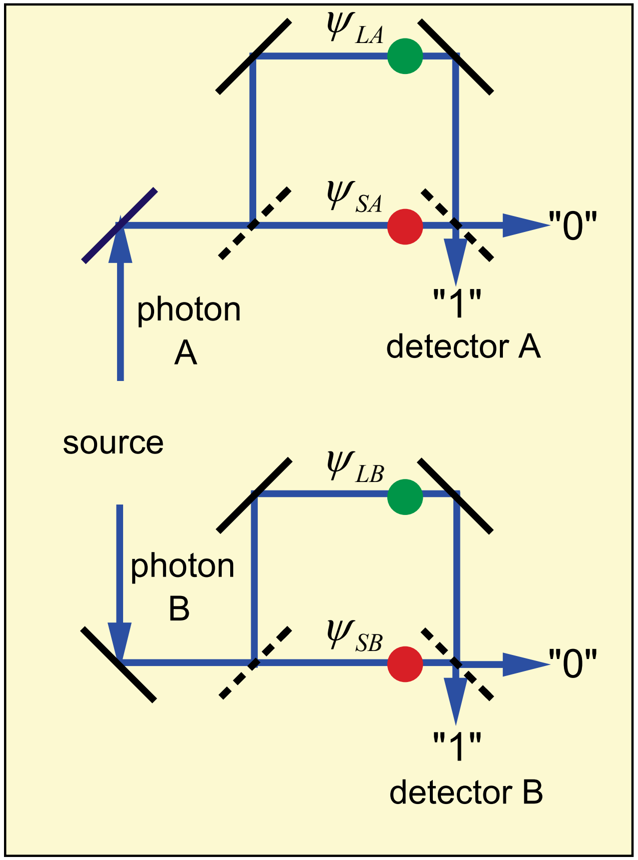
Entangled photons produce correlated outputs from two distant interferometers.

A secret code can be generated if we assign “0” and “1” bit values.

This can be used to encode and decode secure messages.

There is no information for an eavesdropper to intercept.

We demonstrated the first quantum cryptography in optical fibers.



# QUANTUM COMPUTING

Quantum computers are expected to be able to solve problems that would be impossible on a conventional computer.

- Factoring (Shor's algorithm).
- Sorting through a large data base.
- Quantum image processing?

In a quantum computer, the bits, or qubits, can be in a superposition state:

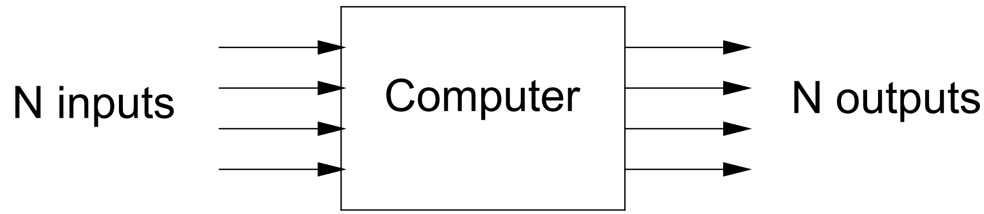
$$\left|\psi\right\rangle = \left|0\right\rangle + e^{i\varphi}\left|1\right\rangle$$

Possible qubits:

- Photons
- Atoms
- Electron spins
- Superconductors (Josephson junctions)

# POWER OF A QUANTUM COMPUTER

Consider a quantum processor that executes a specific algorithm.




We can input a superposition state corresponding to all possible inputs.

The output state will correspond to a superposition of all possible results of the calculations.

Interference between the output states can give results that would have required all of the calculations to have been done simultaneously.

# QUANTUM COMPUTING USING SINGLE PHOTONS

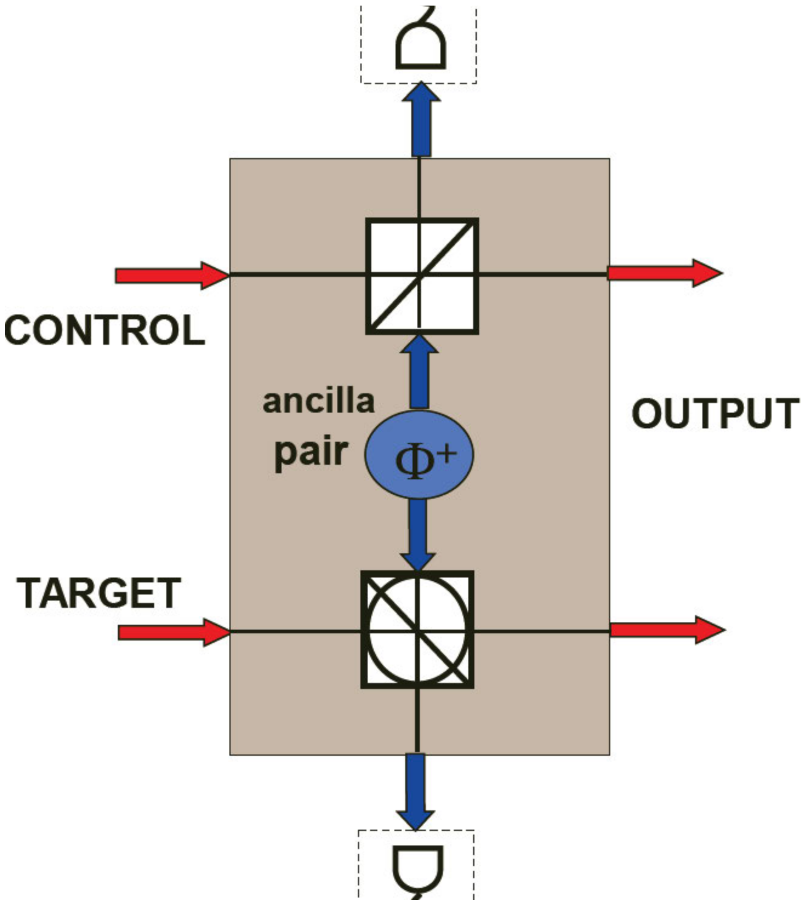
We were the first to demonstrate quantum logic operations using photons, including a CNOT gate.

The value of the target qubit is "flipped" if the control qubit =1

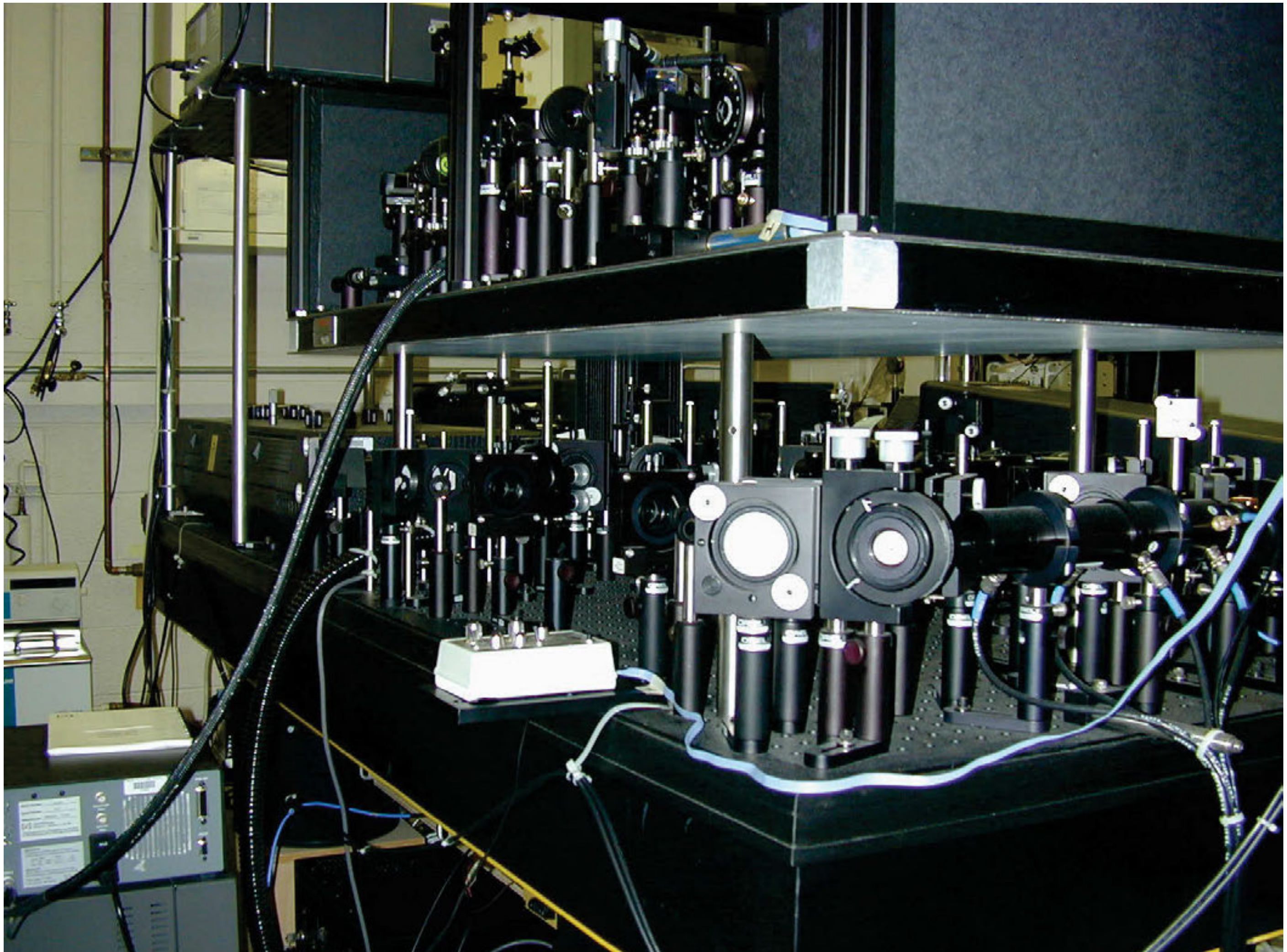
The device is very simple

- Two beam splitters and two detectors
- With an extra pair of photons (ancilla)

It succeeds 25% of the time

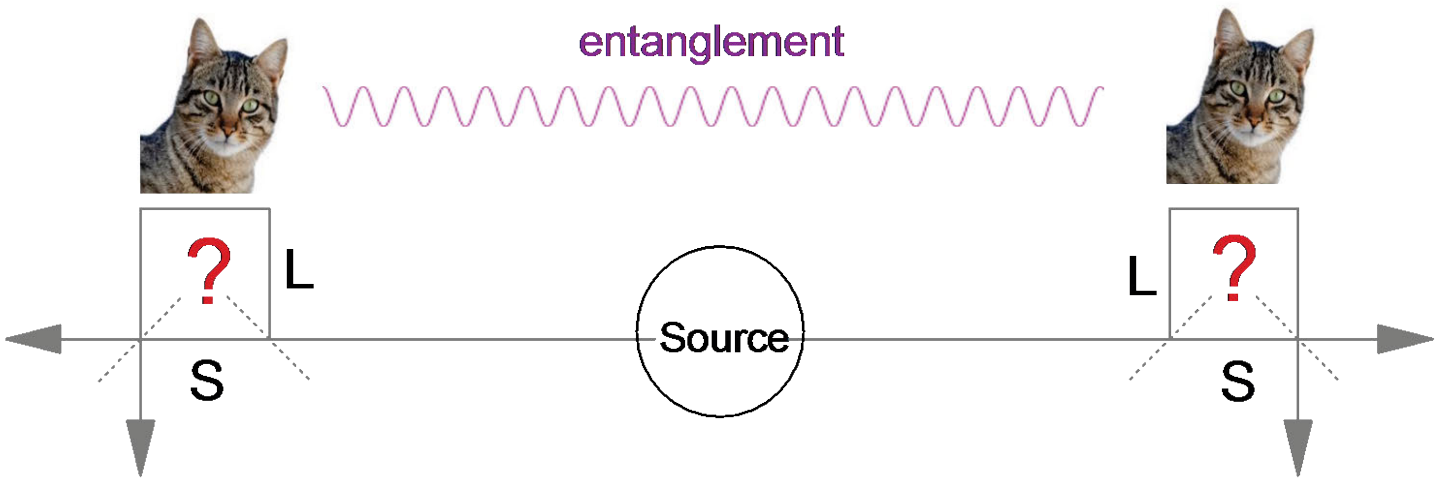


# FIRST DEMONSTRATION OF QUANTUM LOGIC USING PHOTONS



# CURRENT RESEARCH

# NONLOCAL INTERFEROMETRY USING SCHRODINGER CATS




Macroscopic Schrodinger cats propagate through one path or the other.

Entanglement produces a violation of Bell's inequality.

# COLLABORATORS

Todd Pittman
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John Howell
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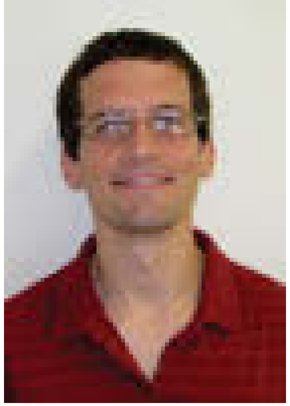
Sasha Sergienko
Boston U.

Brian Kirby
Theory

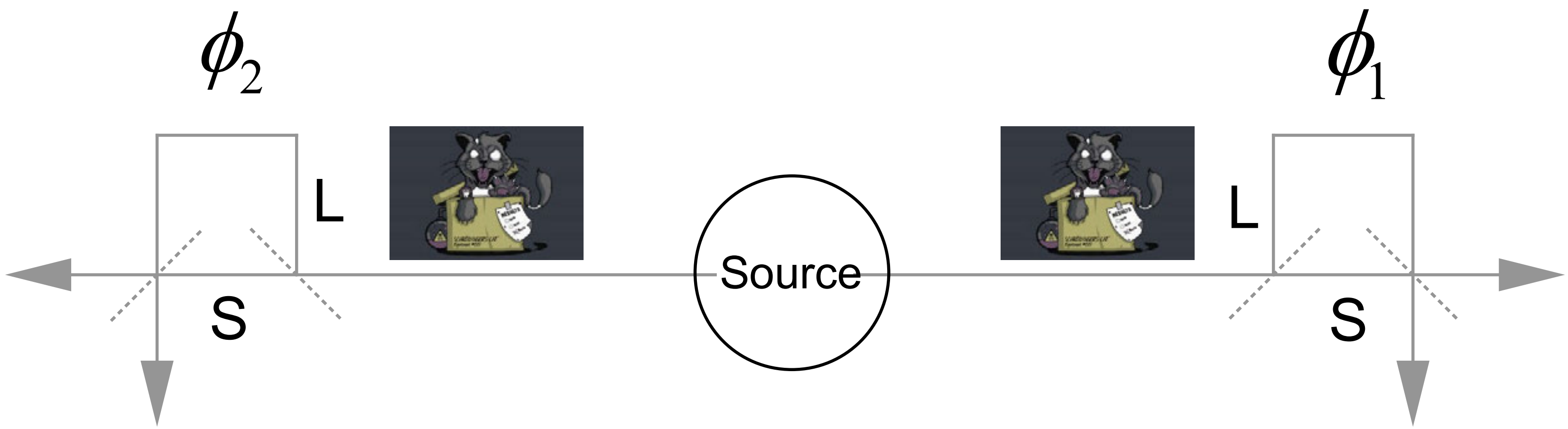


Garrett Hickman
Experiment

Dan Jones
Experiment

# SCHRODINGER CATS AND NONLOCAL INTERFEROMETRY

Basic idea:



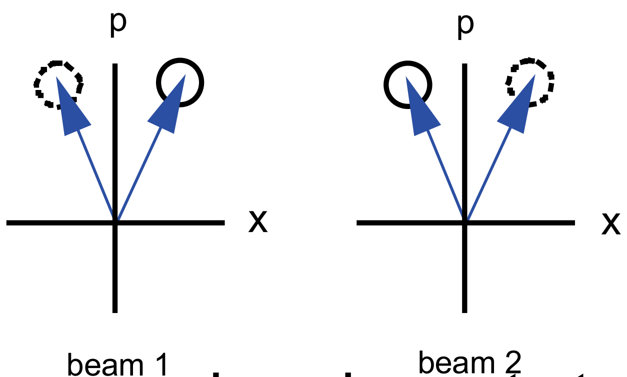

The Schrodinger cats will be macroscopic phase-entangled coherent states (laser beams).

How large is macroscopic? (Visible spot on a wall.)

# ENTANGLED PHASE STATES

We would like to generalize the nonlocal interferometer to use macroscopic phase-entangled states.

Two laser beams with anti-correlated phase shifts:




We may expect macroscopic coherent states to be relatively robust against loss.

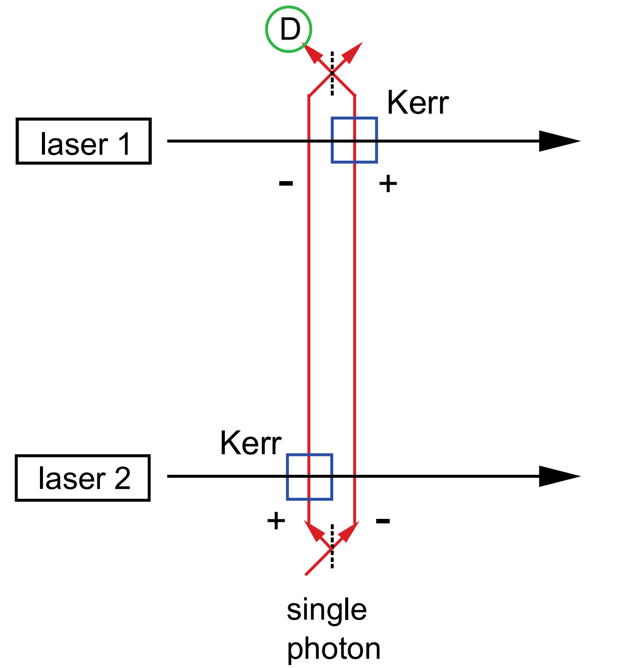
A coherent state subjected to loss remains coherent.

The only concern is “which-path” information left along the way.

# GENERATION OF ENTANGLED PHASE STATES

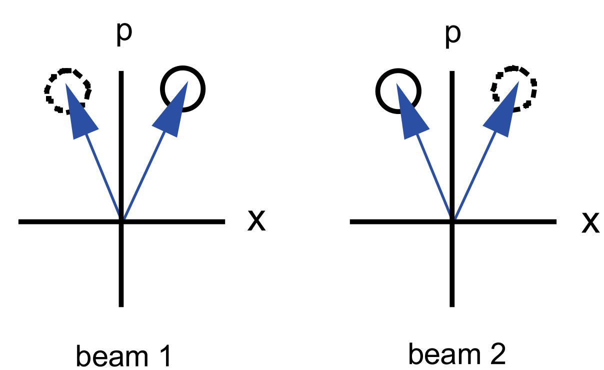
Munro et al.[1] have noted that a single photon can produce a significant phase shift in a coherent state:

Sufficient to produce orthogonal states.




This can be used to produce an entangled state with anti-correlated phase shifts[2].

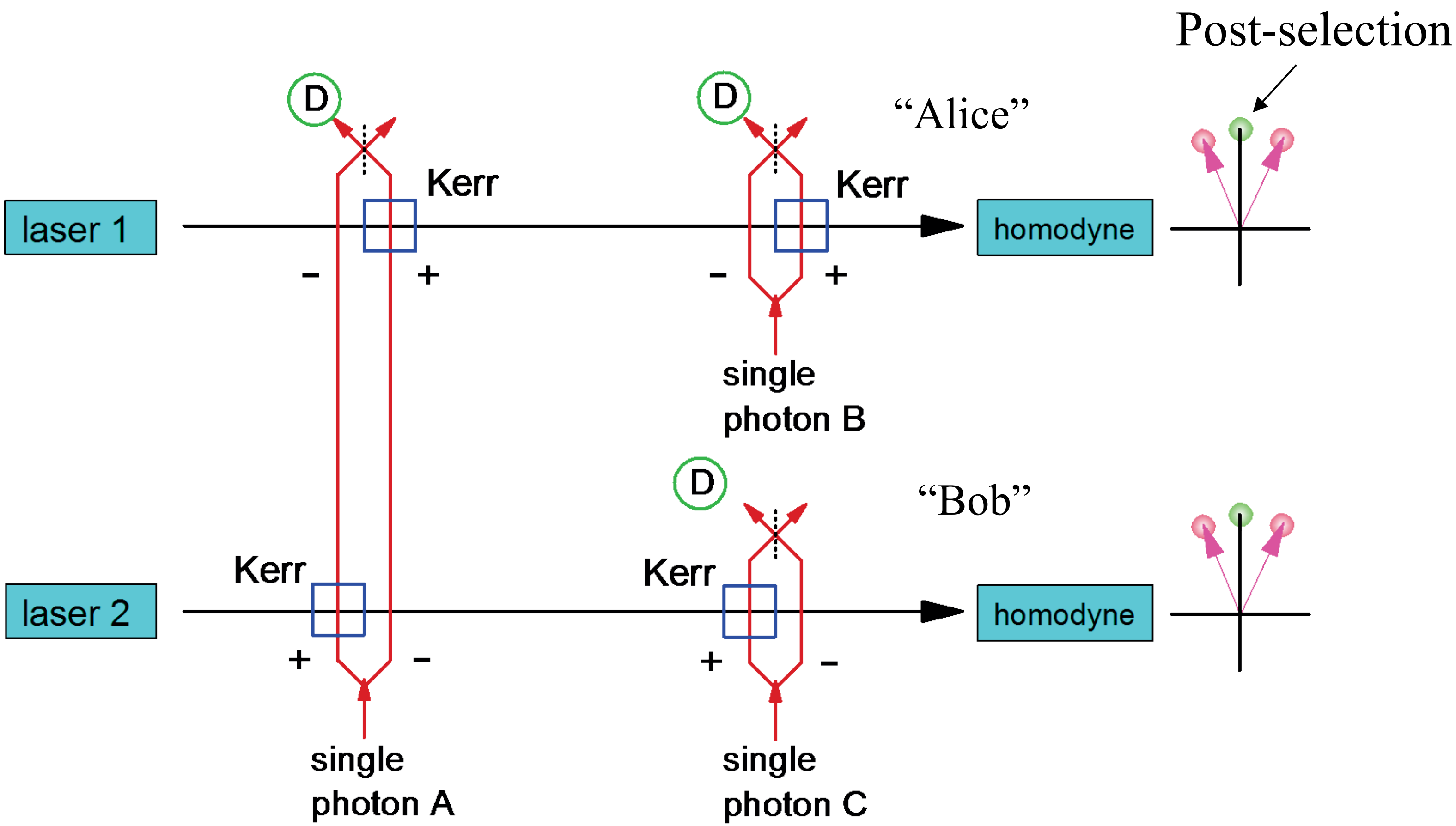
Post-select on a photon in detector D to get a superposition state with a well-defined relative phase.




1. W.J. Munro, K. Nemoto, and T.P. Spiller, New J. Phys. 7, 137 (2005).
2. B. T Kirby and J.D. Franson, Phys. Rev. A **87**, 053822 (2013).

# NONLOCAL INTERFEROMETETRY USING MACROSCOPIC COHERENT STATES

Phase entanglement of coherent states can be used to implement a nonlocal interferometer:



# VIOLATION OF BELL'S INEQUALITY

The projection onto a state in which there is no net phase shift gives

$$| p\rangle = \frac{1}{2\sqrt{2}}[e^{i\sigma_1} \,|\alpha_{+-}\rangle\,|\beta_{-+}\rangle - e^{i\sigma_2} \,|\alpha_{-+}\rangle\,|\beta_{+-}\rangle].$$

Nonlocal interference between these two terms violates Bell's inequality.

This is analogous to the long-long and short-short paths in the original interferometer.

# USE OF A MICRO-CAVITY

A small mode volume increases the magnitude of the nonlinear phase shift[1].

- Nonlinear effects are typically inversely proportional to the mode volume.

Highly reflective mirrors allow the photons to interact for a long time.

- The reflectivity is approximately 99.95%
- The observed quality factor Q is $2 \times 10^8$

[1]Q.A. Turchette, C.J. Hood, W. Lange, H. Mabuchi, and H.J. Kimble, Phys. Rev. A **75**, 4710 (1995).

# METASTABLE XENON

Rubidium is very reactive and quickly destroys optical surfaces at high temperatures and densities.

For high-finesse cavities, we have replaced the use of rubidium with a noble gas (xenon).

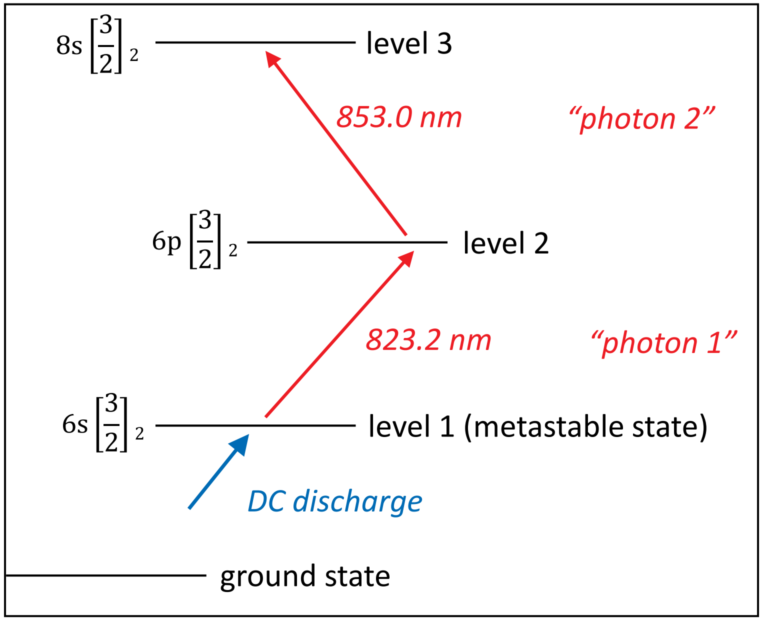
- We have observed no degradation of the mirrors.
- We have observed large nonlinearities (saturated absorption) in both cavities and tapered fibers.

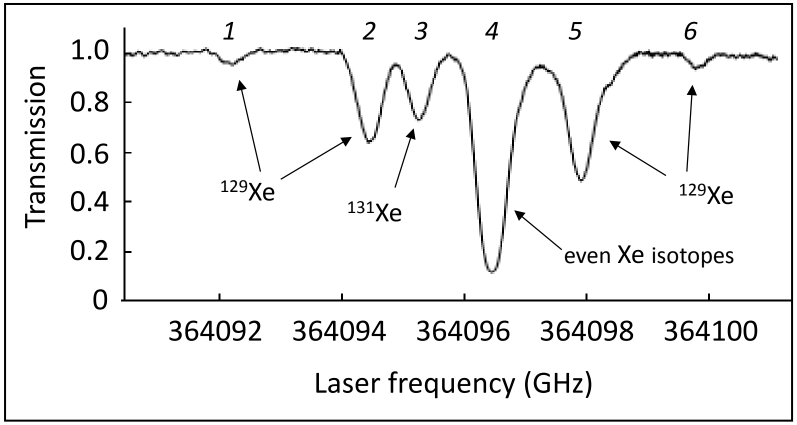
The ground states of noble gases are unsuitable.

- Lowest transition is in the ultraviolet.

Instead, we use metastable xenon as an effective "ground state".

# SPECTROSCOPY OF METASTABLE XENON



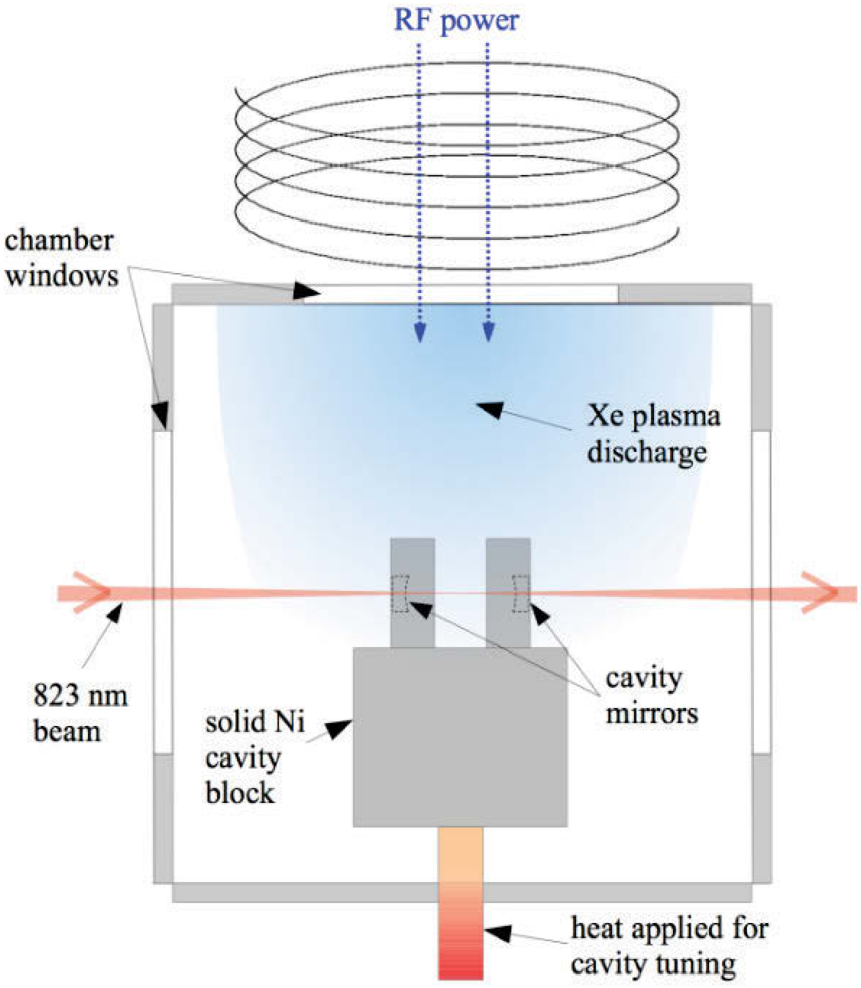

Will switch to single-isotope xenon later.

# RESONATOR DESIGN

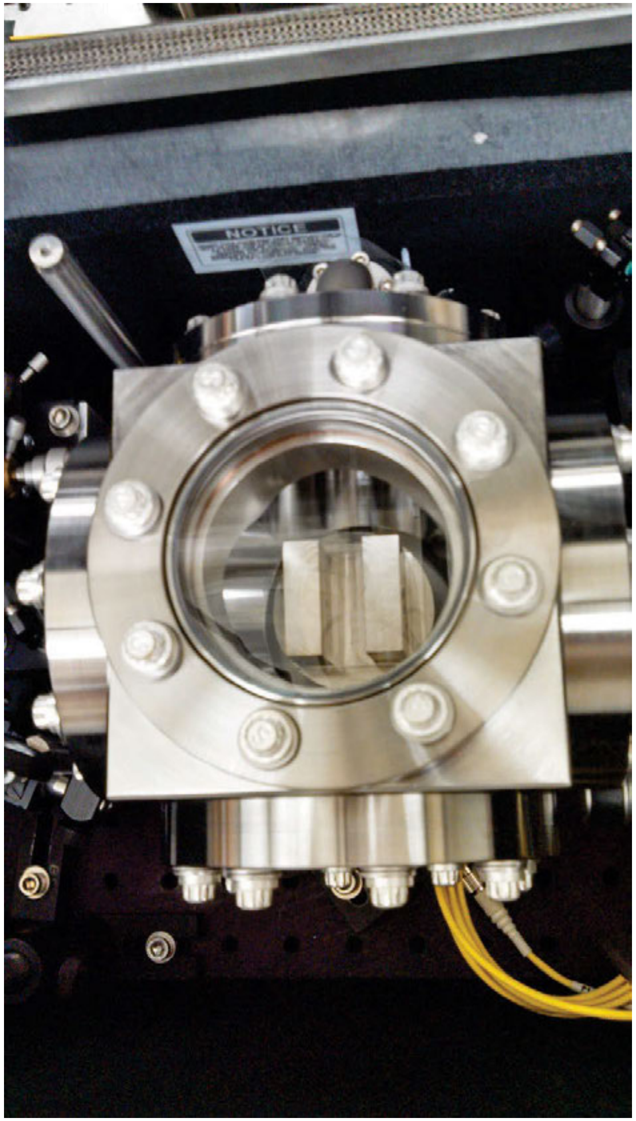
The mirrors are mounted in a metal fixture.

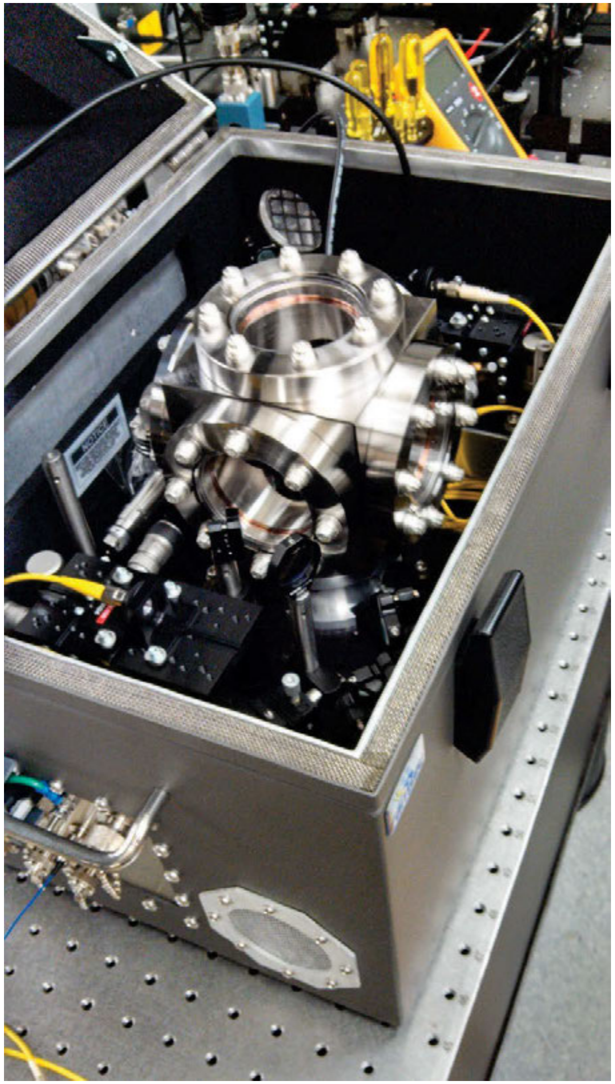
Machined from a solid block of nickel.

The frequency is controlled by varying the temperature.

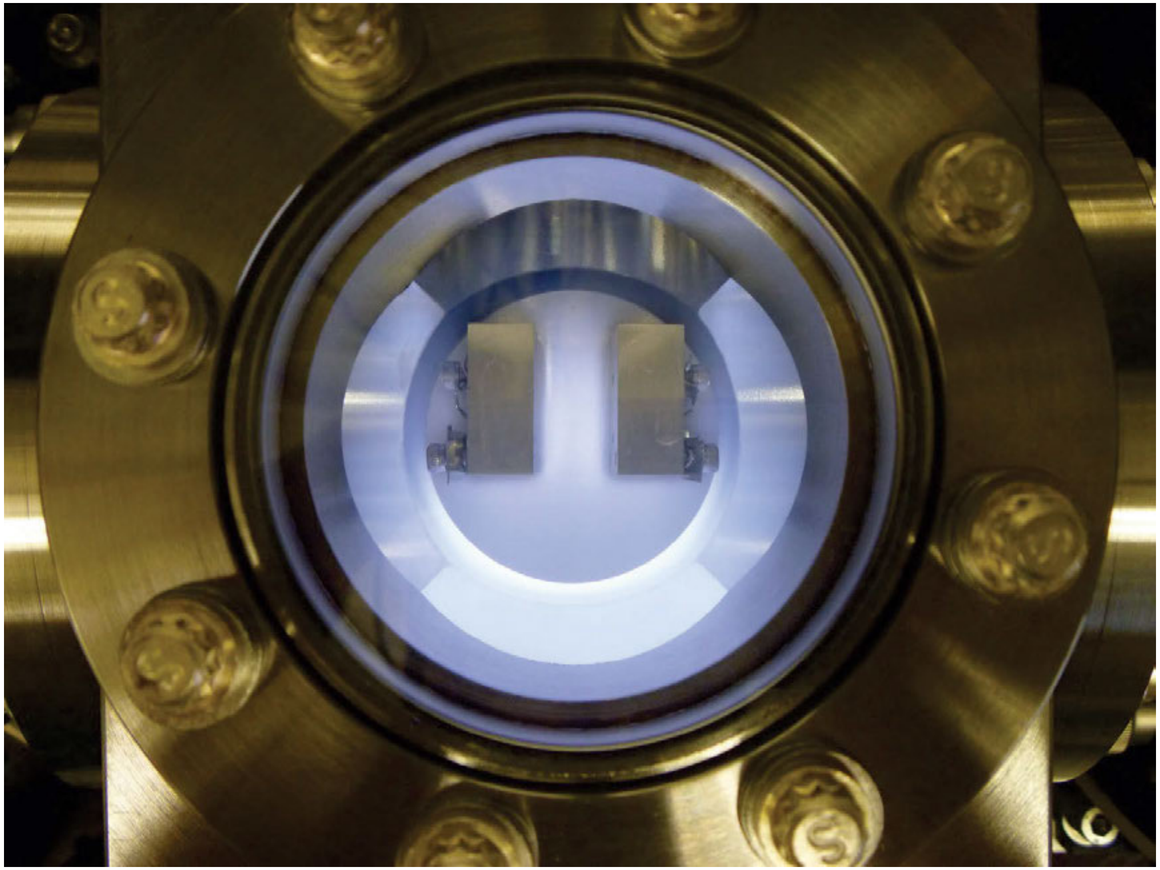


# RESONATOR INSIDE VACUUM CHAMBER

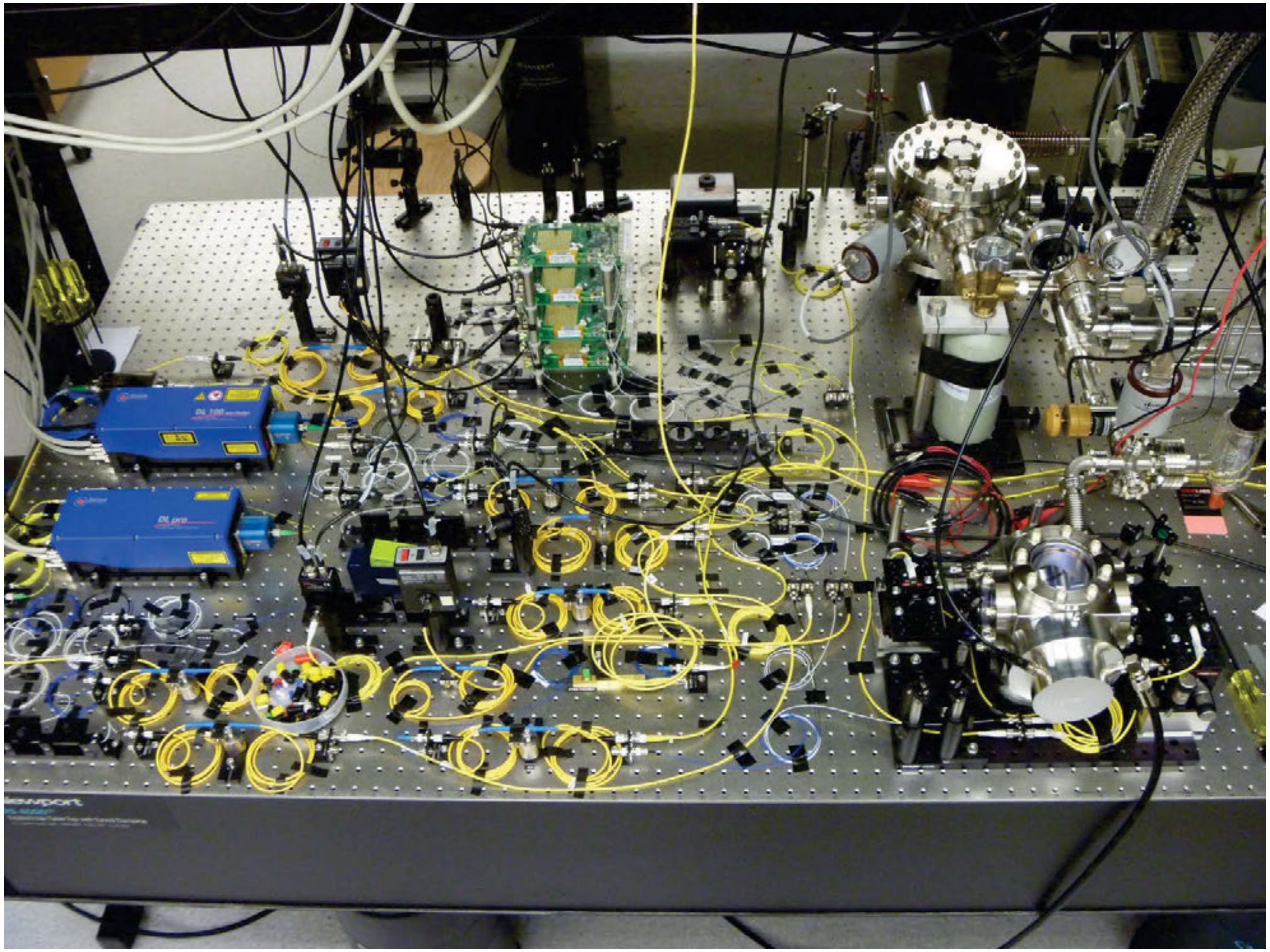


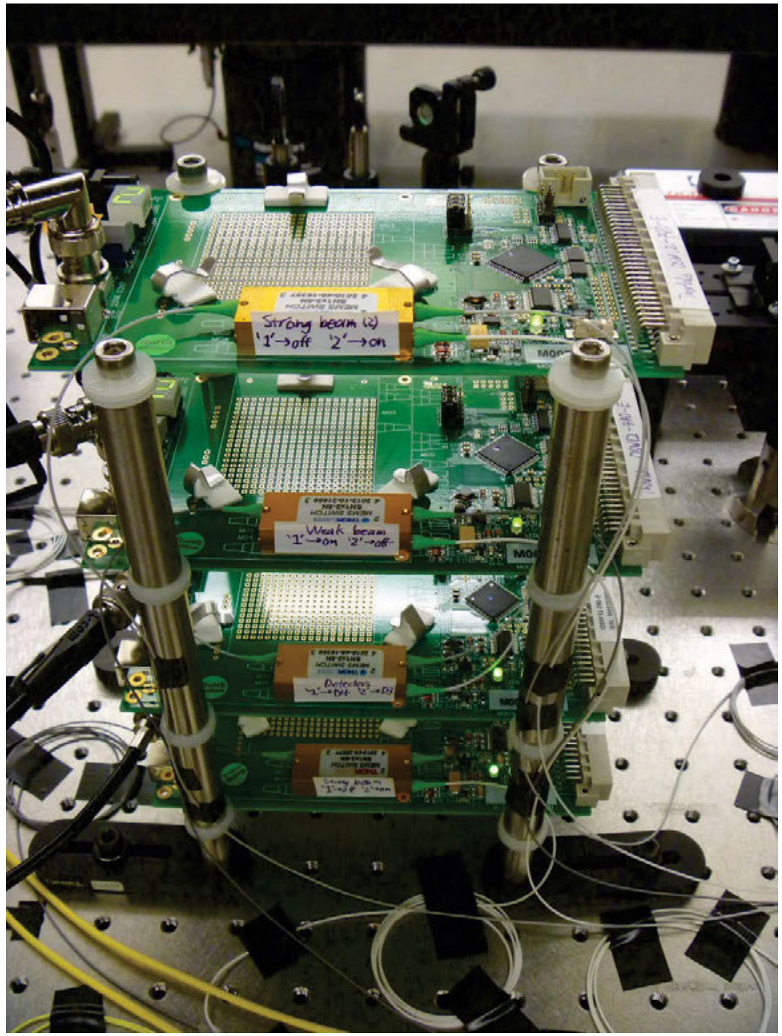
# RESONATOR WITH METASTABLE XENON



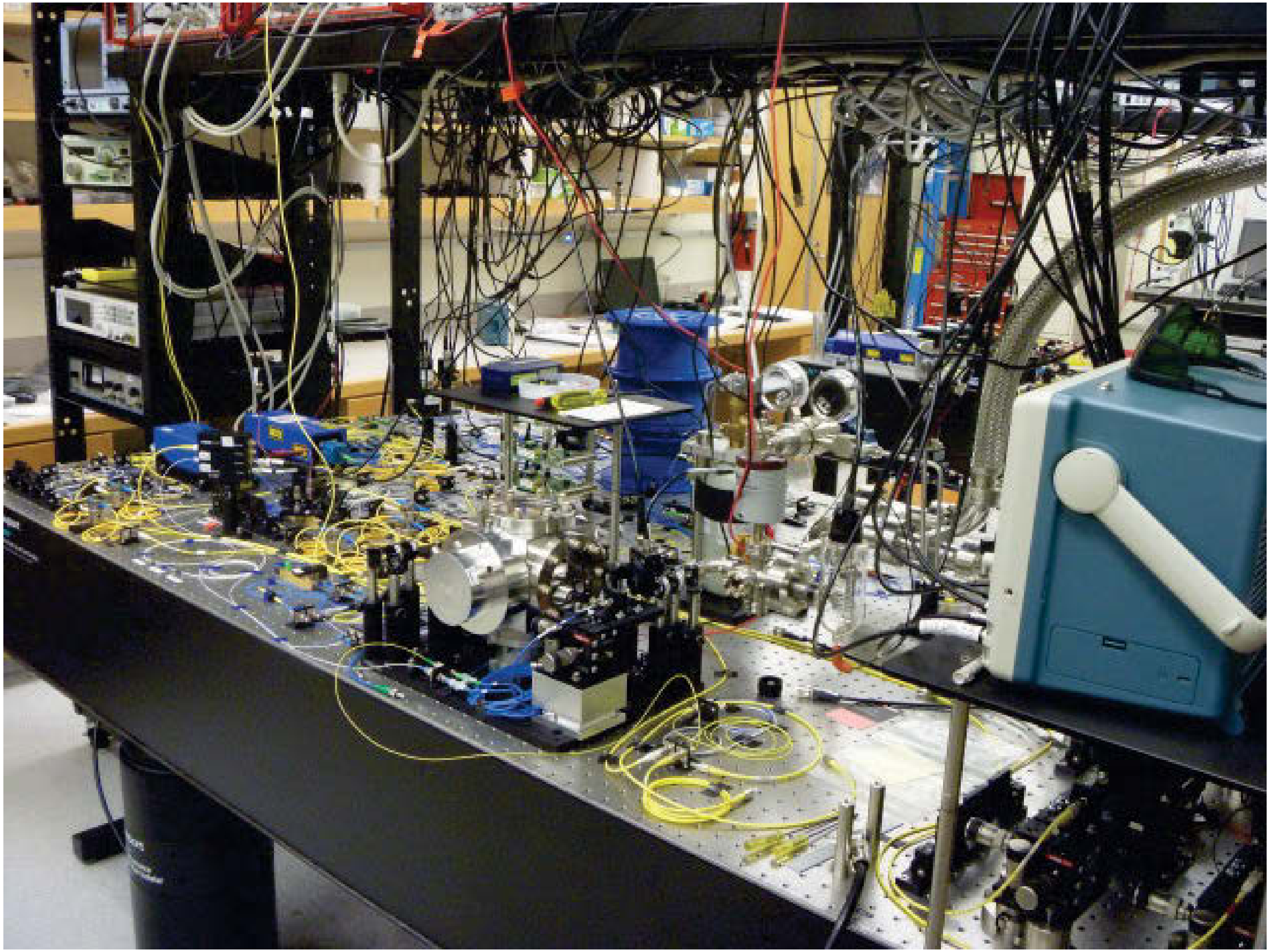
# EXPERIMENTAL APPARATUS



# FOUR MEMS SWITCHES

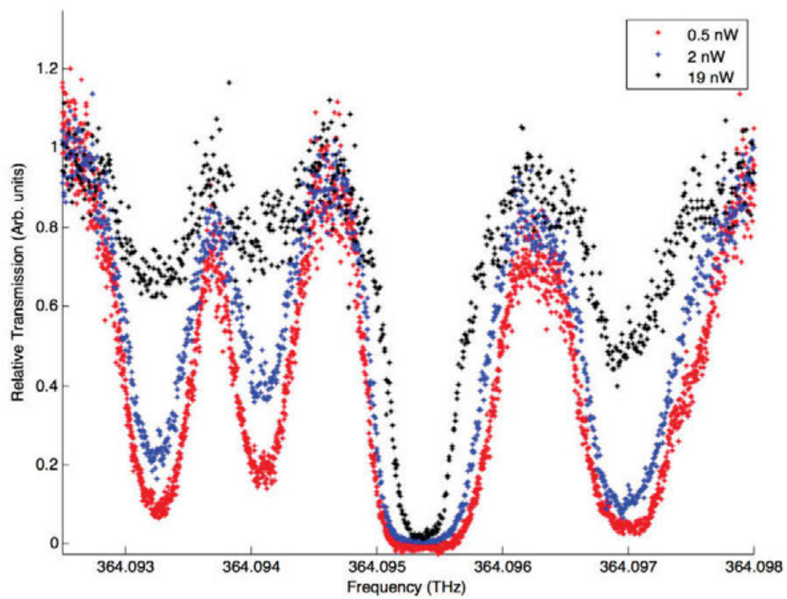


# CURRENT EXPERIMENTAL APPARATUS



# SATURATED ABSORPTION

- Recent results
  - We have measured saturated absorption at ultralow power levels.
  - Saturation effects are visible with input powers <1 nW, indicating a nonlinearity of roughly the strength we expect.




Metastable xenon absorption of 823 nm light for varying intra-cavity power levels

# SUMMARY

Entanglement produces nonlocal effects.

- Any classical interpretation would require signals travelling faster than the speed of light.
- No messages can be transmitted faster than light.

Einstein referred to entanglement 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.

These effects may also have practical applications.