Quantum Experiments

sources

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Classical *versus* Quantum Experiments

- Classical Experiments
  - Experiment with bullets
  - Experiment with waves
- Quantum Experiments
  - Two slits Experiment with electrons
  - Stern-Gerlach Experiment

Experiment with bullets

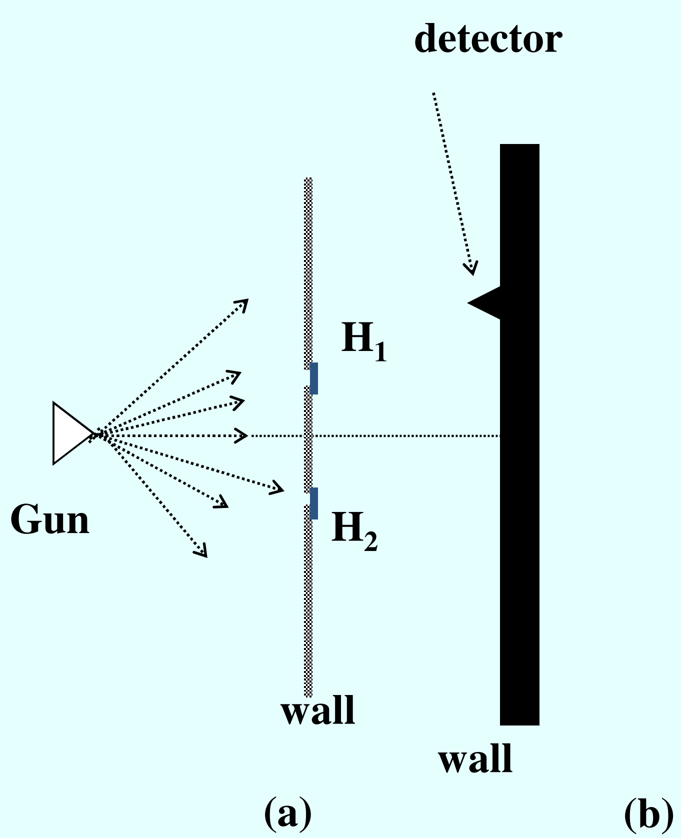
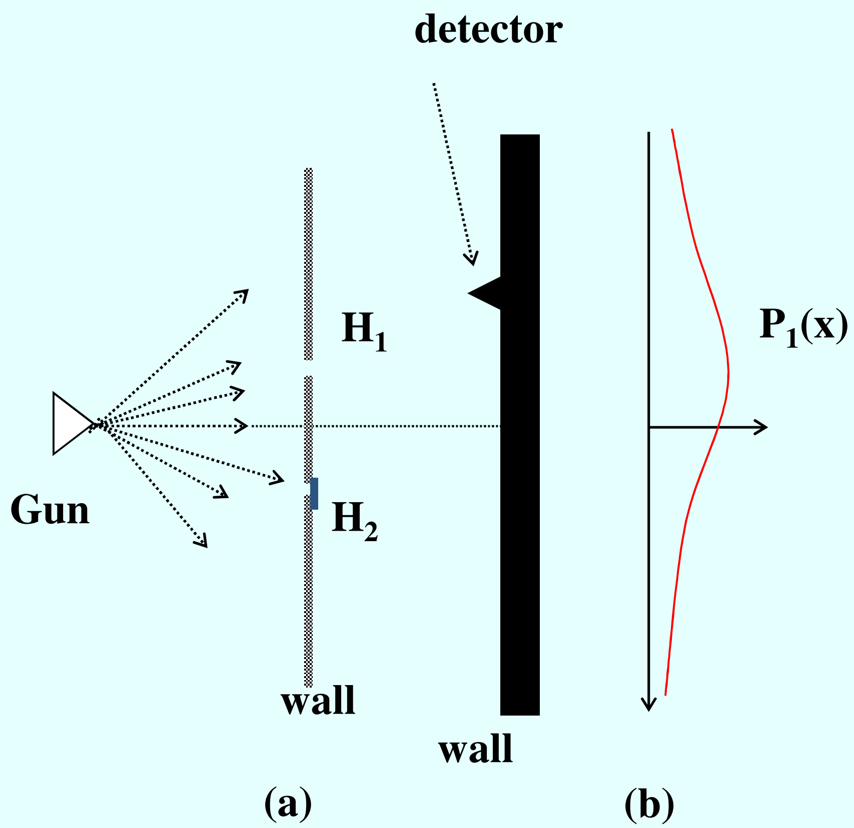


Figure 1: Experiment with bullets

Experiment with bullets



H1 is open

H2 is closed

Figure 1: Experiment with bullets

Experiment with bullets

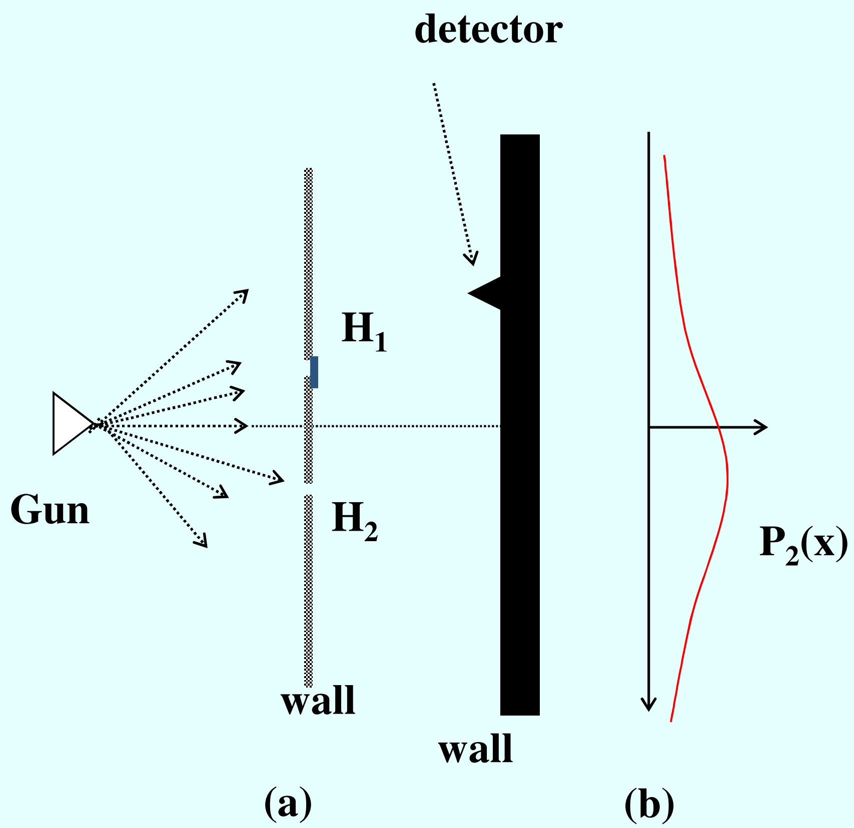


Figure 1: Experiment with bullets

H1 is closed

H2 is open

Experiment with bullets

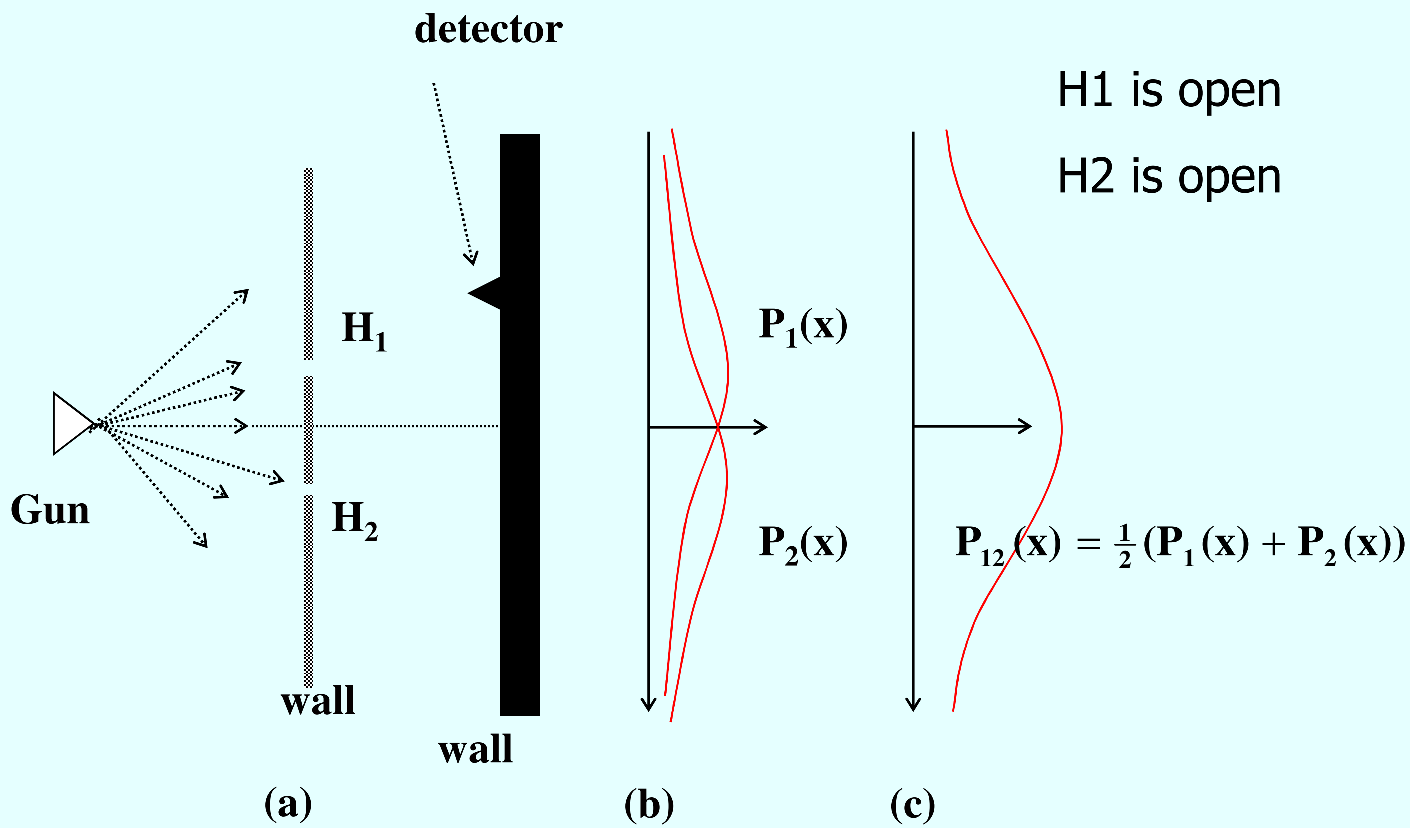
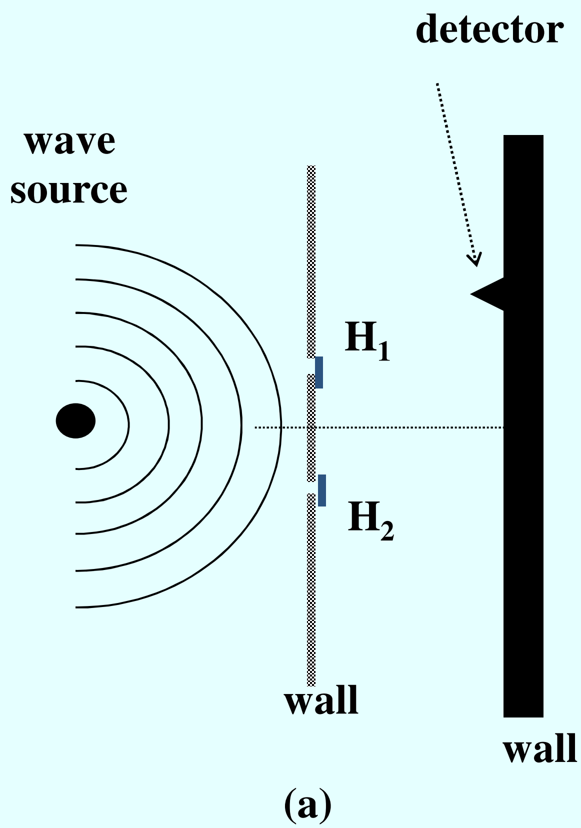


Figure 1: Experiment with bullets

Experiment with Waves

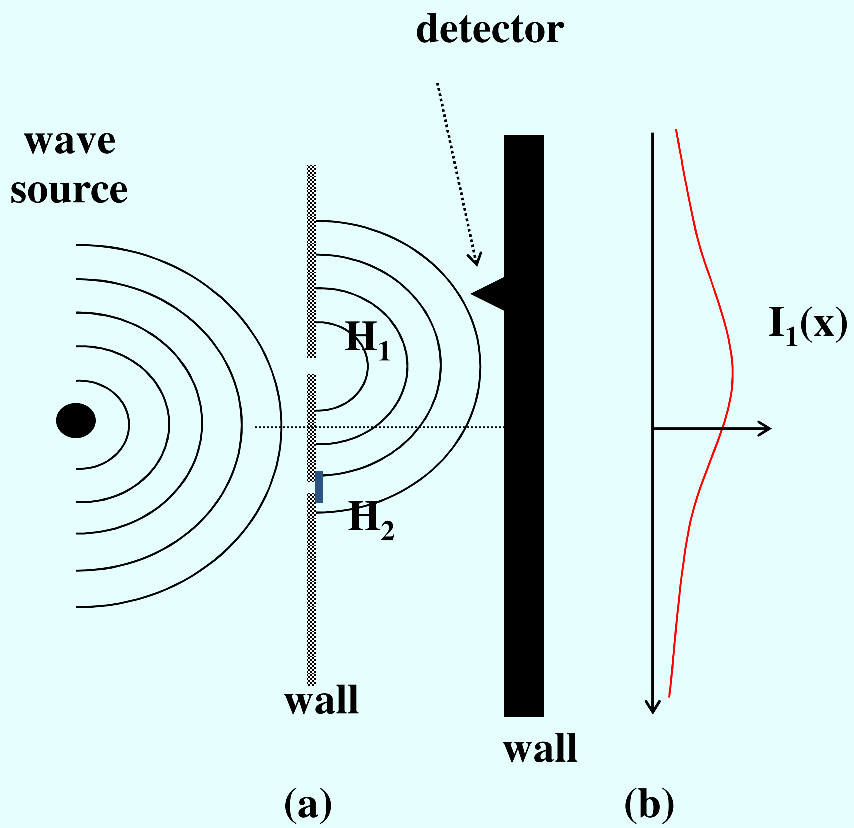


H1 is closed

H2 is closed

Figure 2: Experiments with waves

Experiment with Waves



H1 is open

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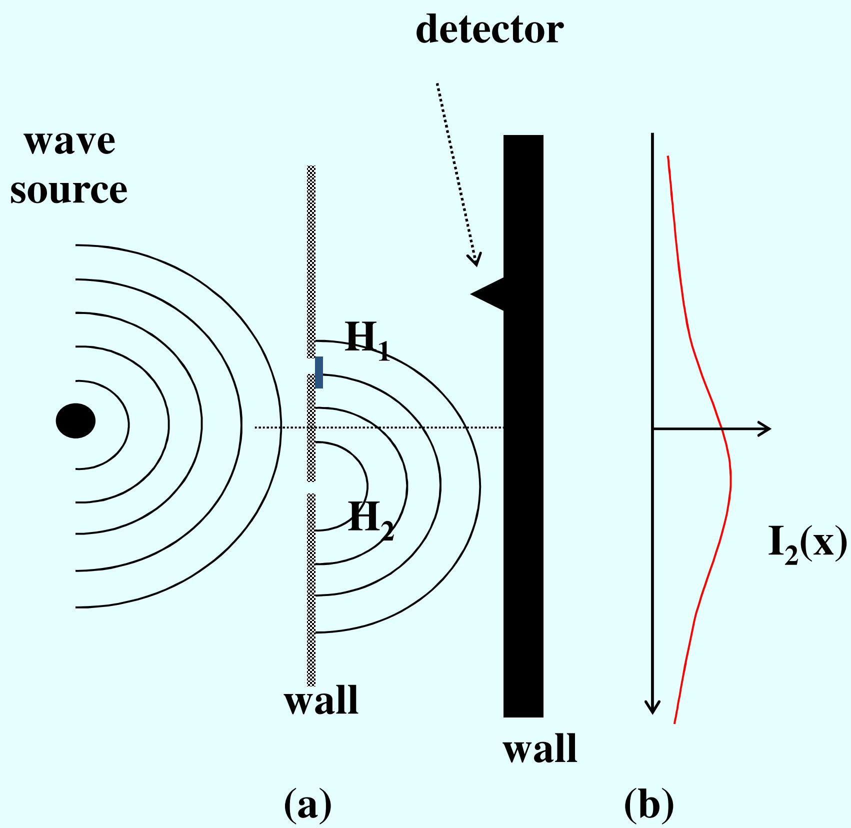
Figure 2: Experiments with waves

Experiment with Waves



H1 is closed

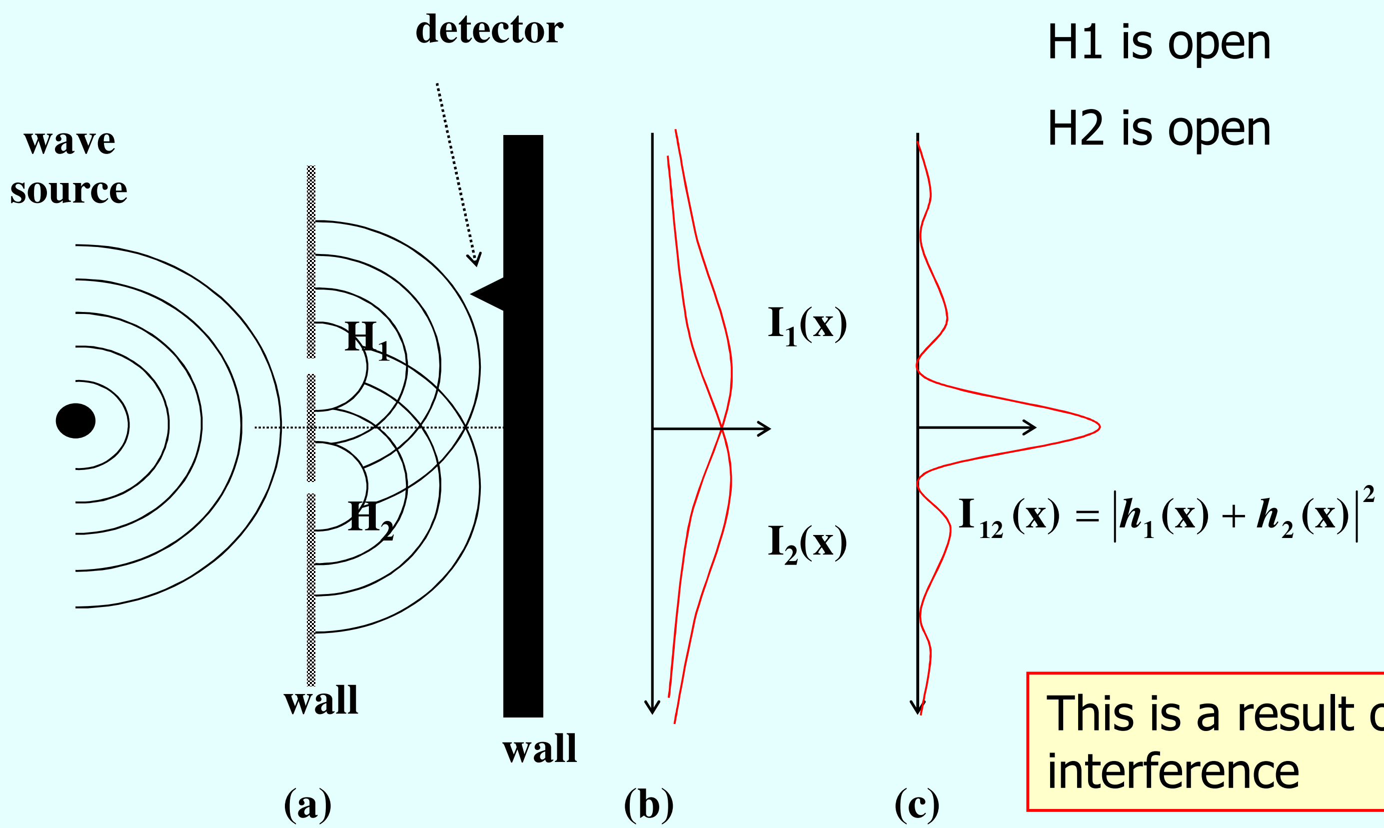
H2 is open

Figure 2: Experiments with waves

Experiment with Waves

H1 is open

H2 is open



This is a result of interference

Figure 2: Experiments with waves

Two Slit Experiment

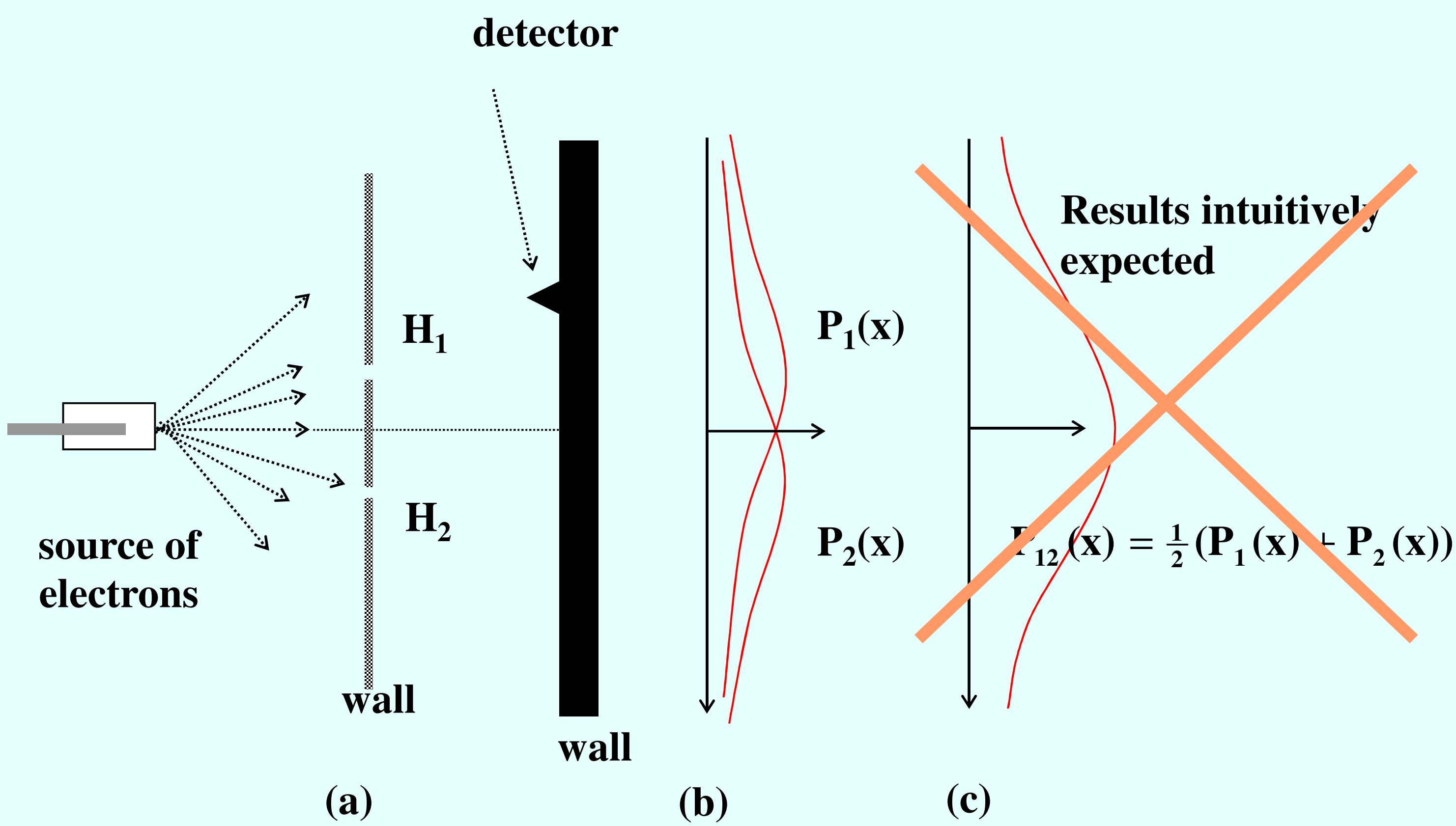


Figure 3: Two slit experiment

Are electrons particles or waves?

Two Slit Experiment

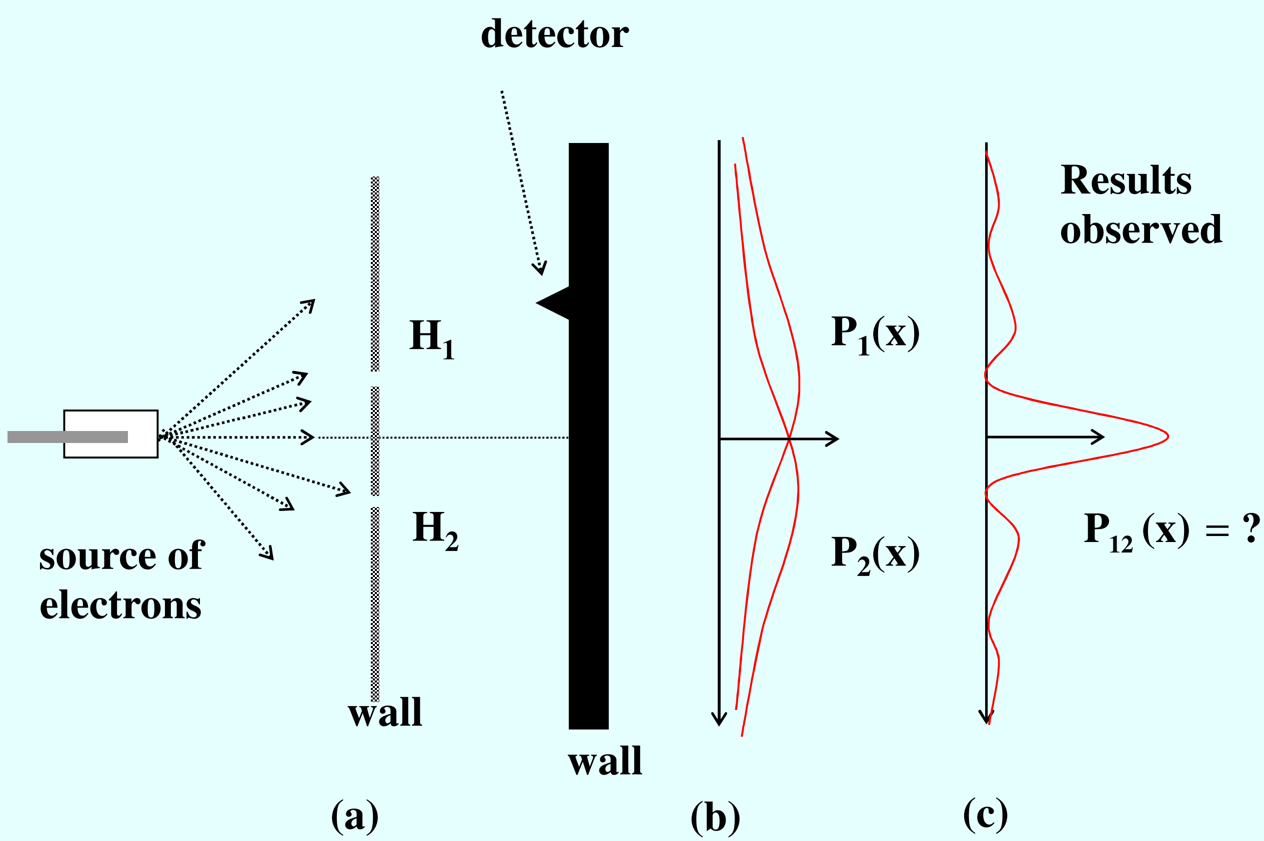


Figure 3: Two slit experiment

Two Slit Experiment With Observation

Now we add light source

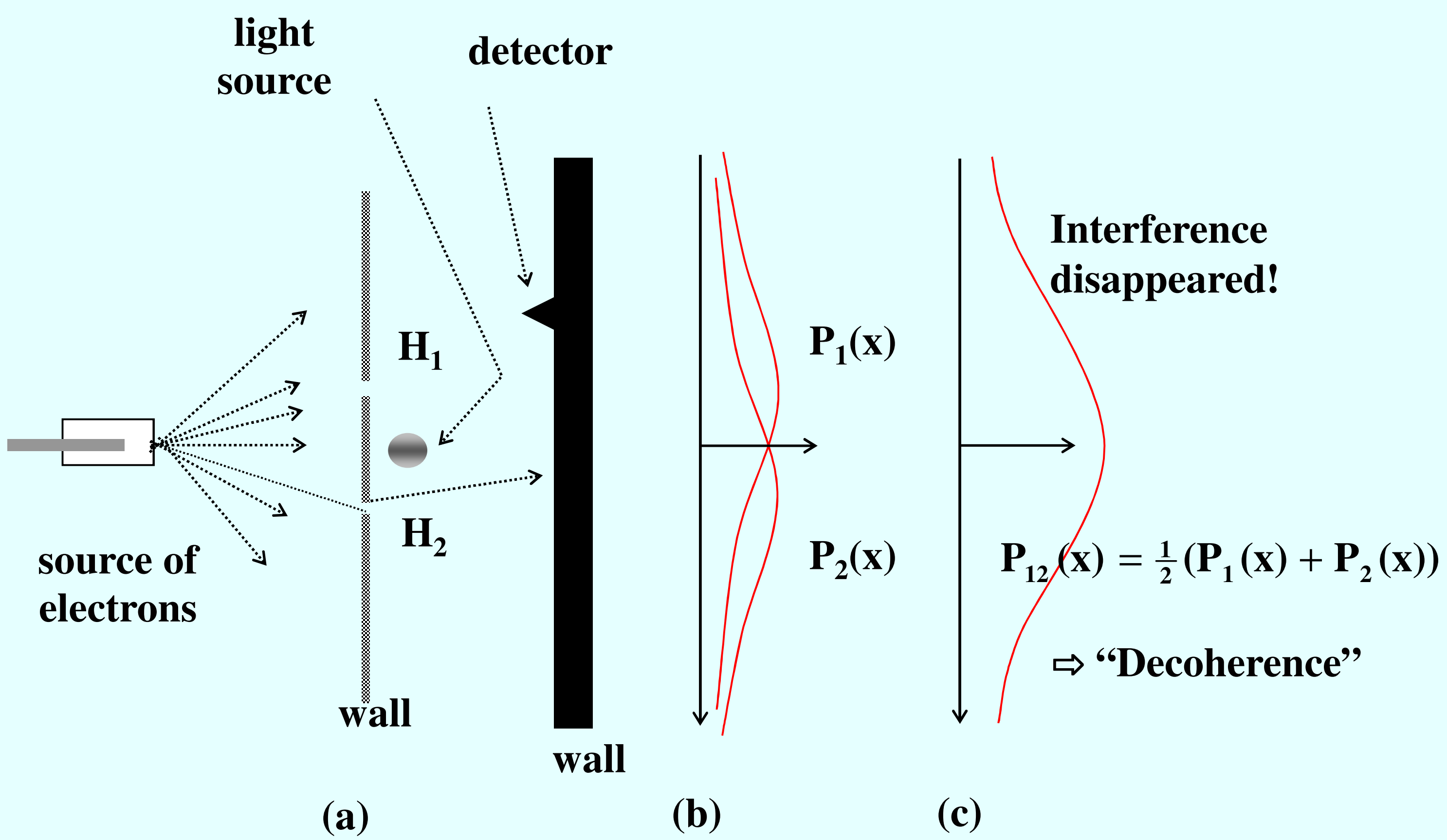


Figure 4: Two slit experiment with observation

Stern-Gerlach Experiment

Will be discussed in more detail later

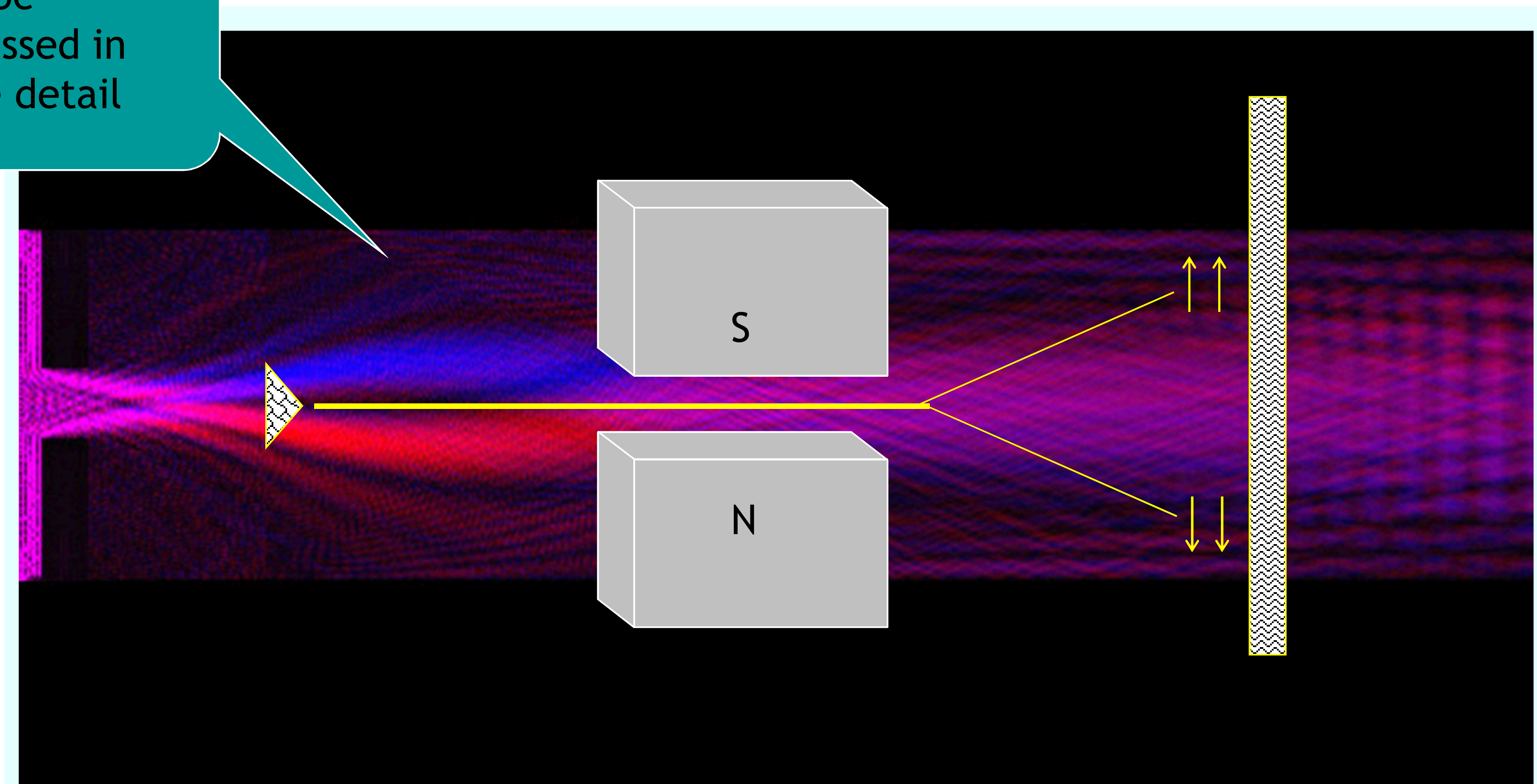


Figure 5: Stern-Gerlach experiment with spin-1/2 particles

Conclusions From the Experiments

- Limitations of classical mechanics
- Particles demonstrate wavelike behavior
- Effect of observations cannot be ignored
- Evolution and measurement must be distinguished

Can we use these phenomena practically?

Quantum computing and information

Technological limits

- For the past two decades we have enjoyed Gordon Moore's law.
- But all good things may come to an end…
- We are limited in our ability to increase
  - the density and
  - the speed of a computing engine.
- Reliability will also be affected
  - to increase the speed we need increasingly smaller circuits (light needs 1 ns to travel 30 cm in vacuum)
  - smaller circuits ➔ systems consisting only of a few particles subject to Heisenberg uncertainty

Energy/operation

- **If** there is a minimum amount of energy dissipated to perform an elementary operation, **then** to increase the speed we have to increase the number of operations performed each second.

- To increase this number, we require a linear increase in the amount of energy dissipated by the device.

- The computer technology in year 2000 requires some 3×10^{-18} Joules per elementary operation.

- Even if this limit is reduced say 100-fold we shall see a 10 (ten) times increase in the amount of power needed by devices operating at a speed 10^3 times larger than the speed of today's devices.

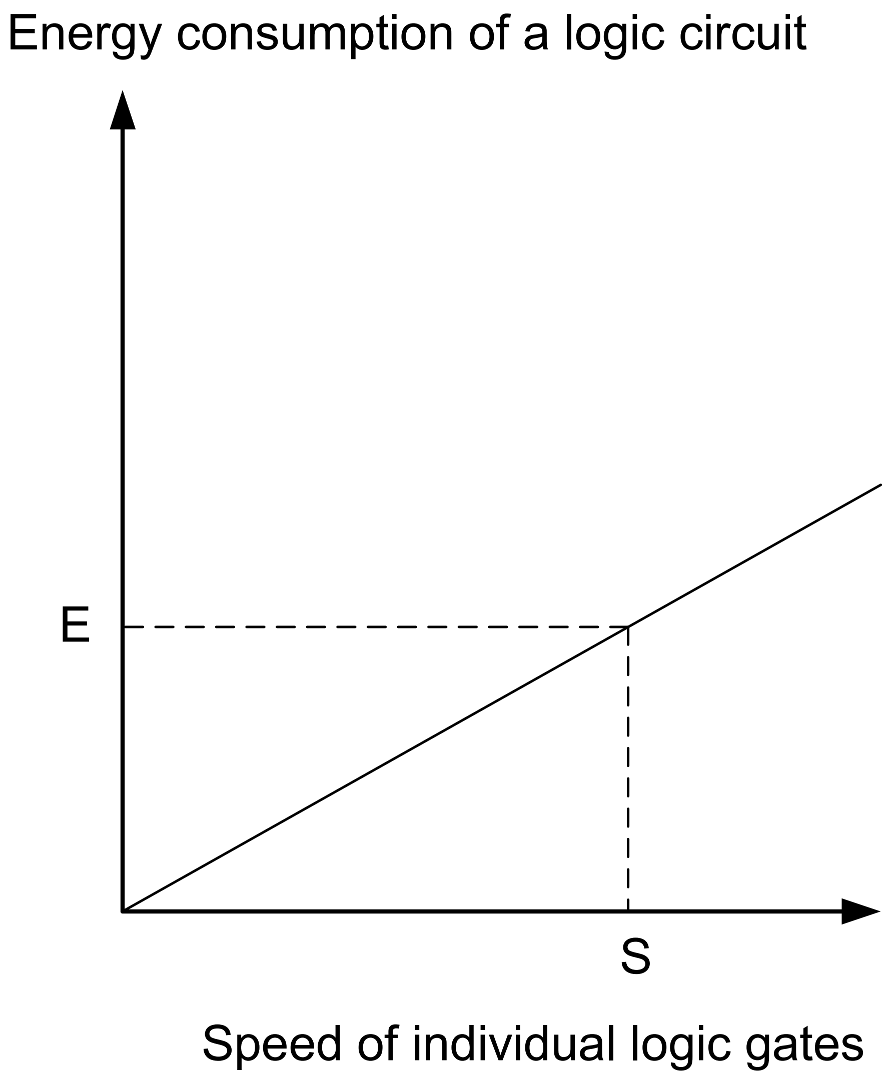
Power dissipation, circuit density, and speed

- In 1992 Ralph Merkle from Xerox PARC calculated that a 1 GHz computer operating at room temperature, with 10^{18} gates packed in a volume of about 1 cm^3 would dissipate **3 MW** of power.
  - A small city with 1,000 homes each using 3 KW would require the same amount of power;
  - A 500 MW nuclear reactor could only power some 166 such circuits.

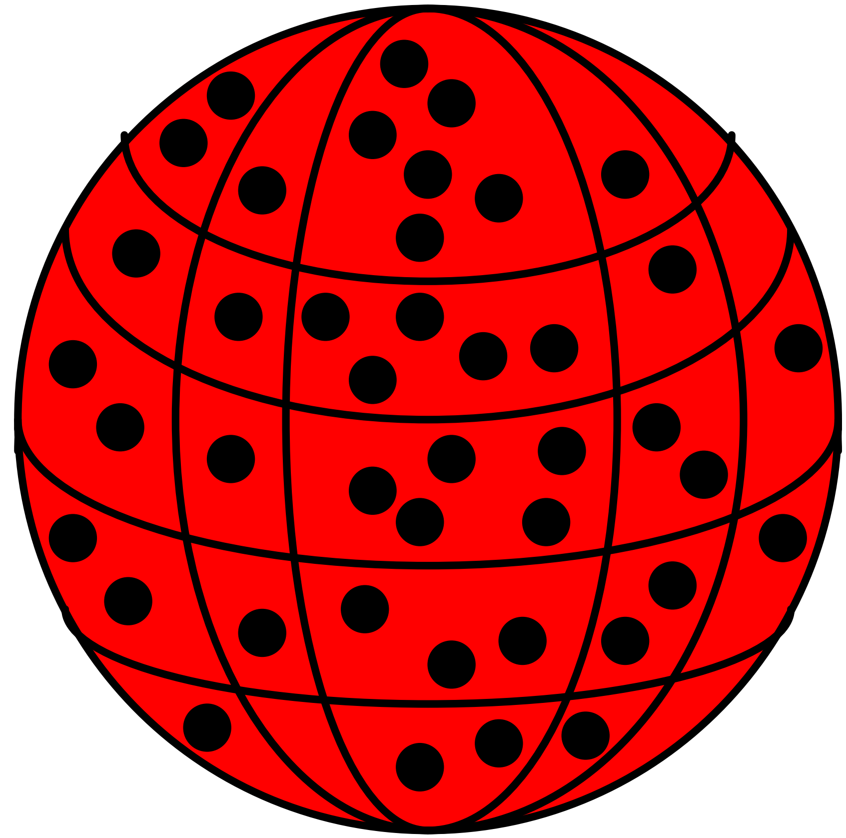
Reducing heat is important…

- The heat produced by a super dense computing engine is proportional to the number of elementary computing circuits.
- Thus, it is proportional to the volume of the engine.
- The heat dissipated grows as the cube of the radius of the device.
- To prevent the destruction of the engine we have to remove the heat through a surface surrounding the device.
- Henceforth, our ability to remove heat increases as the square of the radius while the amount of heat increases with the cube of the size of the computing engine.

Energy consumption is proportional to speed of computing



(a)



Heat removal for a circuit with densely packed logic gates poses tremendous challenges.

(b)

A happy marriage…

- The two greatest discoveries of the 20-th century
  - quantum mechanics
  - stored program computers

produced quantum computing and quantum information theory

Quantum; Quantum mechanics

- *Quantum* is a Latin word meaning some quantity.
- In physics it is used with the same meaning as the word *discrete* in mathematics,
  - i.e., some quantity or variable that can take only sharply defined values as opposed to a continuously varying quantity.
- The concepts *continuum* and *continuous* are known from geometry and calculus.
- For example, on a segment of a line there are infinitely many points, the segment consists of a continuum of points.
- This means that we can cut the segment in half, and then cut each half in half, and continue the process indefinitely.
- Quantum mechanics is a mathematical model of the physical world

Heisenberg uncertainty principle

- Heisenberg uncertainty principle says we cannot determine both the position and the momentum of a quantum particle with arbitrary precision.

- In his Nobel prize lecture on December 11, 1954 Max Born says about this fundamental principle of Quantum Mechanics :
  - ``... *It shows that not only the determinism of classical physics must be abandoned, but also the naive concept of reality which looked upon atomic particles as if they were very small grains of sand. At every instant a grain of sand has a definite position and velocity. This is not the case with an electron. If the position is determined with increasing accuracy, the possibility of ascertaining its velocity becomes less and vice versa*."

A **revolutionary approach** to computing and communication

- We need to consider a revolutionary rather than an evolutionary approach to computing.
- Quantum theory does not play only a supporting role by prescribing the limitations of physical systems used for computing and communication.
- Quantum properties such as
  - uncertainty,
  - interference, and
  - entanglement

  form the foundation of a new brand of theory, the ***quantum information theory.***
- In quantum information theory the computational and communication processes rest upon fundamental physics.

Milestones in quantum physics

- **1900** - Max Plank presents the black body radiation theory; the quantum theory is born.

- **1905** - Albert Einstein develops the theory of the photoelectric effect.

- **1911** - Ernest Rutherford develops the planetary model of the atom.

- **1913** - Niels Bohr develops the quantum model of the hydrogen atom.

Milestones in quantum physics

- **1923** - Louis de Broglie relates the momentum of a particle with the wavelength

- **1925** - Werner Heisenberg formulates the matrix quantum mechanics.

- **1926** - Erwin Schrodinger proposes the equation for the dynamics of the wave function.

Milestones in quantum physics (cont'd)

- **1926** - Erwin Schrodinger and Paul Dirac show the equivalence of Heisenberg's matrix formulation and Dirac's algebraic one with Schrodinger's wave function.

- **1926** - Paul Dirac and, independently, Max Born, Werner Heisenberg, and Pasqual Jordan obtain a complete formulation of quantum dynamics.

- **1926** - John von Newmann introduces Hilbert spaces to quantum mechanics.

- **1927** - Werner Heisenberg formulates the uncertainty principle.

Milestones in computing and information theory

- **1936** - Alan Turing dreams up the Universal Turing Machine, UTM.
- **1936** - Alonzo Church publishes a paper asserting that ``every function which can be regarded as computable can be computed by an universal computing machine". Church Thesis.
- **1945** - ENIAC, the world's first general purpose computer, the brainchild of J. Presper Eckert and John Macauly becomes operational.

Milestones in computing and information theory

- **1946** - A report co-authored by John von Neumann outlines the von Neumann architecture.
- **1948** - Claude Shannon publishes ``A Mathematical Theory of Communication”.
- **1953** - The first commercial computer, UNIVAC I.

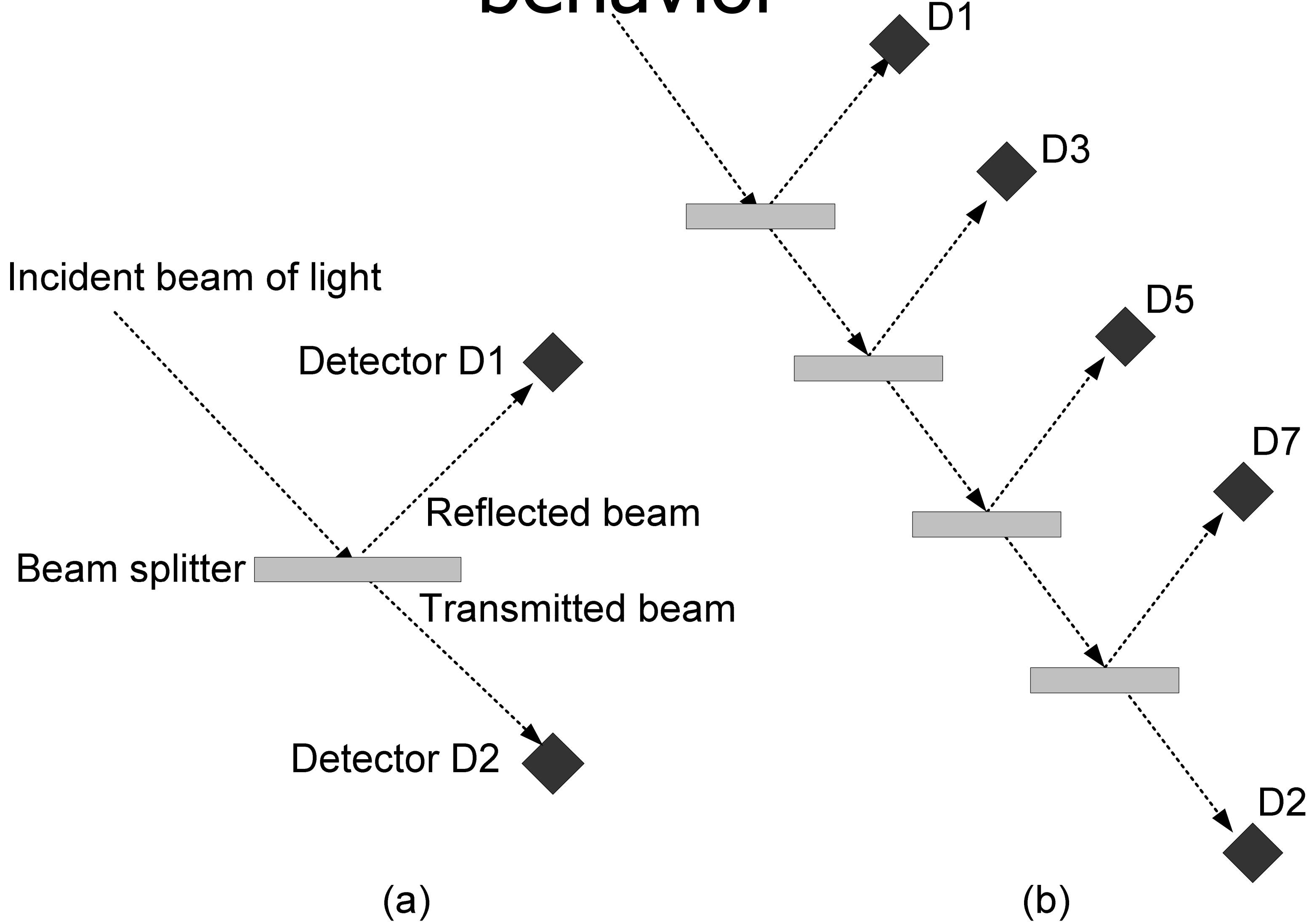
Milestones in quantum computing

- **1961** - Rolf Landauer decrees that computation is physical and studies heat generation.
- **1973** - Charles Bennet studies the logical reversibility of computations.
- **1981** - Richard Feynman suggests that physical systems including quantum systems can be simulated exactly with quantum computers.
- **1982** - Peter Beniof develops quantum mechanical models of Turing machines.

Milestones in quantum computing

- **1984** - Charles Bennet and Gilles Brassard introduce quantum cryptography.
- **1985** - David Deutsch reinterprets the Church-Turing conjecture.
- **1993** - Bennet, Brassard, Crepeau, Josza, Peres, Wooters discover quantum teleportation.
- **1994** - Peter Shor develops a clever algorithm for factoring large numbers.

Deterministic versus probabilistic photon behavior



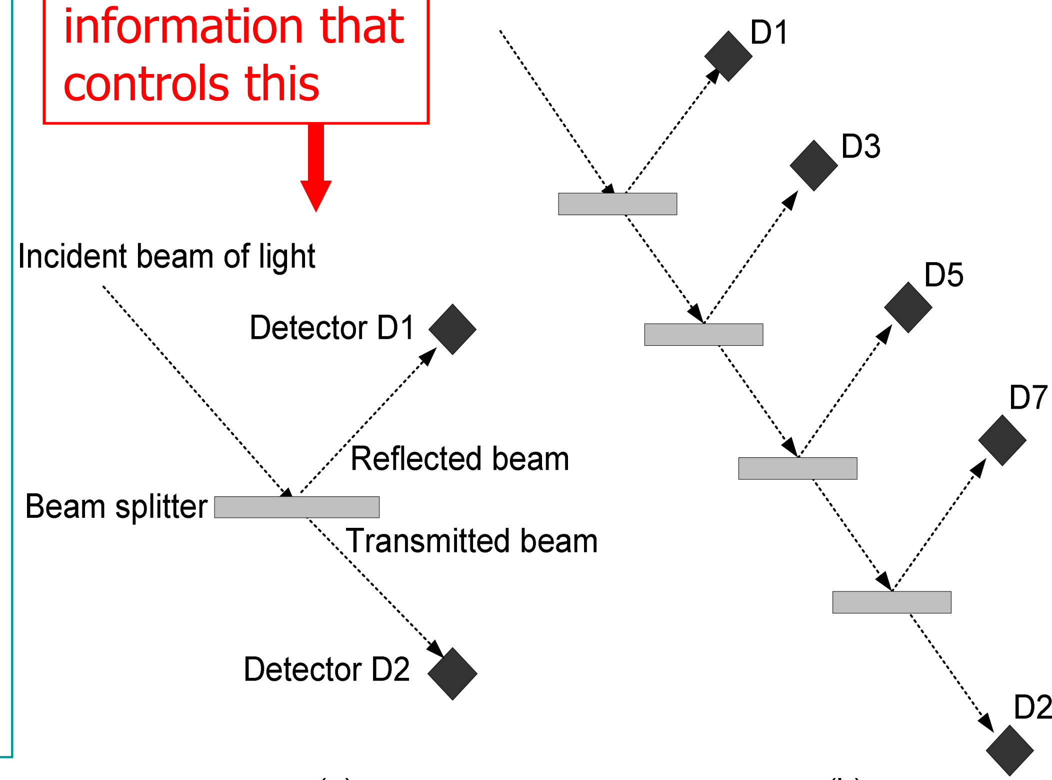
The puzzling nature of light

- If we start decreasing the intensity of the incident light we observe the granular nature of light.
  - Imagine that we send a single photon.
  - Then either detector D1 or detector D2 will record the arrival of a photon.
- If we repeat the experiment involving a single photon over and over again we observe that each one of the two detectors records a number of events.
- Could there be hidden information, which controls the behavior of a photon?
  - Does a photon carry a gene and one with a ``transmit'' gene continues and reaches detector D2 and another with a ``reflect'' gene ends up at D1?

Each detector detects single photons. Why?

What is a hidden information that controls this

In an attempt to solve this puzzle we design this setup

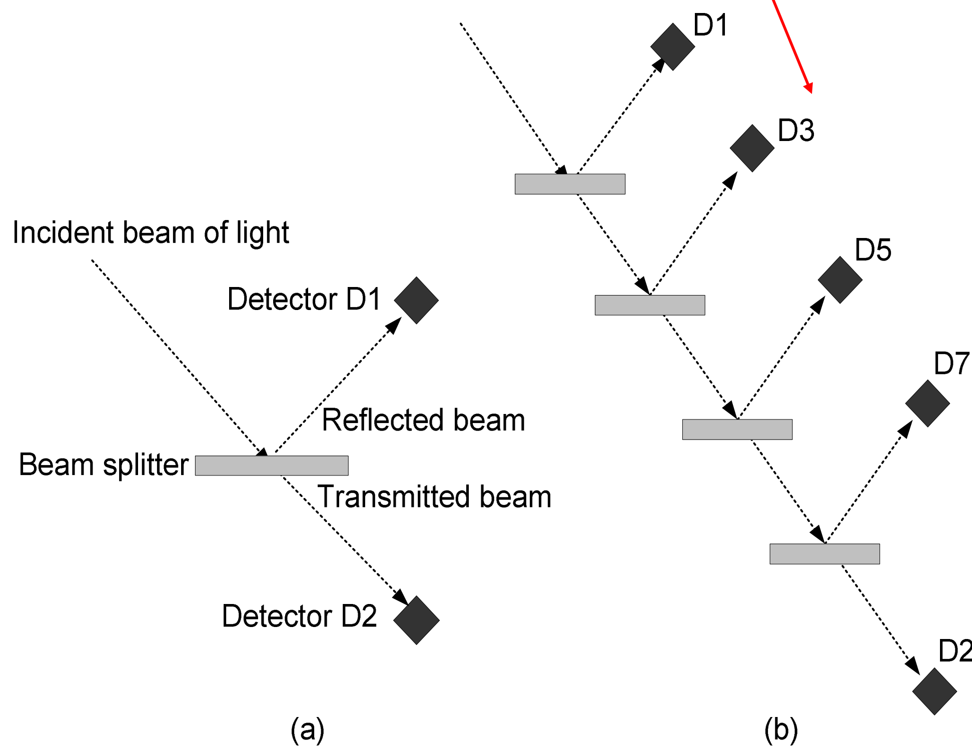


(a) (b)

The puzzling nature of light (cont'd)

- Consider now a cascade of beam splitters.
- As before, we send a single photon and repeat the experiment many times and count the number of events registered by each detector.
- According to our theory we expect the first beam splitter to decide the fate of an incoming photon;
  - the photon is either reflected by the first beam splitter or transmitted by all of them.
- Thus, only the first and last detectors in the chain are expected to register an equal number of events.
- Amazingly enough, the experiment shows that **all the detectors have a chance to register an event.**

Why all these detectors detect light?



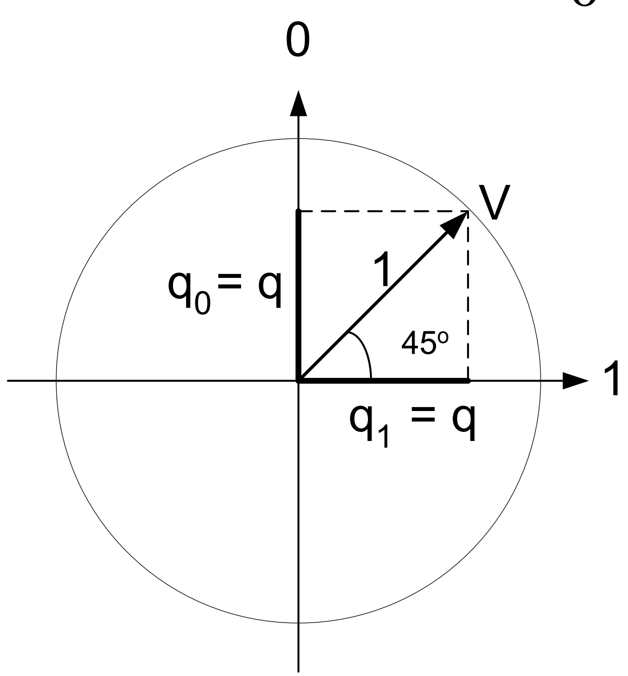
State description

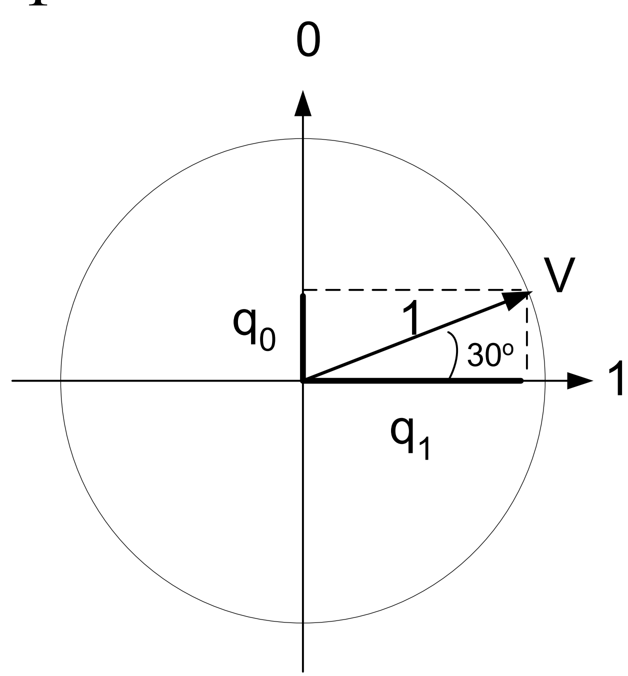
$$|\psi\rangle = \alpha_0|0\rangle + \alpha_1|1\rangle$$

A mathematical model to describe the state of a quantum system

$|\alpha_0, \alpha_1|$ are complex numbers

$$|\alpha_0|^2 + |\alpha_1|^2 = 1$$



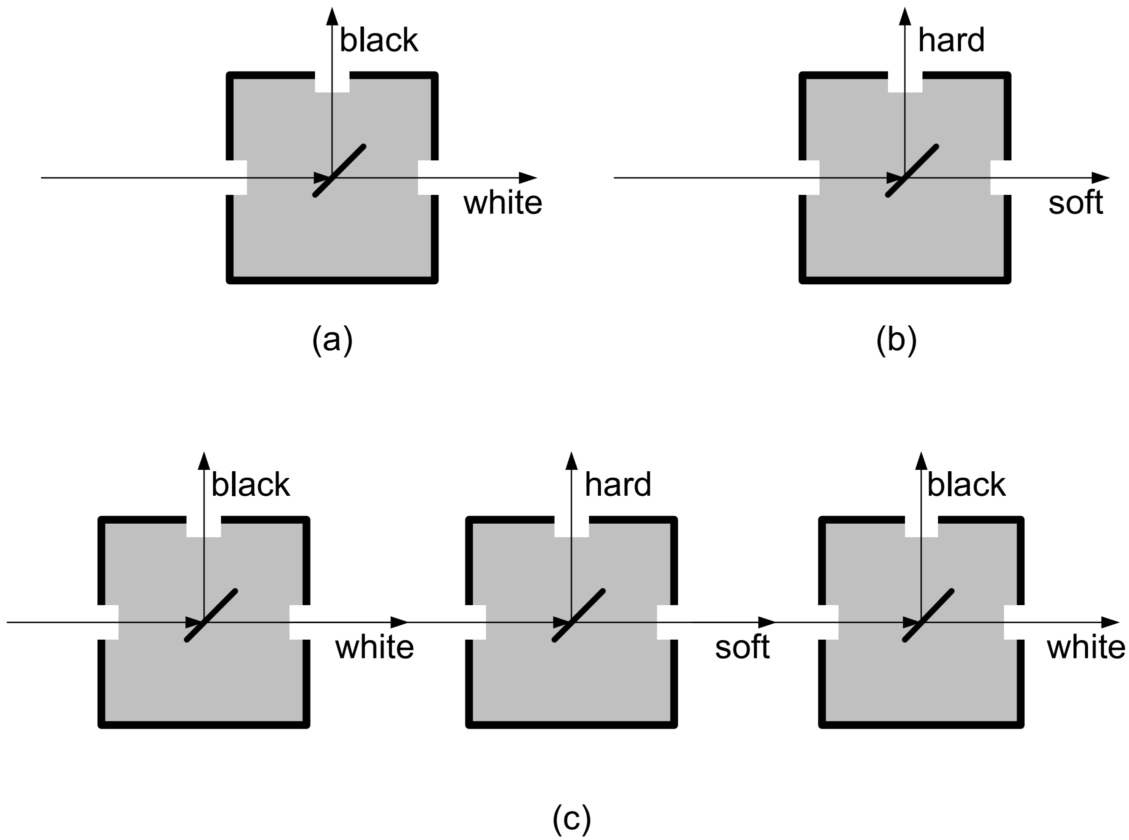


Superposition and uncertainty

- In this model a state $|\psi\rangle = \alpha_0|0\rangle + \alpha_1|1\rangle$ is a superposition of two basis states, "0" and "1"
- This state is unknown before we make a measurement.
- After we perform a measurement the system is no longer in an uncertain state but it is in one of the two basis states.
- $|\alpha_0|^2$ is the probability of observing the outcome "1"
- $|\alpha_1|^2$ is the probability of observing the outcome "0"

$$|\alpha_0|^2 + |\alpha_1|^2 = 1$$

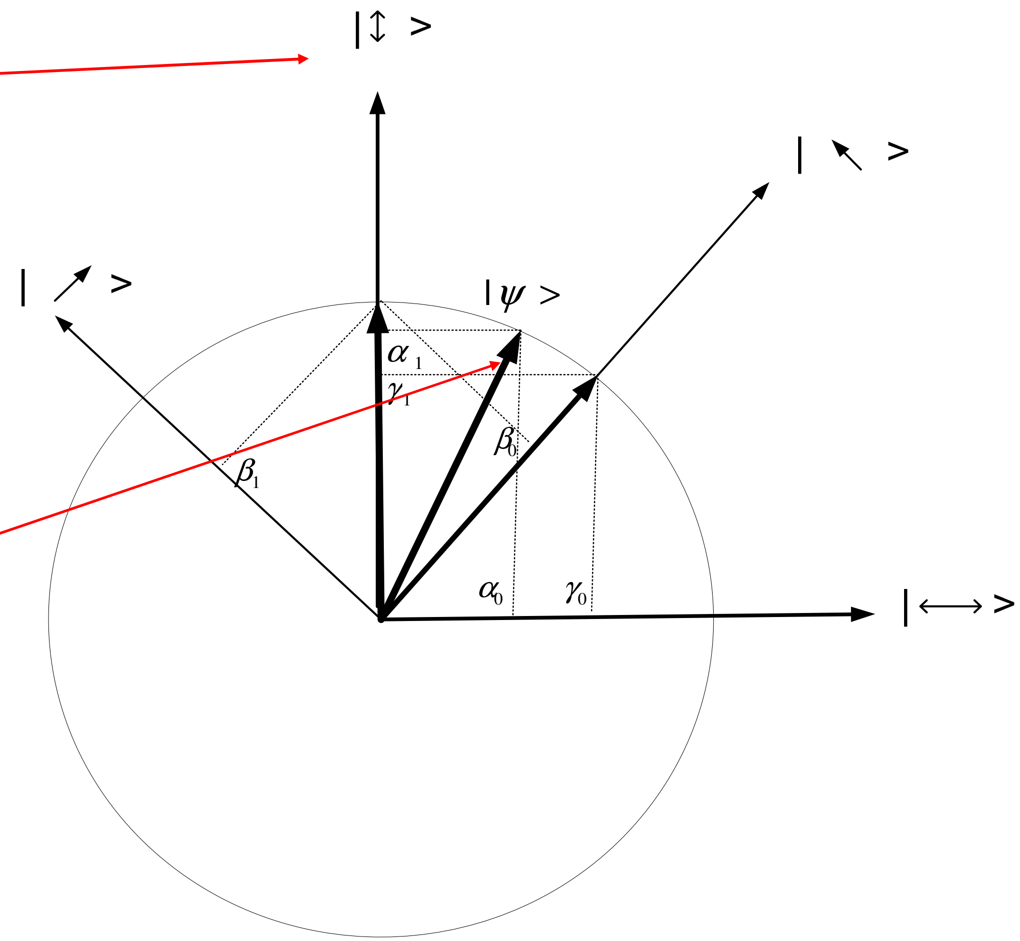
Multiple measurements



Why black appears again in last mirror?

Measurements in multiple bases

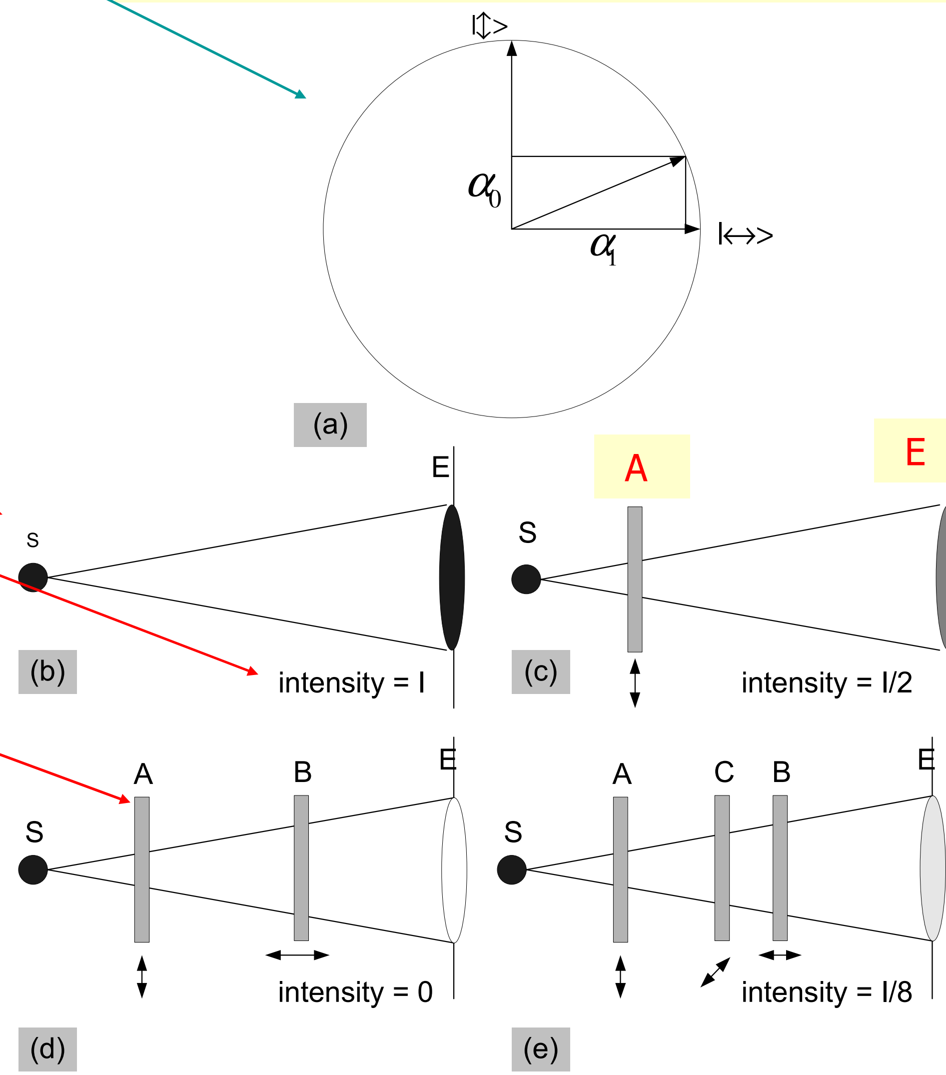
Some of bases



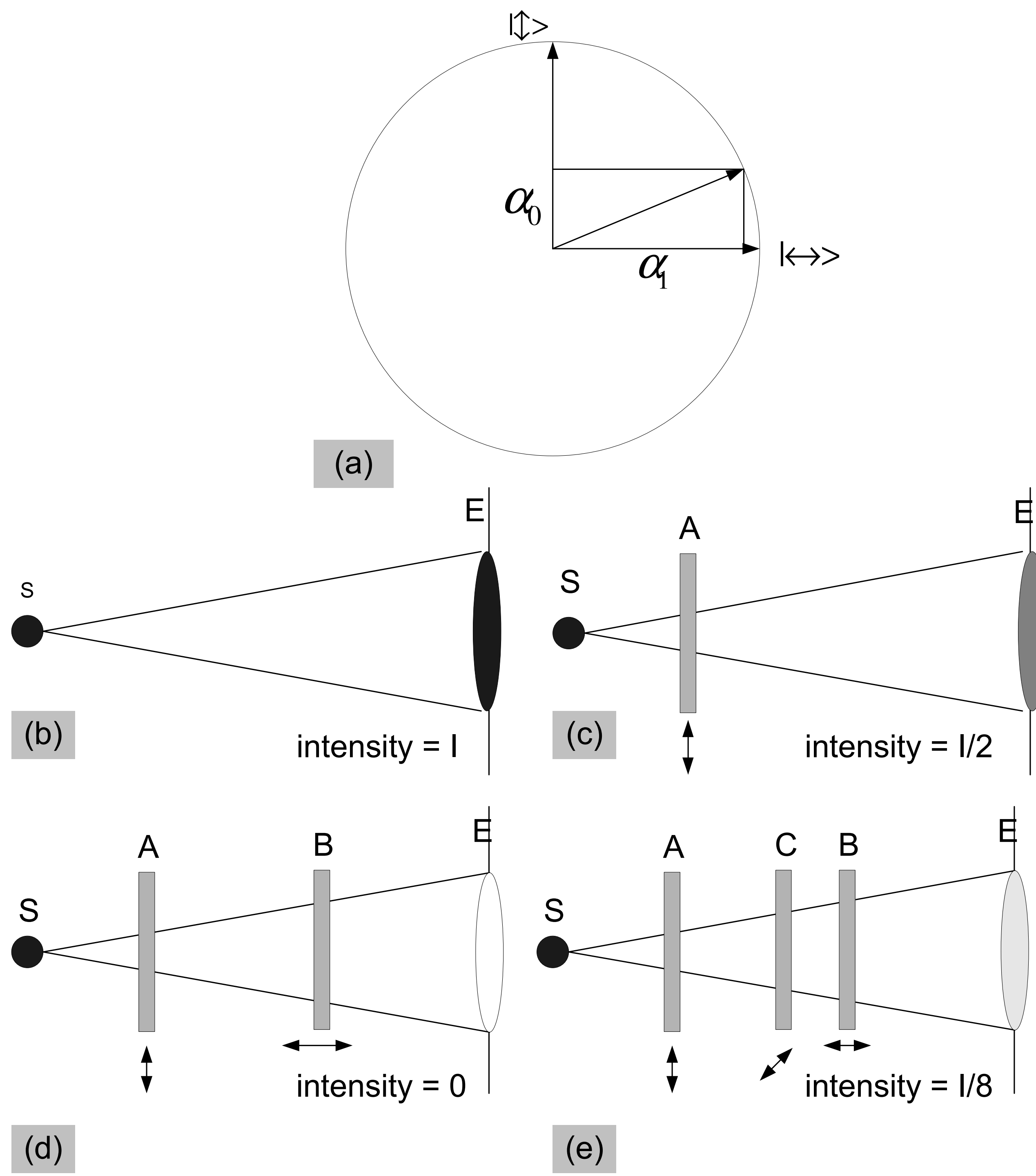
This vector can be measured in different bases

Measurements of superposition states

- The polarization of a photon is described by a unit vector on a two-dimensional space with basis $|0\rangle$ and $|1\rangle$.
- Measuring the polarization is equivalent to projecting the random vector onto one of the two basis vectors.
- Source S sends randomly polarized light to the screen; the measured intensity is I.
- The filter A with vertical polarization is inserted between the source and the screen an the intensity of the light measured at E is about I/2.



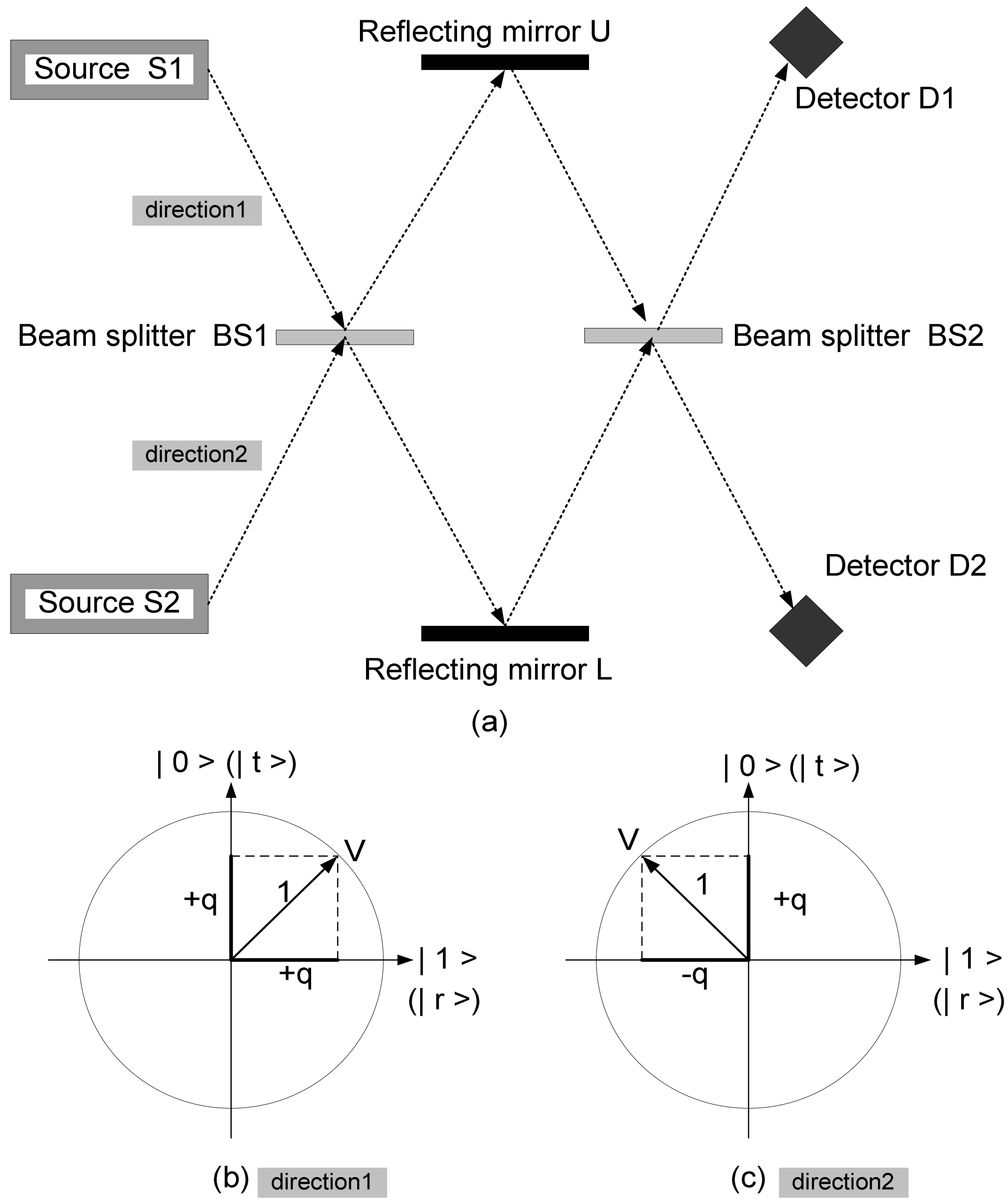
- Filter B with horizontal polarization is inserted between A and E.
  - The intensity of the light measured at E is now 0.
- Filter C with a 45 deg. polarization is inserted between A and B.
  - The intensity of the light measured at E is about 1 / 8.



Measurements of superposition states

The superposition probability rule

- If an event may occur in two or more indistinguishable ways then the probability amplitude of the event is the sum of the probability amplitudes of each case considered separately
  - (sometimes known as *Feynman rule*).


Reflecting mirror U
Source S1
Detector D1
direction1
Beam splitter BS1
Beam splitter BS2
direction2
Detector D2
Source S2
Reflecting mirror L
(a)
| 0 > (| t >)
V
+q
1
+q
| 1 >
(| r >)
| 0 > (| t >)
V
1
+q
-q
| 1 >
(| r >)
(b) direction1
(c) direction2

- In certain conditions, we observe experimentally that a **photon** emitted by S1 is always detected by D1 and never by D2 and one emitted by S2 is always detected by D2 and never by D1.
- A photon emitted by one of the sources S1 or S2 may take one of *four* different paths shown on the next slide, depending whether it is transmitted, or reflected by each of the two beam splitters.

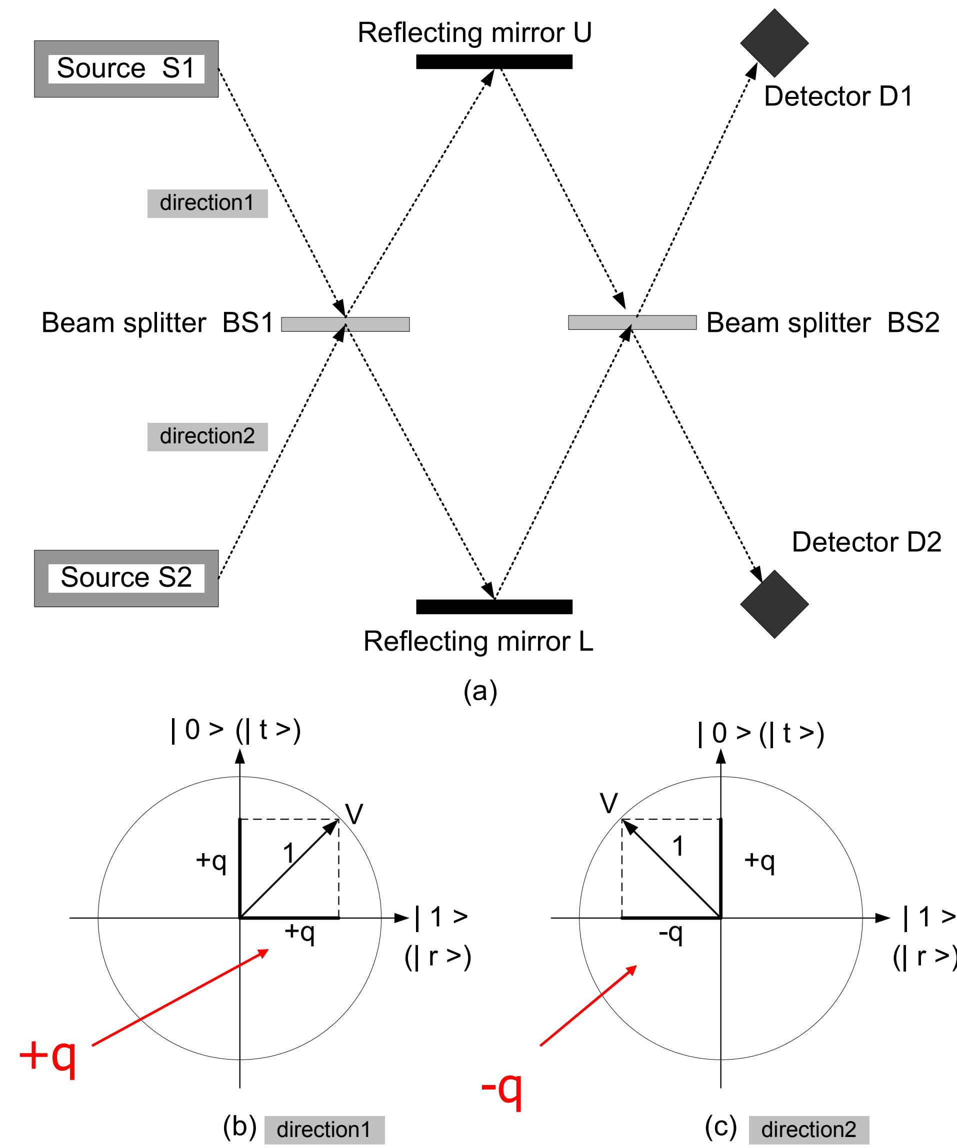
transmit

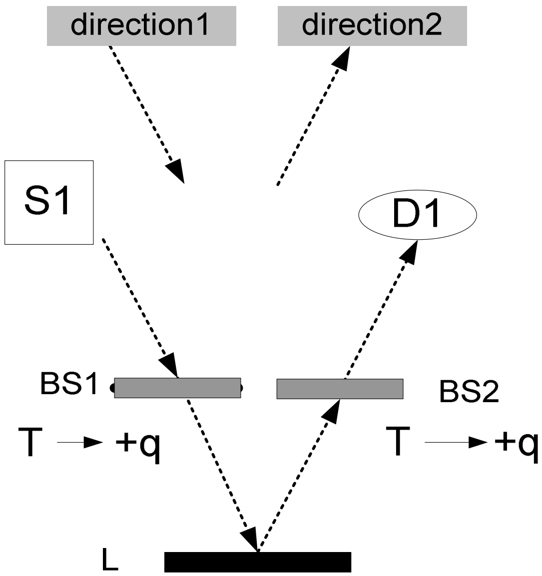
$|0\rangle = |t\rangle$

reflect

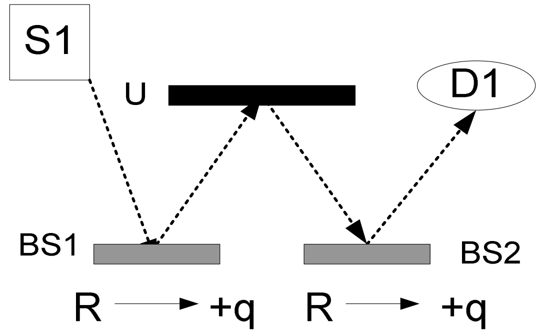
$|1\rangle = |r\rangle$

The experiment illustrating the superposition probability rule



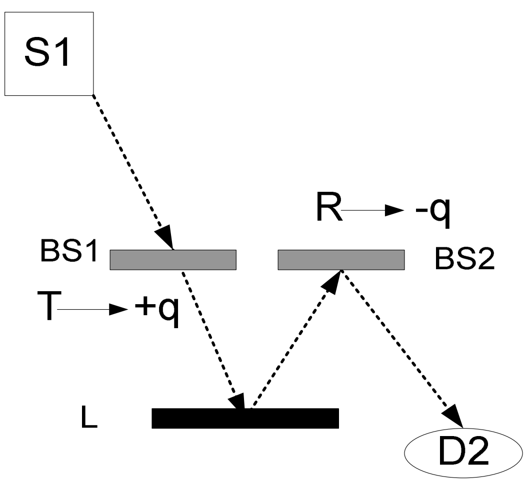


(a) - The TT case: the probability amplitude is (+q)(+q).

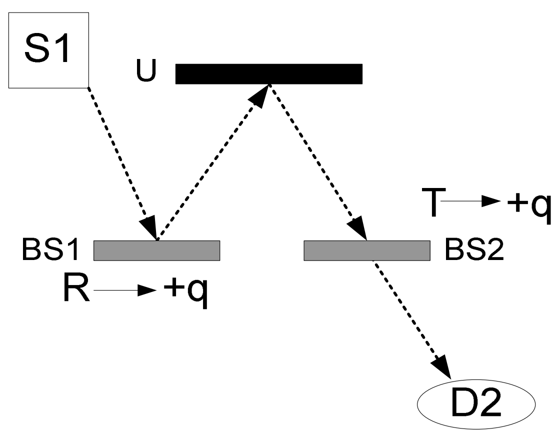


(b) The RR case: the probability amplitude is (+q)(+q).

RR=reflect+reflect



(c) - The TR case: the probability amplitude is (+q)(-q).



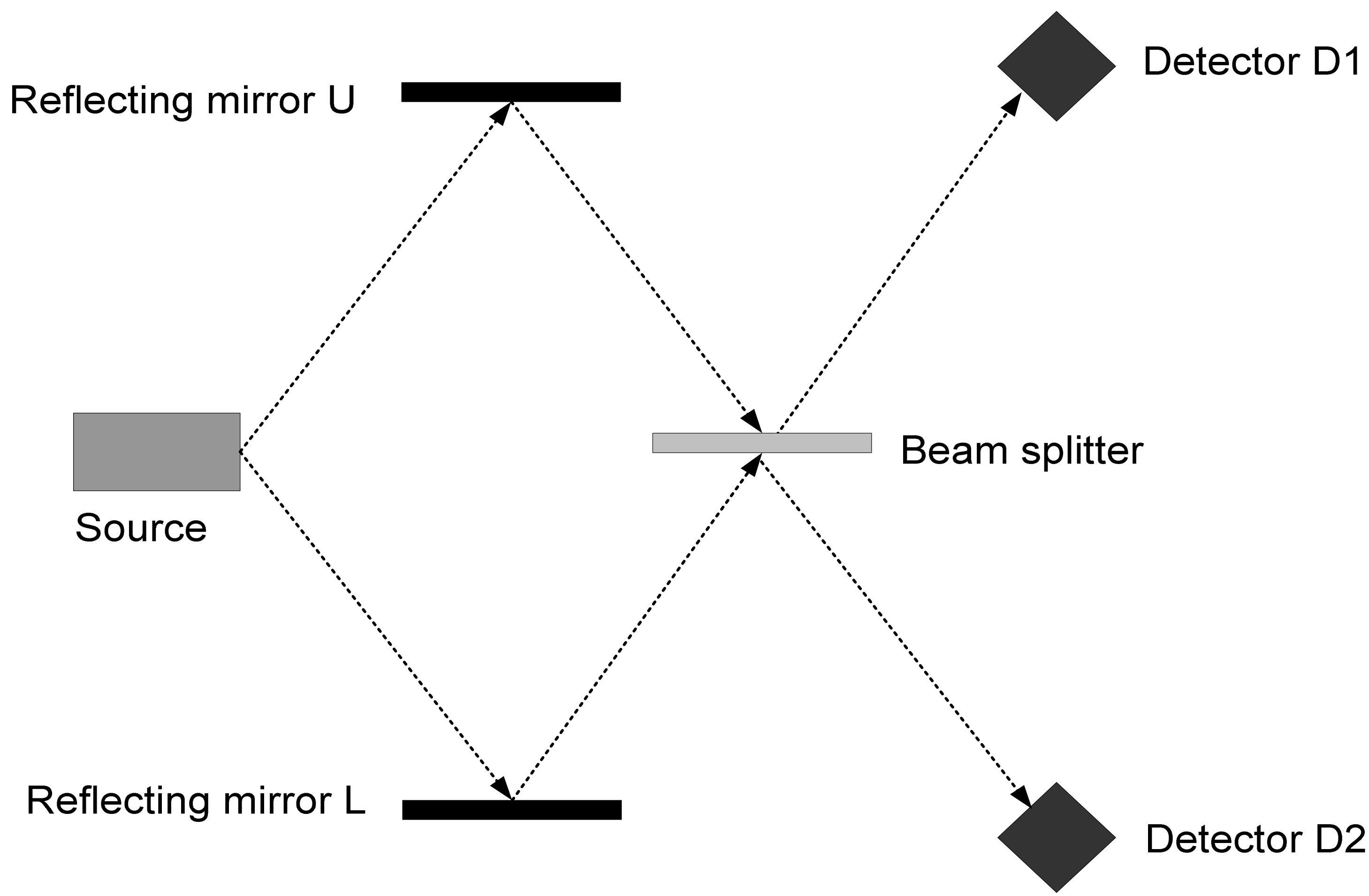
(d) The RT case: the probability amplitude is (+q)(+q).

A photon emitted by one of the sources S1 or S2 may take one of *four* different paths TT. TR, RR and RT, depending whether it is transmitted, or reflected by each of the two beam splitters

photon emitted by S1 is always detected by D1 and never by D2

Why?

A photon coincidence experiment



A glimpse into the world of quantum computing and quantum information theory

- Quantum key distribution
- Exact simulation of systems with a very large state space
- Quantum parallelism