Lecture 40

Fri: Review Final Exam

Final Exam Date: Weds, Dec 13 at 10am

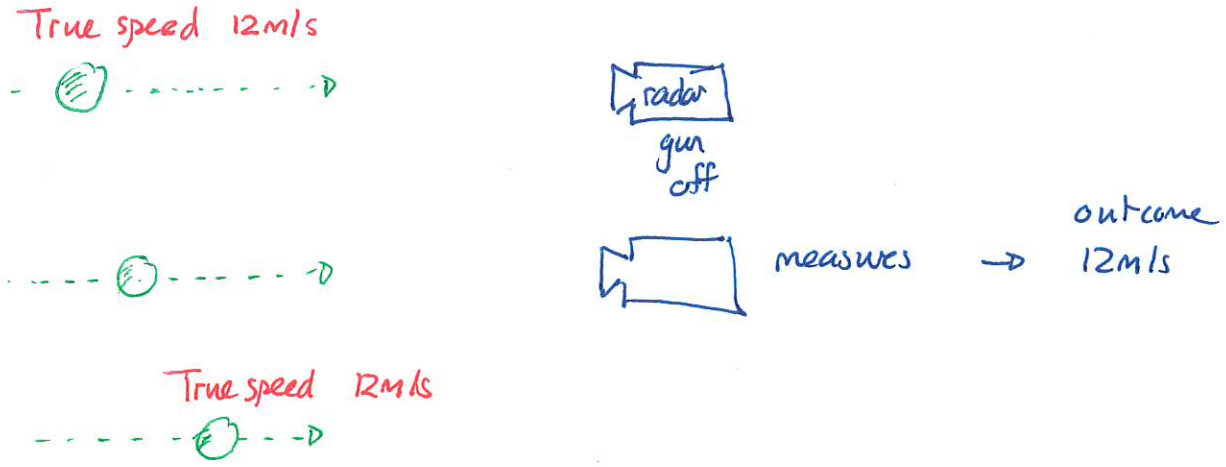
* Comprehensive.

Measurements in quantum physics

In classical physics one can measure any quantity with

* perfect precision
* without affecting the system

For example, we could measure the speed of a moving ball



In general this is not possible in quantum physics. We can explore this in an exercise involving photon measurements.

Phys 100
Fall 2023

SOLUTION

Concepts of Physics: Group Exercise 6

6 December 2023

Names: _____ _____ _____

_____ _____

1 Measurements in quantum physics

In quantum physics choosing to perform a measurement or not can appear to affect the system. This exercise explores this situation for photons passing through an interferometer, which is a device that manipulates light via mirrors and beamsplitters (partially reflective mirrors). One example is illustrated in Figure 1. This consists of two mirrors (M1 and M2), which reflect light along the indicated directions, two beamsplitters (BS1 and BS2) and two detectors (D1 and D2).

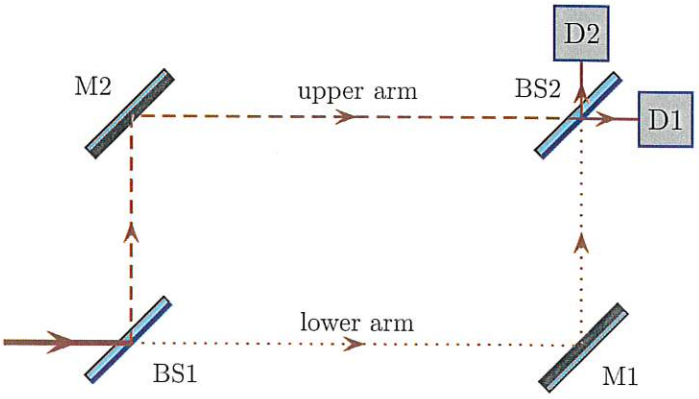


Figure 1: Mach-Zehnder interferometer.

The rules are as follows:

- any photon travels in a straight line until it hits a mirror, beamsplitter or a detector,
- a photon that hits a mirror is reflected at a 90° angle,
- a photon that hits a detector will be detected with certainty and the detector will then signal that it received *one* photon (the other detector signals that it receives no photons),
- a photon that hits a beamsplitter will either be reflected (at a 90° angle) or else transmitted (passing straight through). Each occurs with a 50% probability.

A source sends light, one photon at a time, horizontally from the left toward BS1.

a) Suppose that a photon travels from the left toward BS1. In which arm could it emerge? What are the probabilities that it passes along the upper arm?

b) Suppose that a photon travels along the upper arm toward BS2. At which detector could it arrive? What is the probability that it arrives in D1? And D2?

c) Suppose that a photon travels along the lower arm toward BS2. At which detector could it arrive? What is the probability that it arrives in D1? And D2?

d) Suppose that 4000 photons travel toward BS1. Roughly how many do you expect to emerge in the lower arm versus in the upper arm?

e) Given that 4000 photons travel horizontally toward BS1, roughly how many do you expect to be detected at D1 versus D2?

In an actual experiment of this type where the components are all perfectly aligned, it turns out that every photon that travels horizontally toward BS1 arrives with certainty at D2.

f) Do your conclusions from part d) match those observed in an actual experiment?

Suppose that you want to decide which path each photon takes. This requires a *measurement* that detects which path the photon takes and this can be done (in principle) by inserting detectors that do not destroy or alter the photons into the upper and lower paths. Each detector can register the presence of a photon (at its location) and then lets the photon pass.

g) Suppose that a single photon travels horizontally toward BS1 and is detected in the upper arm. After it is detected it passes toward BS2. The situation is now identical to that where a single photon is fired towards BS2. At which of D1 or D2 do you expect it to arrive?

h) Suppose that a single photon travels horizontally toward BS1 and is detected in the lower arm. After it is detected it passes toward BS2. At which of D1 or D2 do you expect it to arrive?

i) Suppose that 4000 photons travel toward BS1 and there are detectors in either arm. Roughly how many do you expect to be detected at D1 versus D2?

j) Has the action of measuring the path taken by the photon (the upper or lower arm) affected the result of the original experiment? Explain your answer.

a) It could emerge in either
prob upper is 50%

b) It could arrive in either
prob D1 = 50% prob D2 = 50%

c) Same answer as b)

d) Abant 2000 in each.

e) 2000 → 1000 / 1000 ; 1000 / 1000 ; 2000

Abant 2000 in D1
abant 2000 in D2

f) No, actual expt 4000 in D2 0 in D1

g) Either 50% prob each

h) Either 50% prob each

i) Abant 2000 detected in upper → 1000 D1
1000 D2

* same for lower

* combined abant 2000 in D2, 2000 in D1

j) Yes the results of i) are different to f.)

2 Which path?

The same interferometer arrangement from the previous question can be applied to a different issue: "Did any photon that reaches the detectors travel along only one path or not?"

First assume that **BS2 is absent.** Single photons are fired into BS1 as before.

a) Suppose that a photon arrives at D1. Could it have traveled along the upper arm? Could it have traveled along the lower arm?

b) Suppose that a photon arrives at D2. Could it have traveled along the upper arm? Could it have traveled along the lower arm?

c) Experiments show that a single photon will either arrive at D1 or else at D2 but not both. Given that it is eventually detected, can one say with certainty which path it did take? Can one say that it only took one path?

Suppose that **BS2 is present.** Experiments indicate that all photons arrive at D2.

d) Is it possible to say, when BS2 is present, that a single photon definitely traveled along the upper arm? Is it possible to say that it definitely traveled along the lower arm? Can one say that the photon only took one path?

e) How does answer to the question "Did any photon that reaches the detectors travel along only one path or not?" depend on whether BS2 is present or not?

a) Yes it must have traveled along upper. Could not along lower.

b) No impossible to have traveled along upper. Must have along lower.

c) Yes. If it arrived at D1 must have used upper
If it arrived at D2 " " used lower
Only one of these is possible and so it only used one path.

d) If it did travel along upper it could emerge in D1 or D2 but D1 is impossible. So we cannot say it definitely traveled along upper. Same for lower. We cannot say it took one path.

e) Without BS2 — can say it took one path
With BS2 — cannot say it took one path.