# Elitzur-Vaidman Bomb summary and its consequences

Juan Gonzalez De Mendoza
Physics Department, University of Texas at Austin

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## 1 Introduction

In this paper I will be reviewing "Quantum Mechanical Interaction-Free Measurements" by Avshalom C. Elitzur and Lev Vaidman, and its implications on the Copenhagen interpretation. In their paper, they propose an experiment which effectively detects the presence of an object blocking a photon's path without interacting with said object. What is also very convenient about this idea is that it requires very basic math and quantum physics knowledge to understand, yet it has great implications on our understanding of locality.

## 2 Building a Math Framework

As they do in their paper, lets define the eigenstate of a photon moving to the right as $|1\rangle$ and a photon moving upwards as $|2\rangle$.
If a photon is moving to the right and hits a mirror it is redirected upwards, and if its moving upwards it will be redirected towards the right. We also have to take into account that a reflected wave gains a phase shift of $\frac{\pi}{2}$.The equations that describe this are as follows

$$|1\rangle \xrightarrow{\text{mirror}} i\,|2\rangle \tag{1}$$

$$|2\rangle \xrightarrow{\text{mirror}} i\,|1\rangle \tag{2}$$

The other way we will interact with the photons in this experiment is with 50/50 beamsplitters. Any photon that goes through a beamsplitter will be put in an equal super position of being reflected like above, and remaining unchanged

$$|2\rangle \xrightarrow{50/50} \frac{1}{\sqrt{2}}[|2\rangle + i\,|1\rangle] \tag{3}$$

$$|1\rangle \xrightarrow{50/50} \frac{1}{\sqrt{2}}[|1\rangle + i\,|2\rangle] \tag{4}$$

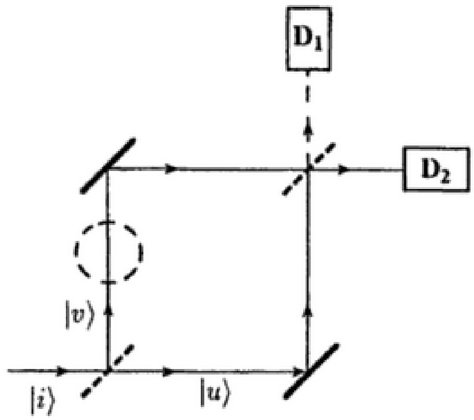


Figure 1: Experimental setup for Interaction-Free measurement. It involves a source of photons, two mirrors, two 50/50 beam-splitters, two detectors(D1 and D2) and any object to obstruct the path $|v\rangle$

## 3 The Experiment

Lets construct an arrangement of two mirrors, two beamsplitters, a photon source and two detectors as shown in Figure 1. The circle represents the object that can be chosen to block the photon's path. The detectors are placed such that if both paths are clear, both paths destructively interfere at D2, but don't at D1. As a consequence, D1 is able to detect all photons, but D2 can only detect photons if one of the paths is obstructed and thus eliminating the interference.

To make it more clear, after a photon goes through our system there are three possibilities:
1) No detector clicks: In this case, the photon did not make it to any detector, which means it was scattered by the object.
2) Detector D1 Clicks: D1 clicks no matter which path the photon takes, so this gives us no information.
3) Detector D2 clicks: As stated before, due to destructive interference, the only way for a photon to reach this detector is if there is an object blocking path $|v\rangle$.

Lets analyze these outcomes carefully. In the first case we obtain information, the object has to be blocking path $|v\rangle$ and the photon interacted with it. In the second case we obtain no information as this can happen with or without the obstruction. In the third case, we can conclude that the object is blocking path $|v\rangle$, but how is this different from the first case? For the photon to reach D2 with the object in place, it must go through path $|u\rangle$ and be reflected by the second beamsplitter. This means we were able to tell if an object was present in our experiment without interacting with it in any way.

Figure 2: The bomb on the left is real, a single photon hitting the detector depicted in orange will set it off. On the right we can depicted a counterfeit bomb, photons can go through it without setting the bomb off.

### 3.1 Quantum Mechanical Formalism

Lets discuss the quantum mechanics math in these scenarios. If the object was absent, the evolution of the photon would go as follows

$$|1\rangle \rightarrow \frac{1}{\sqrt{2}}[|1\rangle + i\,|2\rangle] \rightarrow \frac{1}{\sqrt{2}}[i\,|2\rangle - |1\rangle] - \frac{1}{2}[|1\rangle + i\,|2\rangle] \rightarrow -\,|1\rangle \tag{5}$$

In this case as explained in the previous section we can only reach detector D1. In the case that the object is present we describe the evolution as

$$|1\rangle \rightarrow \frac{1}{\sqrt{2}}[|1\rangle + i\,|2\rangle] \rightarrow \frac{1}{\sqrt{2}}[i\,|2\rangle + i\,|scattered\rangle] \rightarrow \frac{i}{2}[i\,|2\rangle - |1\rangle] + \frac{i}{\sqrt{2}}\,|scattered\rangle \tag{6}$$

Where scattered is the state where the photon interacts with the object. If we square these amplitudes we obtain the probabilities
P($|2\rangle$)=P(D2 Clicks) $= \frac{1}{4}$
P($|1\rangle$)=P(D1 Clicks) $= \frac{1}{4}$
P($|scattered\rangle$)=P(No clicks) $= \frac{1}{2}$
Which means we can successfully obtain interaction-free information with $\frac{1}{4}$ probability. The experiment can be tweaked to obtain a higher probability by changing the transmission/reflection ratio of the beamsplitters, but this will not be discussed in this summary.

# 4 Elitzur-Vaidman Bomb

The authors on the paper suggest considering this experiment in a specific scenario to better illustrate its capabilities. Lets say we have a stock of bombs where some of them are real, and some are counterfeits. The real bombs have a photon detector, if a single photon hits this piece, the bomb explodes. The counterfeit lacks the detector, so a photon can go through the bomb and nothing will happen.

It is possible to direct light at a bomb, and if it explodes it was real. If it doesn't, it was a counterfeit. Due to the bomb's design, it seems impossible to know which bombs are real without destroying them first, and it is, at least under classical physics. However quantum physics has a different answer for this.
We place the bomb in our experiment, to obstruct path $|v\rangle$ in such a way that the photon would hit the sensor if the bomb is real, or go through it and hit a detector if it is fake. Here there are two possibilities either the bomb explodes, or one of our detector clicks. If D2 clicks, this means the bomb's sensor is blocking the path, and therefore is real. This allows us to ensure a bomb is real without setting it off!

# 5 Conclusion

The idea of obtaining information about a system without interacting with it would have never crossed a physicist's mind before the quantum revolution. Even after quantum mechanics was born, phenomena like entanglement allowed us to obtain instantaneous information about another particle without interacting with it. The difference is that for entangled systems, you would need to already have some knowledge about the system, for example you must know that the particle is entangled. In this paper, an idea is presented where it is shown to be possible to learn about a system, without any previous knowledge about it.
The Copenhagen interpretation is centered around "The measurement" part of the experiment. For a long time physicists backed this interpretation as it is intuitive to think that by measuring a system, we are altering it, and therefore changing its state. Through the idea presented in this paper we now know we are able to measure the state of a system without interacting with it at all. This means that instead of a bomb we can place a particle in a superposition of blocking path $|v\rangle$ and not blocking path $|v\rangle$. Run this experiment, and successfully collapse the wavefunction of such particle without interacting with it at all. It shows us that the "collapse" of a wavefunction is something much deeper than what we thought, which can be collapsed instantaneously from light years away, without interacting with it in the present or past(just like entanglement does). In the many worlds interpretation, this means that every time we run the experiment with a real bomb, it explodes in a timeline, but not in the other. Whatever interpretation you may believe in, this experiment shows us that ideas that once could have been deemed impossible, can be possible later on, as we try to understand our universe further.