Michelle Chen Einstein’s Dice

11/19/17 Final Paper Outline

Looking For Luck: Copenhagen Quantum Concepts Behind Interaction-Free Measurements

There are many essential principles of quantum mechanics that are used to construct

interaction-free measurements. Proposed in 1993 by Avshalom C. Elitzur and Lev Vaidman, the

concept of interaction-free measurement allows one to detect an object’s location without any

particle interacting with the object, unlike classical methods of measurement.[[1]](#footnote-1) Though

interaction-free measurement is able to detect the existence of an unstable system without

disturbing its internal quantum state[[2]](#footnote-2), collapse, or the moment when multiple unpredictable

possibilities represented by a quantum entity’s wave function collapse and force the entity into a

single possibility upon measurement, still occurs. This demonstrates a new aspect to the

classical Copenhagen theory of quantum mechanics, proving that physical interaction is not

necessary for collapse to happen and a possibility to be selected from an uncertain array of

unpredictable possibilities. While interaction-free measurement introduces this new element of

interaction-free collapse to the Copenhagen theory, certain pillars of the Copenhagen theory such

as non-locality and the nature of wave functions and collapses are still especially prominent and

useful in explaining interaction-free measurement. [[3]](#footnote-3) Many experiments exist that illuminate

these quantum principles behind interaction-free measurement as well as the element of chance

behind this type of measurement’s success and efficiency. This sets it apart from classical, non-

quantum-mechanical methods of measurement and prevents this type of measurement from

being used outside of certain specialized situations. However, using the quantum Zeno effect,

physical devices that allow interaction-free measurement can be built so that the probability of

success for each interaction-free measurement increases. This makes more efficient and accurate

measurements possible using this useful technique, which has fascinating implications for fields

such as medicine, imaging quantum objects, and the demonstration of quantum effects on the

macroscopic scale.[[4]](#footnote-4) Copenhagen ideas and interaction-free measurement greatly inform each

other and by thinking about each through the lens of the other our understandings of quantum

mechanics and interaction-free measurement’s processes can improve.

In Copenhagen thinking, non-locality is highly suggested and plays a large role in

distinguishing the concepts of classical quantum mechanics from classical physics. This concept

is also a strong construction behind interaction-free measurement as all interaction-free

measurements are implied to be non-local. Locality is the concept that events cannot have

instantaneous effects at a distance or effects that propagate faster than light[[5]](#footnote-5) but through

interaction-free measurement, one can instantaneously know the position or path of a particle and collapse

the wave function, or the superposition of all the possible outcomes, without interacting with the particle

locally.[[6]](#footnote-6) Interaction-free measurement thus violates locality just as the Copenhagen quantum

interpretation does, since information can be gained despite a complete lack of local interaction. In this

way, it is possible to confirm the existence of an object in a given region of space beyond a doubt even if

no particles or photons, the most basic quantum particle of light, bounce off it. While classical methods of

measurement require the contact of least one particle for observation, such as a photon bouncing off it to

the eye or a detector,[[7]](#footnote-7) the Copenhagen theory’s violation of locality lends support to quantum interaction-

free measurement.

One example of the important concept of nonlocality in interaction-free measurements is

the Renninger negative-result thought experiment. A single photon is emitted and hits a fifty-

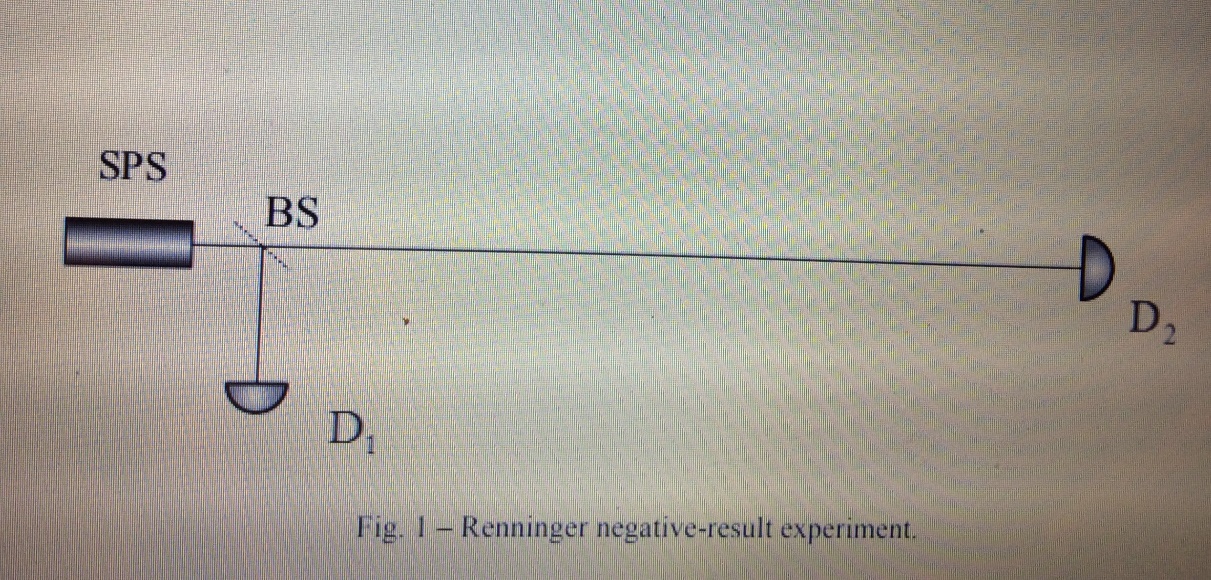
percent beam splitter where there is an equal chance of traveling along either path. One of the

paths is shorter than the other, there are detectors at the ends of both paths, and only the results

of the first and closest detector are measured. If the photon is detected by the detector on the

shorter path, it is not an interaction-free measurement as the detector interacts with the photon.

However, if the photon is not detected by the first detector after the expected period of time

Cardoso, A., Cordobil, J.L., and Croca, J.R. (2015), “Interaction-Free Measurements: A Complex Nonlinear Explanation,” *University of Lisbon*, pp. 2, http://arxiv.org/ftp/arxiv/papers/1501/1501.01993.pdf.

within which it might hit the first detector, the probability wave collapses and the location of the

photon is certain to be heading along the second path toward the other detector no matter how

much further away the second detector is. Since there is a collapse of the wave function without

any detection, it is called a “negative” measurement. There is a fifty-percent likelihood that the

measurement will succeed in being interaction-free as in this thought experiment, the detectors

are assumed to be a hundred percent efficient.[[8]](#footnote-8) In this example, non-locality plays a prominent

role and lens for the concept of interaction-free measurement as certain information is gathered

about the photon’s path without any local interaction at all. In this case, the photon is shown to

have traveled along the longer path without a doubt when the first detector measures nothing

within the time period for a photon to be detected if it had traveled along the shorter path. The

collapse of the probability wave occurs in the moment when either nothing or something is

detected by the first detector. In fifty percent of the cases, where the photon travels the longer

path, simply measuring the closer detector’s lack of a measurement will ascertain the path of the

photon.[[9]](#footnote-9) The essence of interaction-free measurement is the fact that collapse can occur and a

possibility be selected even without local interaction with the measured particle, which

contradicts classical physics but is supported by the Copenhagen theory’s own non-locality. This

demonstrates the importance of non-locality in constructing and understanding interaction-free

measurement.

Another aspect of Copenhagen quantum mechanics that aids the process of

understanding interaction-free measurement is the nature of wave functions and collapse. In the

Elitzur-Vaidman bomb-testing thought experiment, a light source emits one photon at a time

toward a Mach-Zehnder interferometer, where it hits a beam splitter and recombines at a second

beam splitter that sends the photon to one of two detectors. The two paths are of equal length and

one detector shows constructive interference while the other shows destructive interference,

which means that normally it will never detect a photon.[[10]](#footnote-10) When an object, or a bomb that goes

off upon classical observation through bouncing a single particle off it, is placed in one path,

there is up to a fifty percent chance the photon does not hit the object and continues so there is no

interference at the second splitter.[[11]](#footnote-11) There, the photon now makes a random choice, so that it is a

possibility that the photon will travel to the detector that had previously never received a photon

when there was no bomb in one of the paths.[[12]](#footnote-12) The interaction-free measurement is made during

the occasional times the photon goes to the detector that usually detects destructive interference

as it is only possible for that to happen with an object in a path. It is interaction-free because the

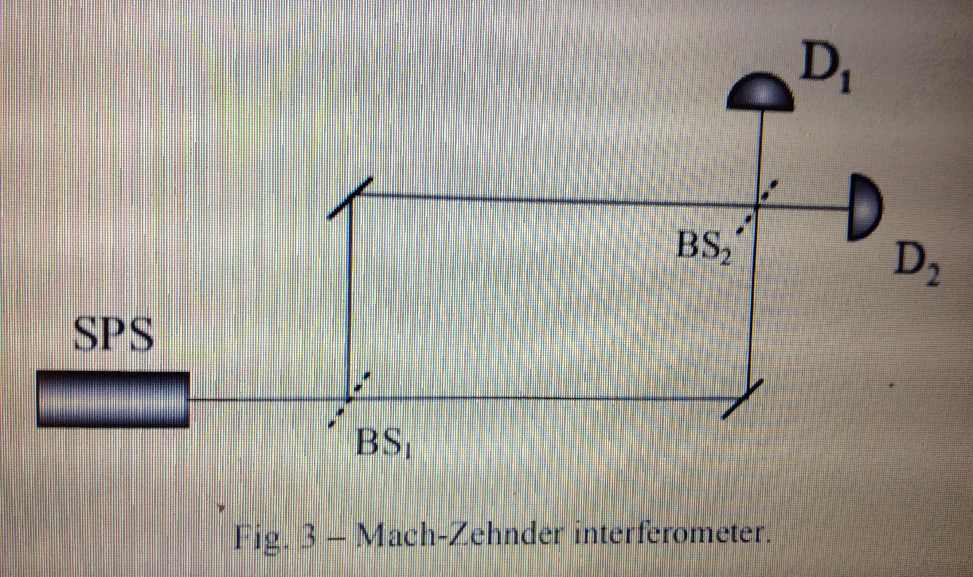
photon can only go one path and never touched the object in this situation yet determined its

presence, or otherwise found a bomb without it going off.[[13]](#footnote-13) Interaction-free measurement is

shown through this experiment to use the same definitions of wave functions and collapse as the

Copenhagen theory. In Copenhagen theory, a wave function is the concept of the quantum state

as a mathematical object that represents the states of physical systems[[14]](#footnote-14),where an unobserved



Cardoso, A., Cordobil, J.L., and Croca, J.R. (2015), “Interaction-Free Measurements: A Complex Nonlinear Explanation,” *University of Lisbon*, pp. 2, http://arxiv.org/ftp/arxiv/papers/1501/1501.01993.pdf.

quantum entity exists in a superposition of all the possible states permitted by its wave function.

This overlap of possibilities only exists until a measurement is made that is capable of

distinguishing these states, at which point the wave function collapses and the entity is forced

into a single state.[[15]](#footnote-15) As a result, Copenhagen quantum mechanics legitimizes interaction-free

measurement as a form of measurement in interaction-free measurement’s ability to cause

collapse. Additionally, because of interaction-free measurement’s unique ability to collapse a

wave function without any physical or local interaction, it adds a previously undemonstrated

dimension to the Copenhagen concept of collapse, proving that the selection of a single

possibility is not dependent on the physical interaction that defines classical measurement

techniques. Overall, interaction-free measurement has both roots in Copenhagen wave function

theories and influence over the evolution of Copenhagen interpretations of collapse.

Beyond thought experiments, interaction-free measurement is highly useful when its

efficiency is improved using the quantum Zeno effect. Experimentally, there is an inherent

element of chance behind interaction-free measurement: only up to fifty percent of

measurements in a real-world Mach-Zehnder interferometer can be made interaction-free without

the quantum Zeno effect.[[16]](#footnote-16) However, the usefulness of modified interaction-free measurement

has been realized. This was originally demonstrated in the quantum Zeno thought experiment

using devices that rotate the polarization of a horizontally polarized photon 15 degrees, where

after passing through six the photon’s polarization changes from horizontal to vertical and is then

absorbed by the final horizontal polarizer, never arriving at the detector. If a horizontal polarizer

is placed after each rotator, the chance that the photon will become absorbed in the first polarizer

is very small, and if it passes it returns to horizontal polarization as that is the only possible state

for light that passes a horizontal polarizer. The process repeats, with the probability of the photon

being transmitted all the way through increasing by increasing the number of rotators and

decreasing the angles of each rotator accordingly: with an infinite number of stages, the photon

would always get through, and the rotation would have been completely inhibited. By

repeatedly not measuring a quantum system, its time evolution can be halted, and with an infinite

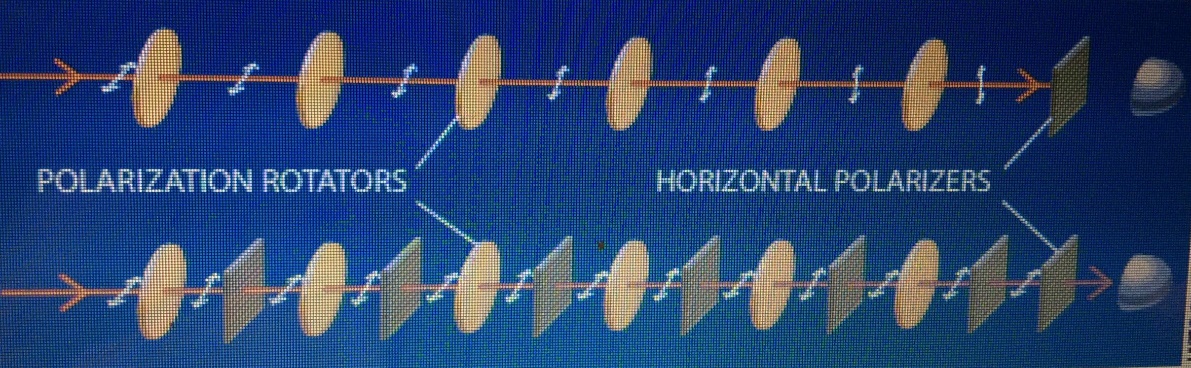
number of rotators and polarizers, the state of the photon remains the same indefinitely.[[17]](#footnote-17) An

efficient experimental system has been created for interaction-free measurement that optimizes

the quantum Zeno effect. A polarizing beam splitter and polarization rotator are used along with

mirrors that can be rapidly switched on and off for a horizontally polarized photon to pass

through the system for a few cycles. When an object is placed in the vertical polarization path, it

is similar to the insertion of polarizers after each rotator in the quantum Zeno thought

Kwiat, P., Weinfurter, H., and Zeilinger, A. (November 1996), “Quantum Seeing in the Dark,” *Scientific American*, Vol. 275 (No. 5), pp. 73, http://jstor.org/stable/24993449.

experiment, where the chance of the photon entering the vertical polarization path and hitting the

object is low and the photon typically becomes reset to its initial horizontal polarization. While

without the object the leaving photon is vertical, the presence of an object is shown when the

leaving photon is horizontal. By using more cycles, the probability that the photon is absorbed by

the object can be made as small as possible, and it is more likely for the interaction-free

measurement to be performed correctly[[18]](#footnote-18). When interaction-free measurement works, it works

completely by confirming an object’s path or existence without any doubt.[[19]](#footnote-19) Because of the

quantum Zeno effect greatly increasing the probability of success, interaction-free measurement

could potentially be useful for photography without light exposure, medical imaging without x-

ray exposure, imaging ultra-cold atom clouds, and create quantum objects at the macroscopic

scale[[20]](#footnote-20). In this way, interaction-free measurement brings the Copenhagen quantum mechanical

concepts of non-locality, wave functions, and collapse to practical use in the macroscopic world.

Once thought to be impossible, interaction-free measurement is a method that has both

practical and theoretical impacts. Principles from the Copenhagen theory of quantum mechanics

that are used to construct interaction-free measurement include non-locality and the nature of

wave functions, but interaction-free measurement also uniquely informs Copenhagen notions of

collapse by demonstrating that collapse can occur without local or physical interaction. The

Renninger negative-result and Elitzur-Vaidman bomb-testing thought experiment especially

illuminate interaction-free measurement’s solid grounding in these principles. While these

thought experiments demonstrate how chance is a factor behind the efficiency and success of

interaction-free measurement as opposed to classical measurement, the quantum Zeno effect can

greatly increase the probability of a successful interaction-free measurement. Through

experimental devices that utilize the quantum Zeno effect, interaction-free measurement can be

developed to the point where it could have many efficient uses and advantages over classical

methods of measurement such as its complete accuracy when used successfully and its versatility

in different scientific fields. Overall, interaction-free measurement’s basis in ideas of

Copenhagen quantum theory allows us to clarify other aspects of the Copenhagen premise such

as the nature of collapse. Ultimately, the impact of the quantum Zeno effect on the efficiency of

interaction-free measurement allows us to bring the most theoretical aspects of Copenhagen

quantum mechanics into the experimental world.

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19. Ibid., 74. [↑](#footnote-ref-19)
20. Ibid., 77-78. [↑](#footnote-ref-20)