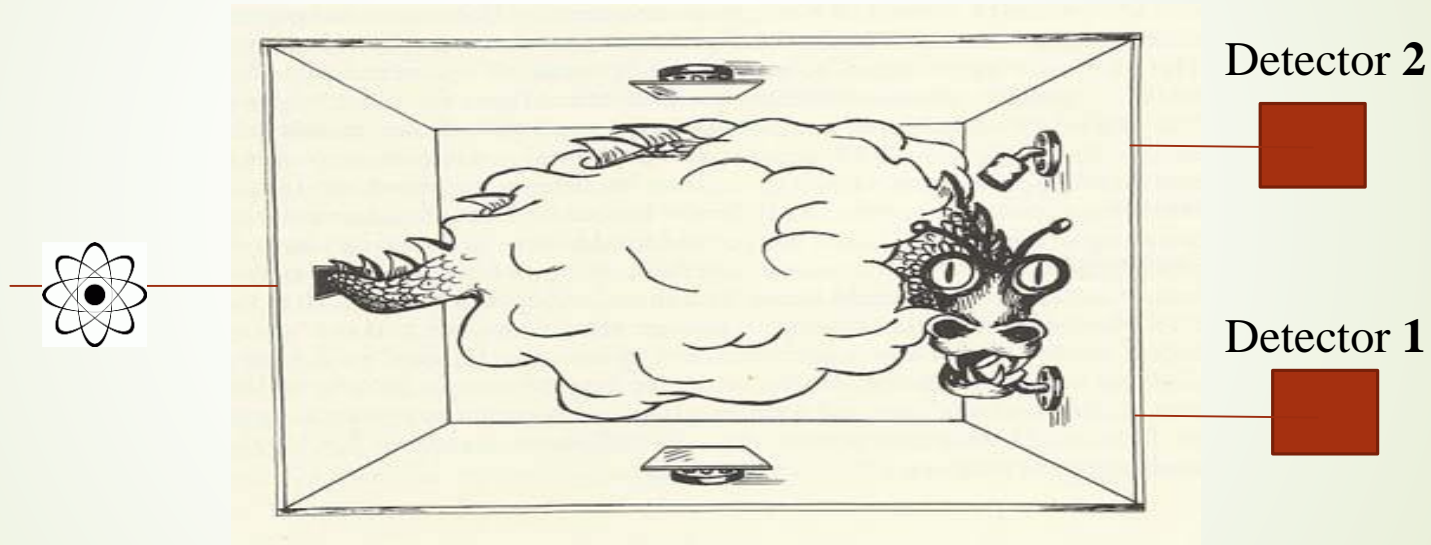


What is there inside of “*the great smoky dragon*”?



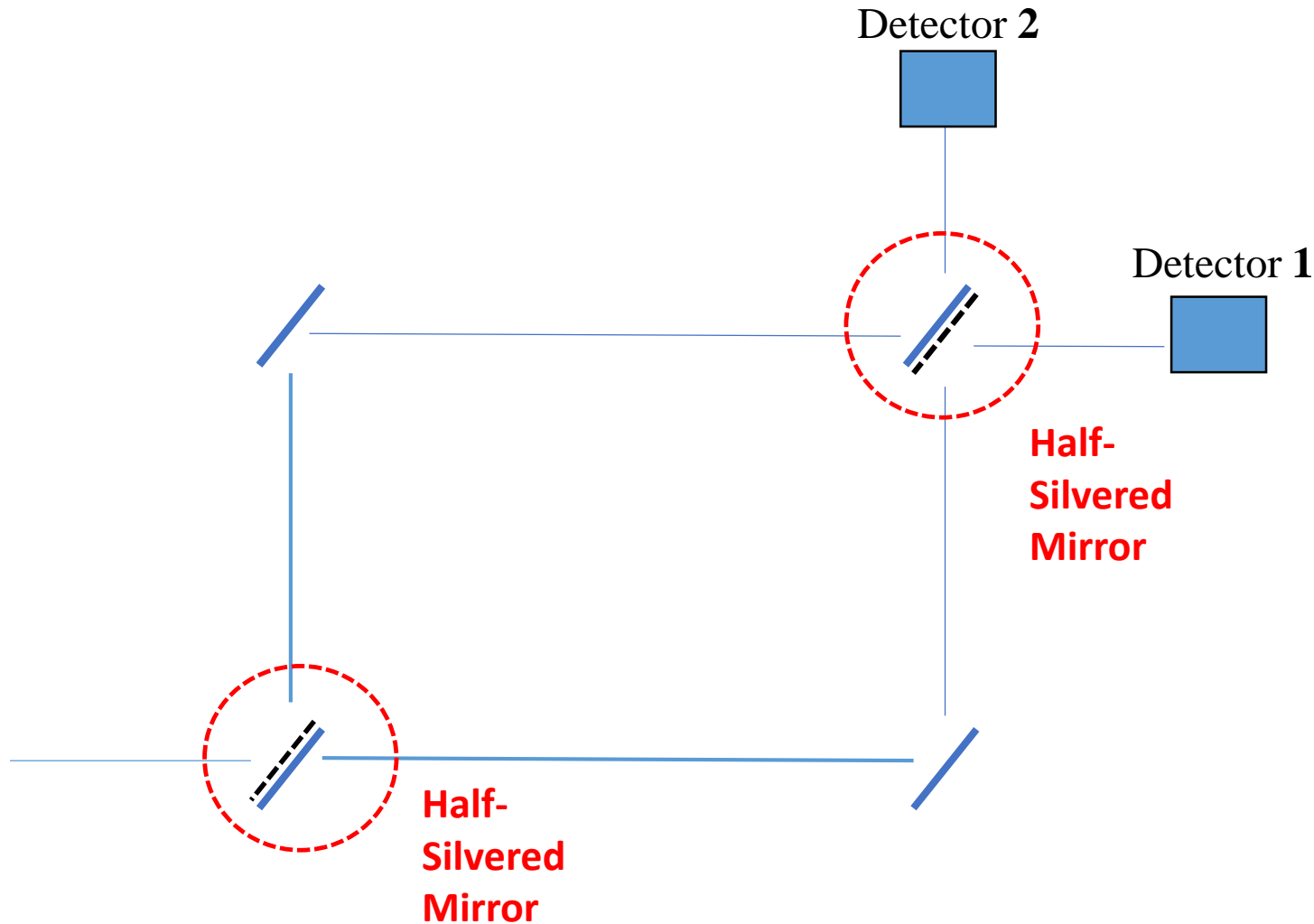
Cristian López

31th of March

First Part

Setting up the experiment

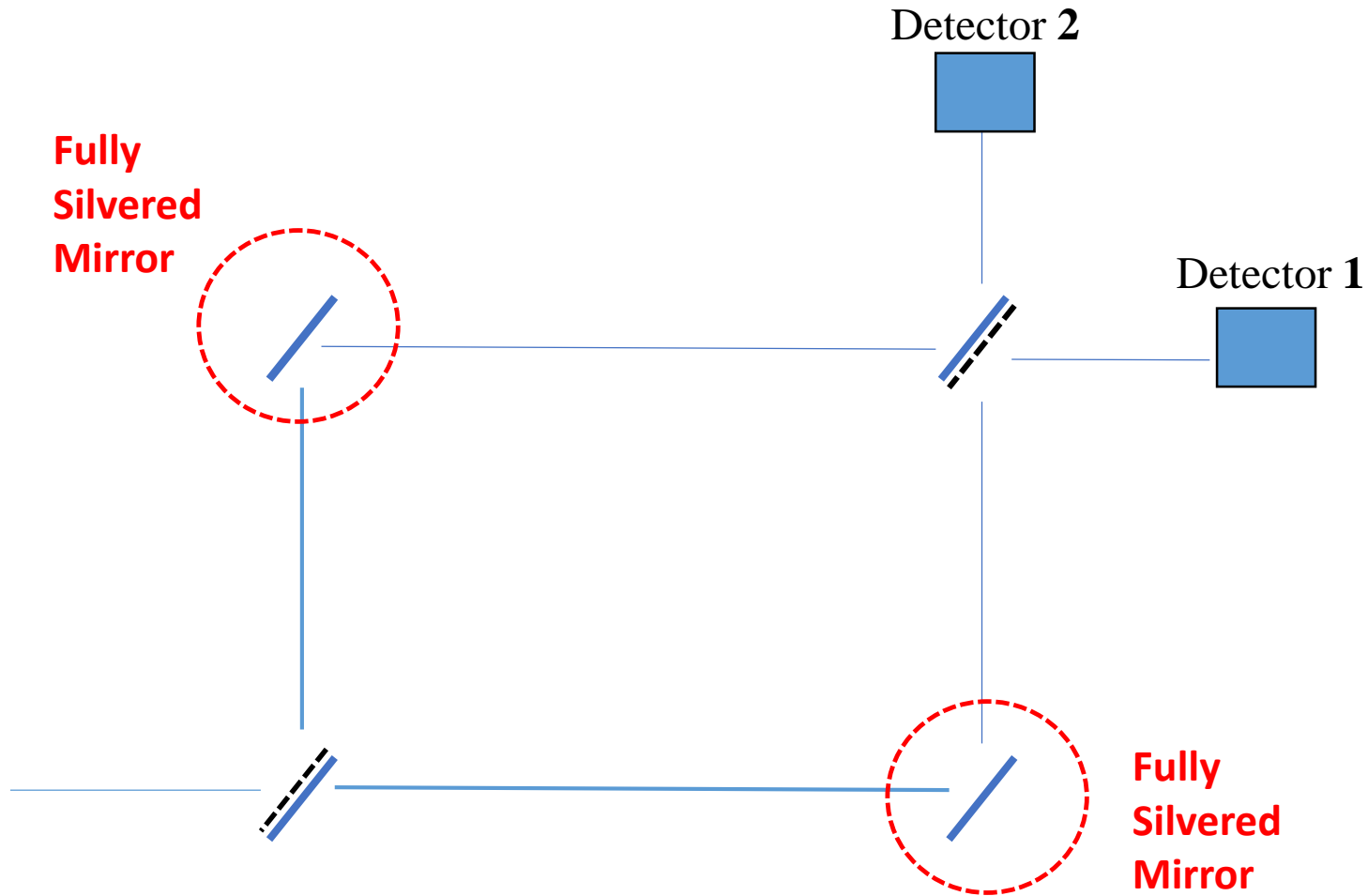
What is a Mach-Zehnder Interferometer?



Interferometer setup

- Two **half-silvered mirror** = reflect half of the light beam and allow the other half to pass through
- Two **fully silvered mirror** = reflect all the light
- Only when the beam is reflected out it undergoes a $\frac{\lambda}{2}$ phase shift.
- Equal path lengths

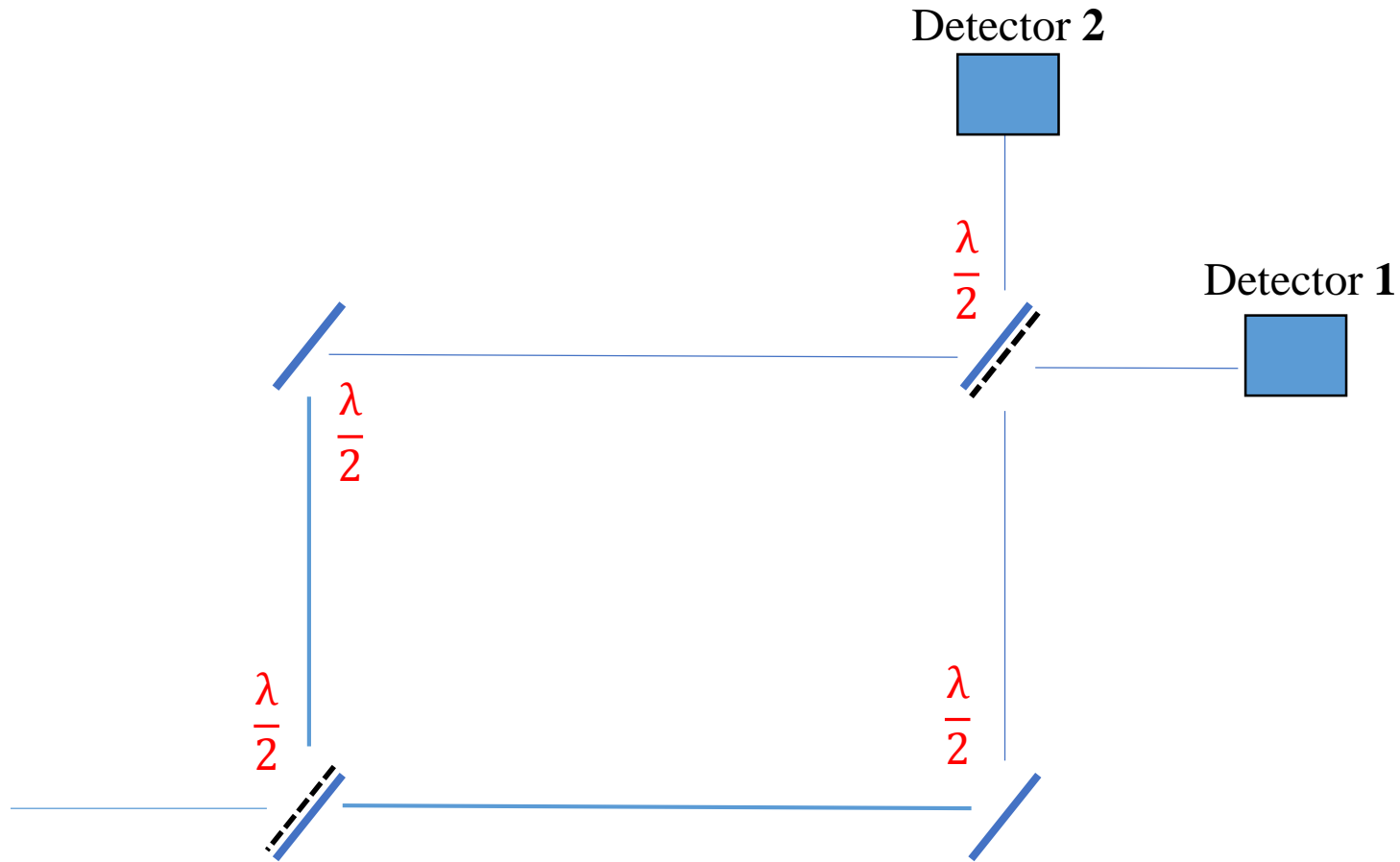
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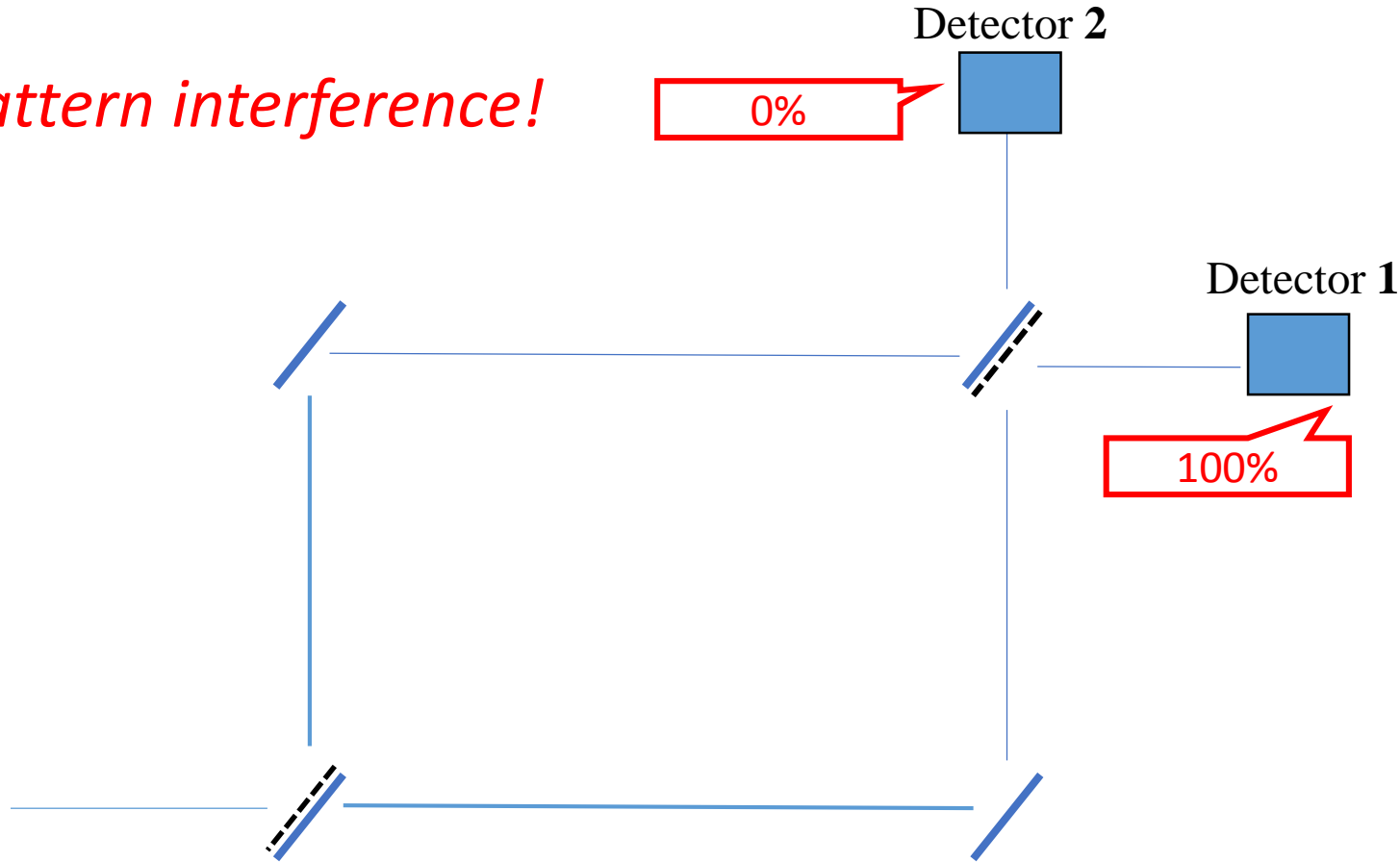


Interferometer setup

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What is a Mach-Zehnder Interferometer?

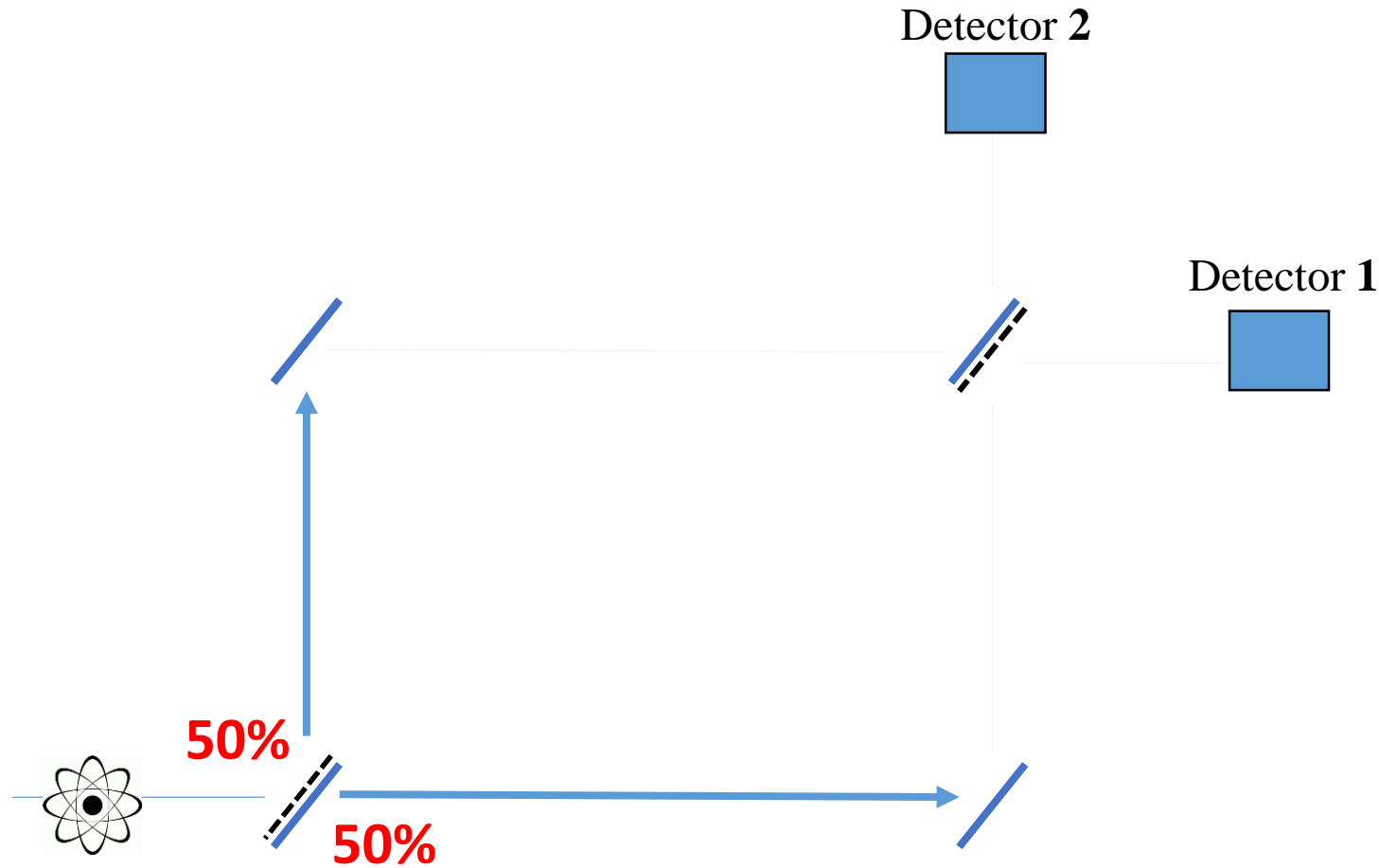
Pattern interference!



Interferometer setup

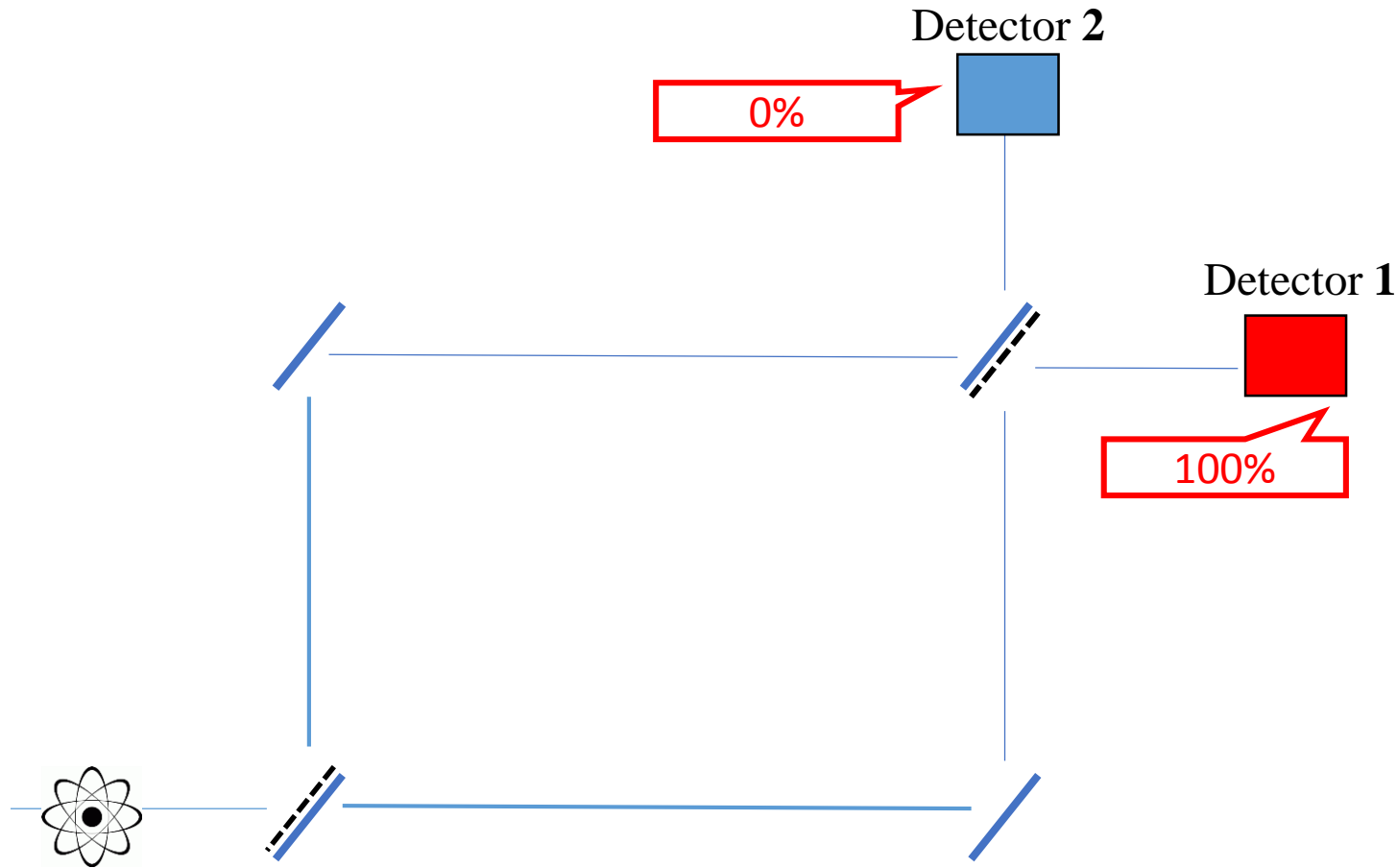
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What is a Mach-Zehnder Interferometer?



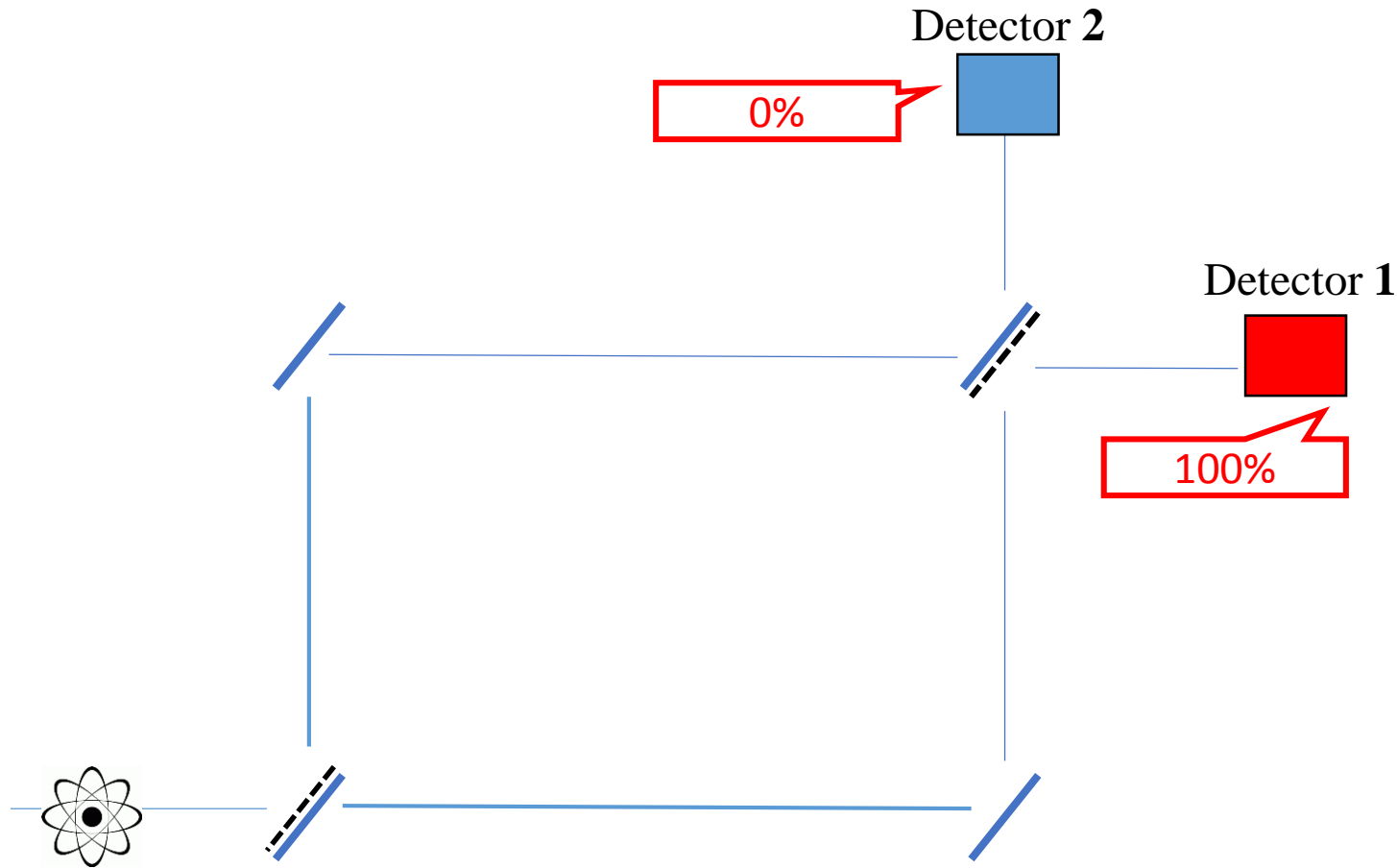
- **Turning** the laser intensity **down**, we can be sure that only **one photon** is inside the interferometer during one running.
- There seems to be a **50%** chance that an **individual photon** will be transmitted or reflected by the half-silvered mirror

What is a Mach-Zehnder Interferometer?



- ❑ After performing the experiment many times, we'll get no photons arriving at D2.
- ❑ Despite a **single particle** is involved each time, at the end of the entire experiment an **“interference-like pattern”** is displayed!
- ❑ **Wave-like behavior!**

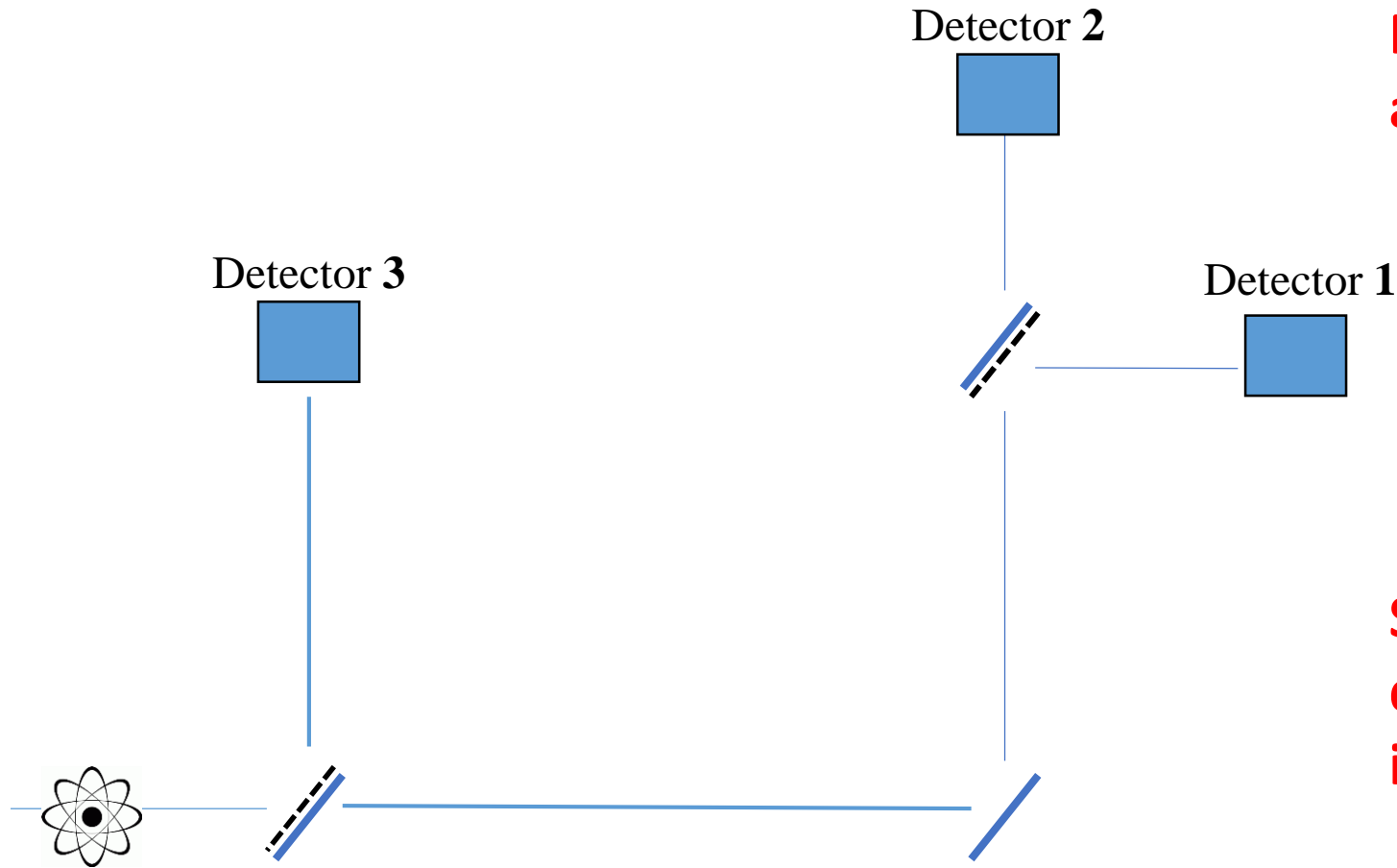
What is a Mach-Zehnder Interferometer?



Some questions and problems!

- If a photon is genuinely a small particle of light, then **how can the different paths have any effect on one single photon?**
- A single photon must surely have information about only one path (either the upper path or the lower path), **so how can single photon experiment produce interference patterns?**

What is a Mach-Zehnder Interferometer?

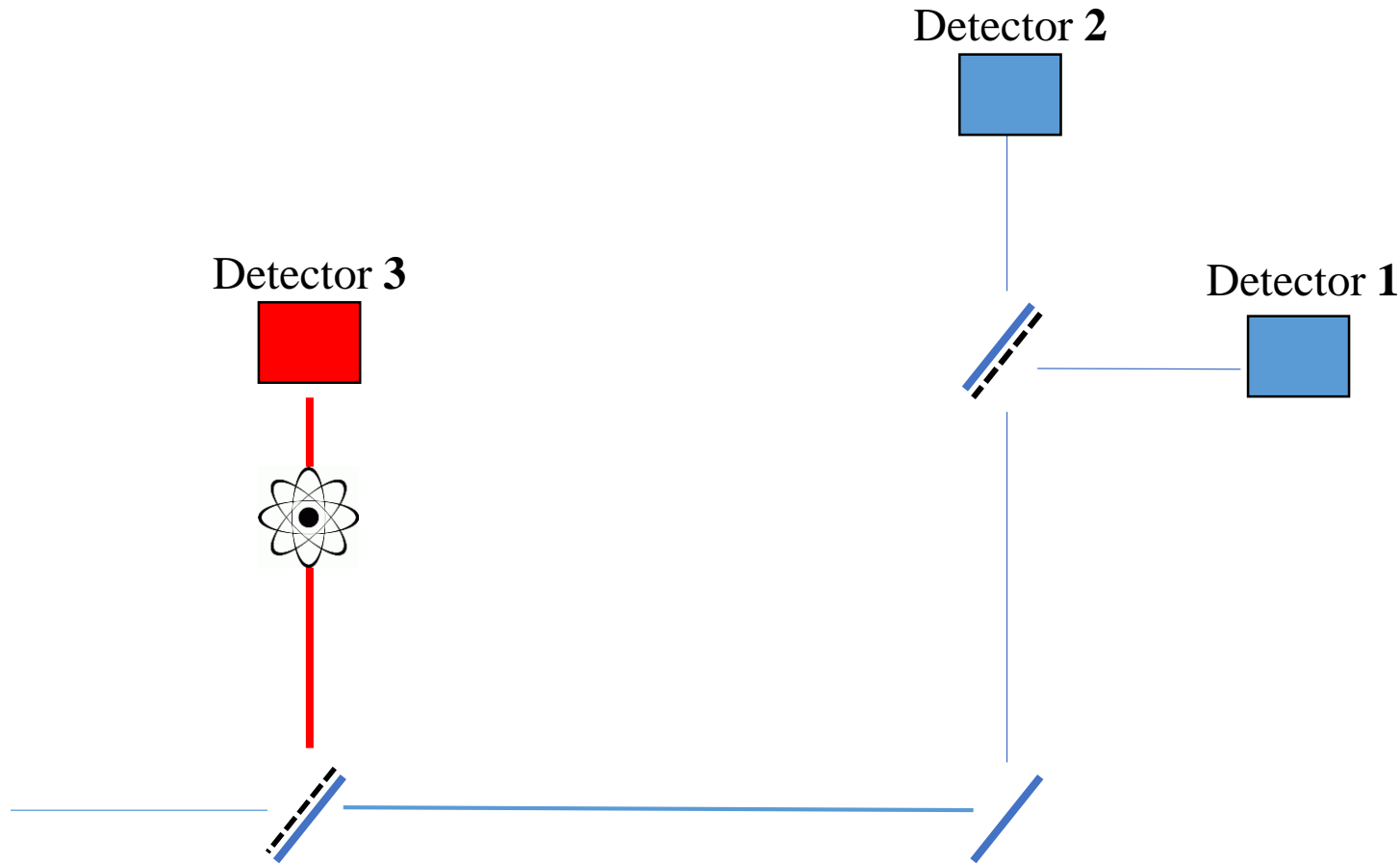


Now, we are about to slightly alter the experiment....

- We've placed one detector on the upper path
- Doing that, we'll know which path the photon took.

So, the question is: which detectors will we pick up photons in?

What is a Mach-Zehnder Interferometer?

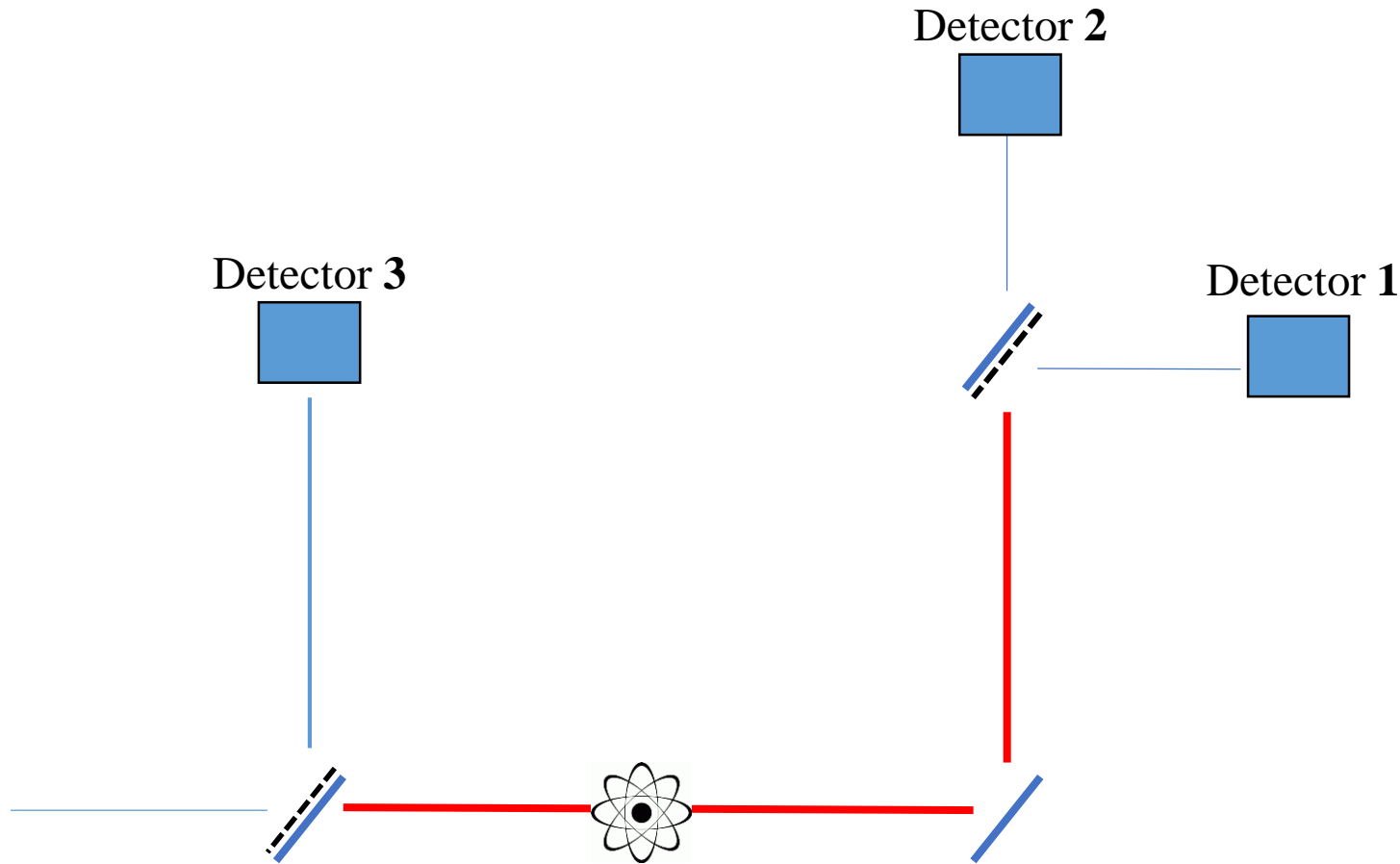


Bearing in mind that each photon has 50% chance to be reflected out by the first half-silvered mirror and 50% chance to go through, we'd expect...

First scenario

- A photon may take the upper path so that it'll arrive at the Detector 3. So, we know that **the half of the photons will end up at Detector 3**

What is a Mach-Zehnder Interferometer?

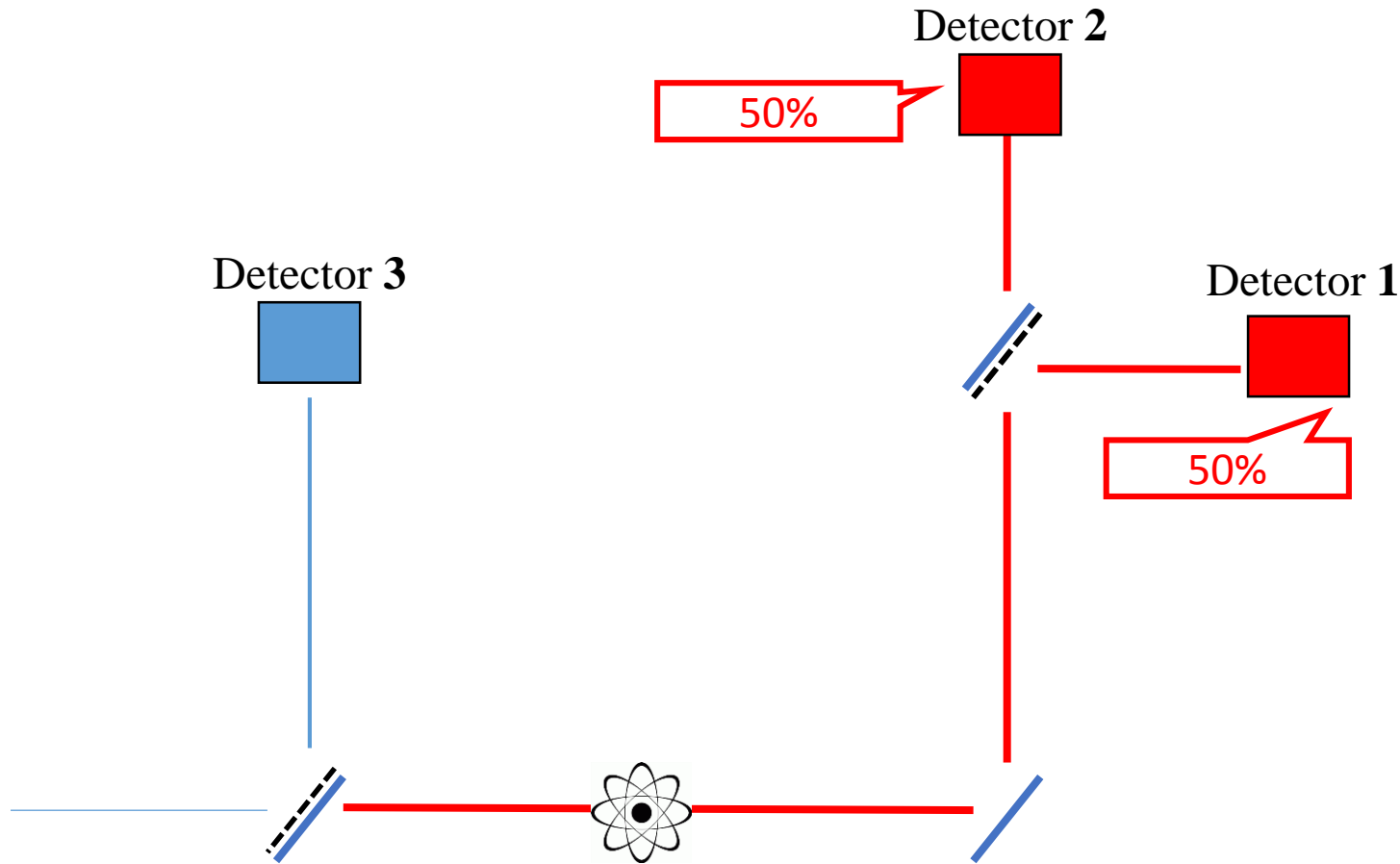


Bearing in mind that each photon has 50% chance to be reflected out by the first half-silvered mirror and 50% chance to go through, we'd expect...

Second scenario

- A photon may take the lower path so that it'll arrive at the far end (either D1 or D2).

What is a Mach-Zehnder Interferometer?

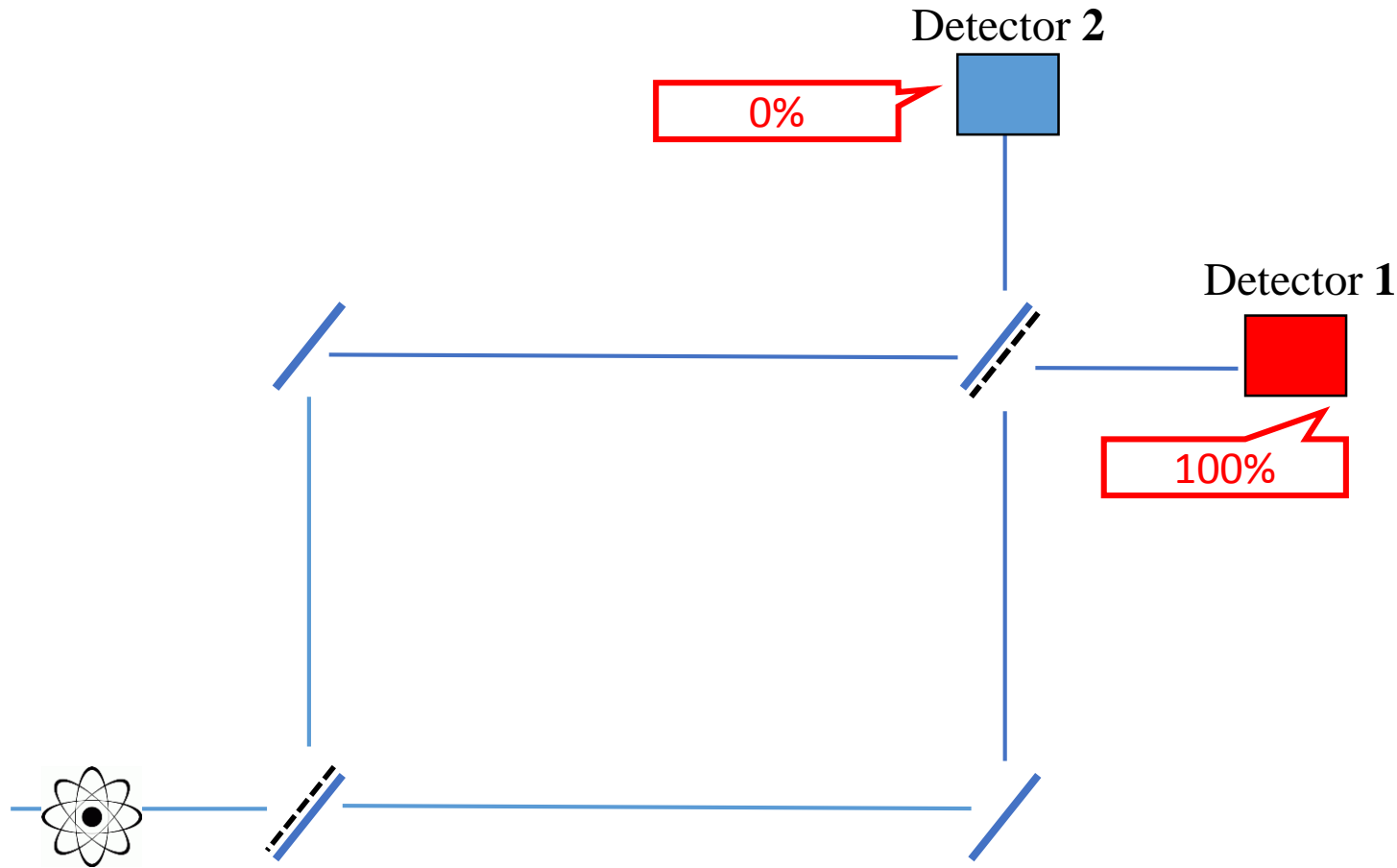


Bearing in mind that each photon has 50% chance to be reflected out by the first half-silvered mirror and 50% chance to go through, we'd expect...

Second scenario

- What we find for photons taking the lower path is that half of them arrive at D1 and the other half at D2!
- There is no interference taking place! Particle-like behavior**

What is a Mach-Zehnder Interferometer?



Obviously, if the Detector 3 is removed (removing any direct knowledge about which paths the photon took), an **interference pattern is restored**.

What is a Mach-Zehnder Interferometer?

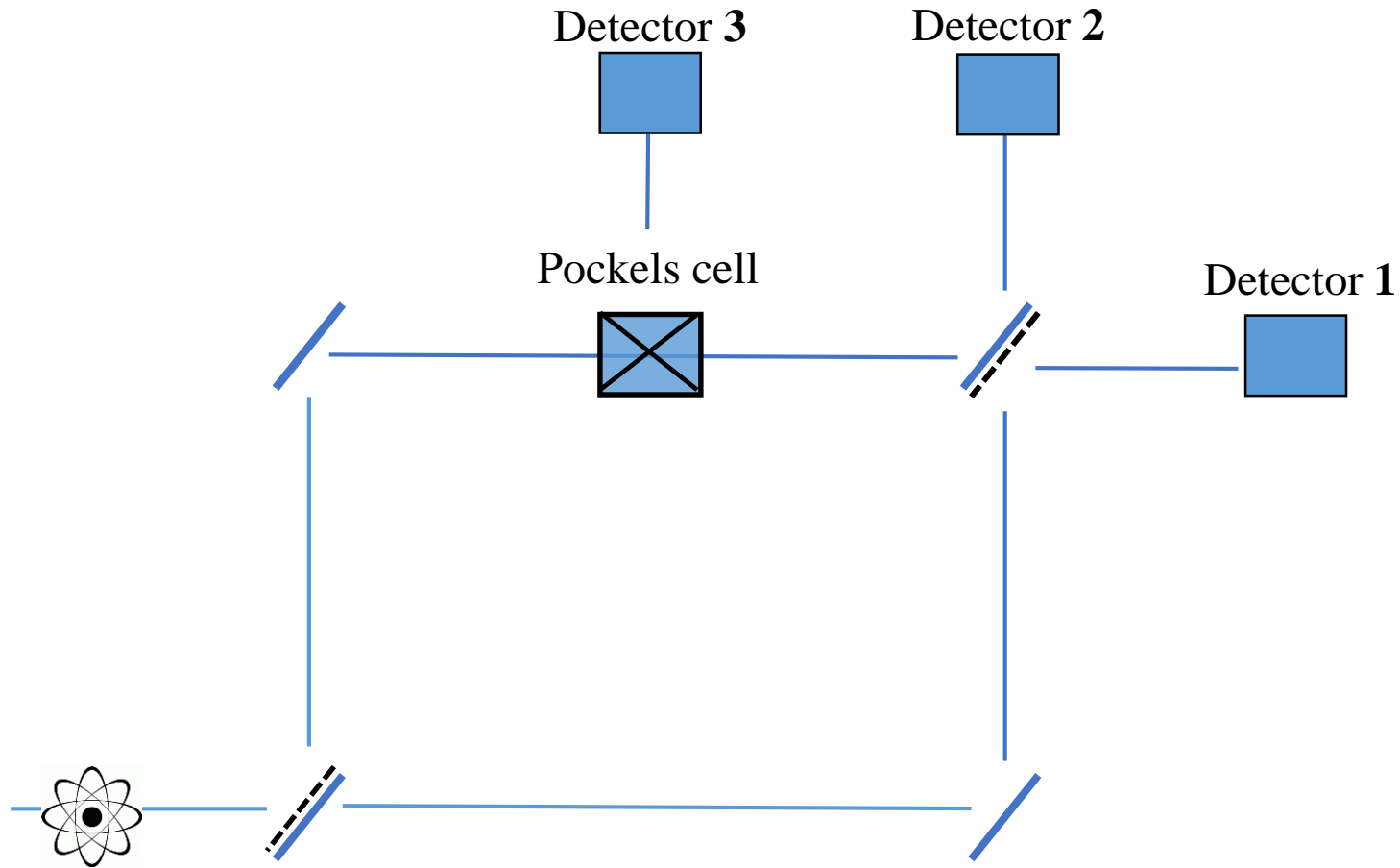
Summarizing...

- ❑ Despite a single particle went through the interferometer, an interference pattern was displayed, did the photon travel through both paths so as to get an interference pattern at the end of the experiment?
- ❑ If we setup the experiment so that we can tell which path was taken by the photon (directly or indirectly), then the interference pattern is destroyed, getting a particle-like behavior!
- ❑ However, if we setup the experiment so that we cannot tell which path was taken by the photon, we get a wave-like behavior and an interference pattern.

The conclusion seems to be...

- ❑ In setting up the experiment, **we are “choosing “ the nature of the photon** –wave or particle one

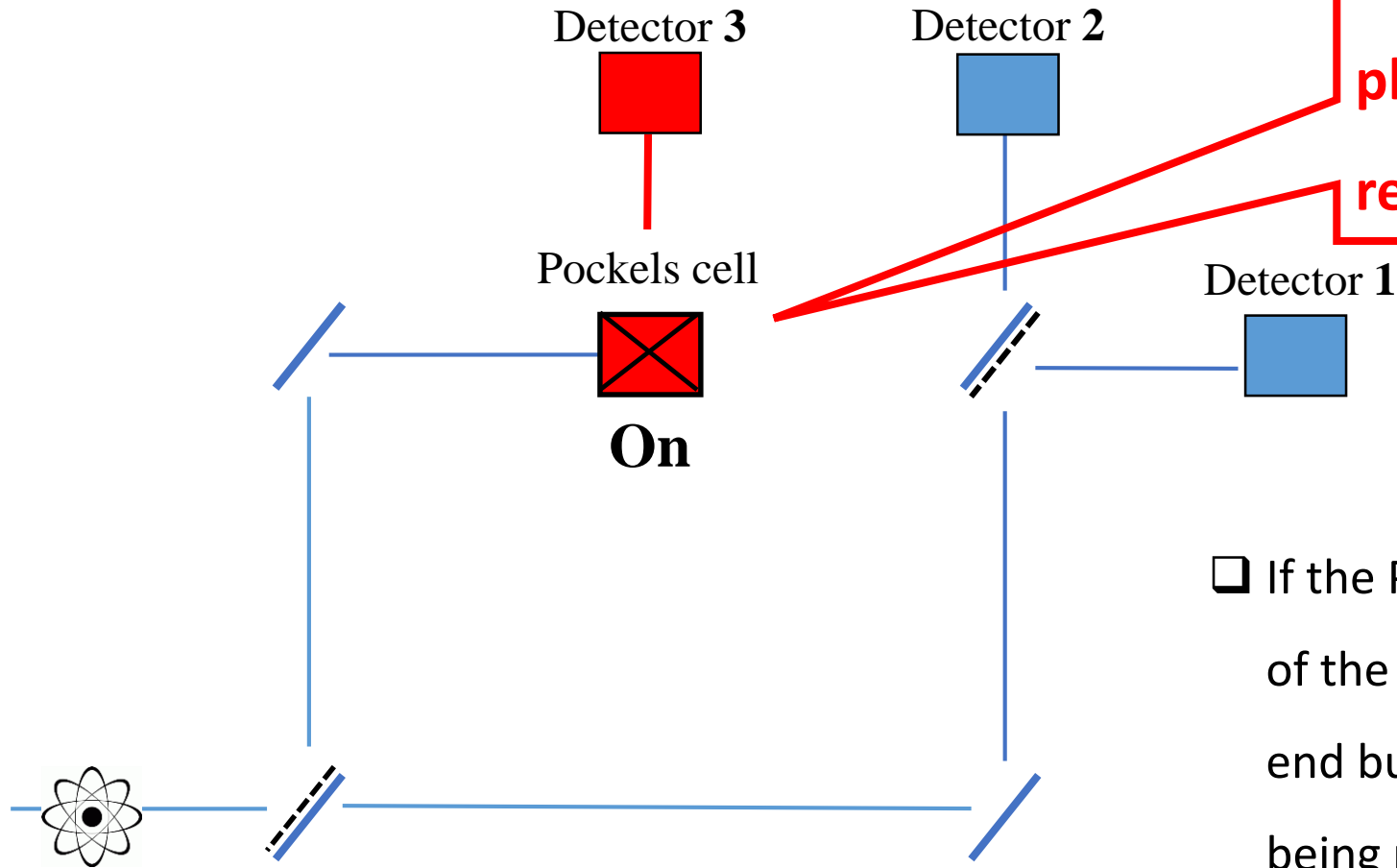
Delayed-choice experiment



In a delayed-choice experiment, we can **suddenly** alter the interferometer setup **once the photon is inside of the interferometer**. We could do this using a Pockels Cell and changing its configuration quickly.

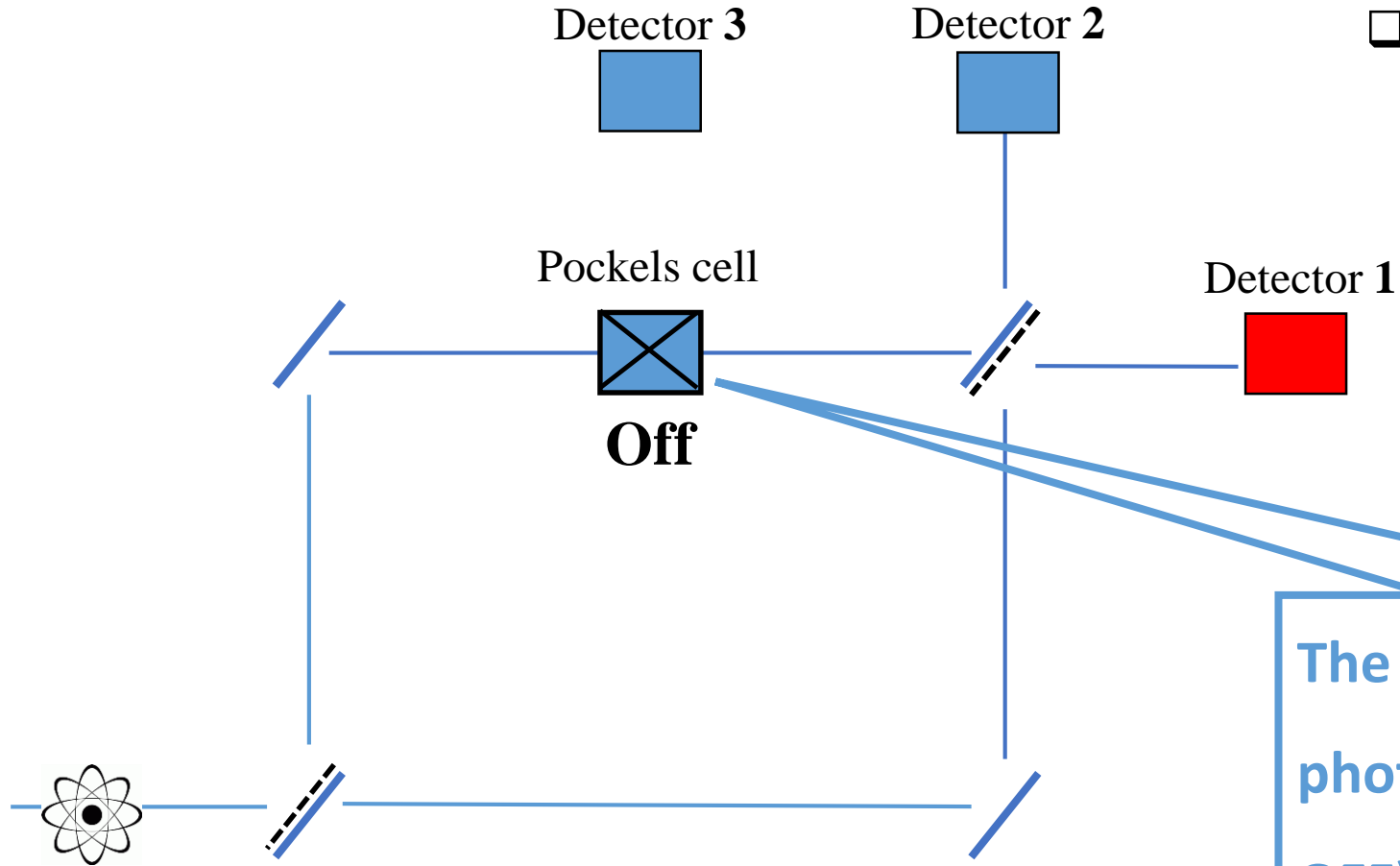
Delayed-choice experiment

The device can be set to divert photons (it is ON) and photons reach the Detector 3



- If the PC is **set to *divert***, then only half of the photons get detected at the far end but they have an equal chance of being picked up at either D2 or D1.

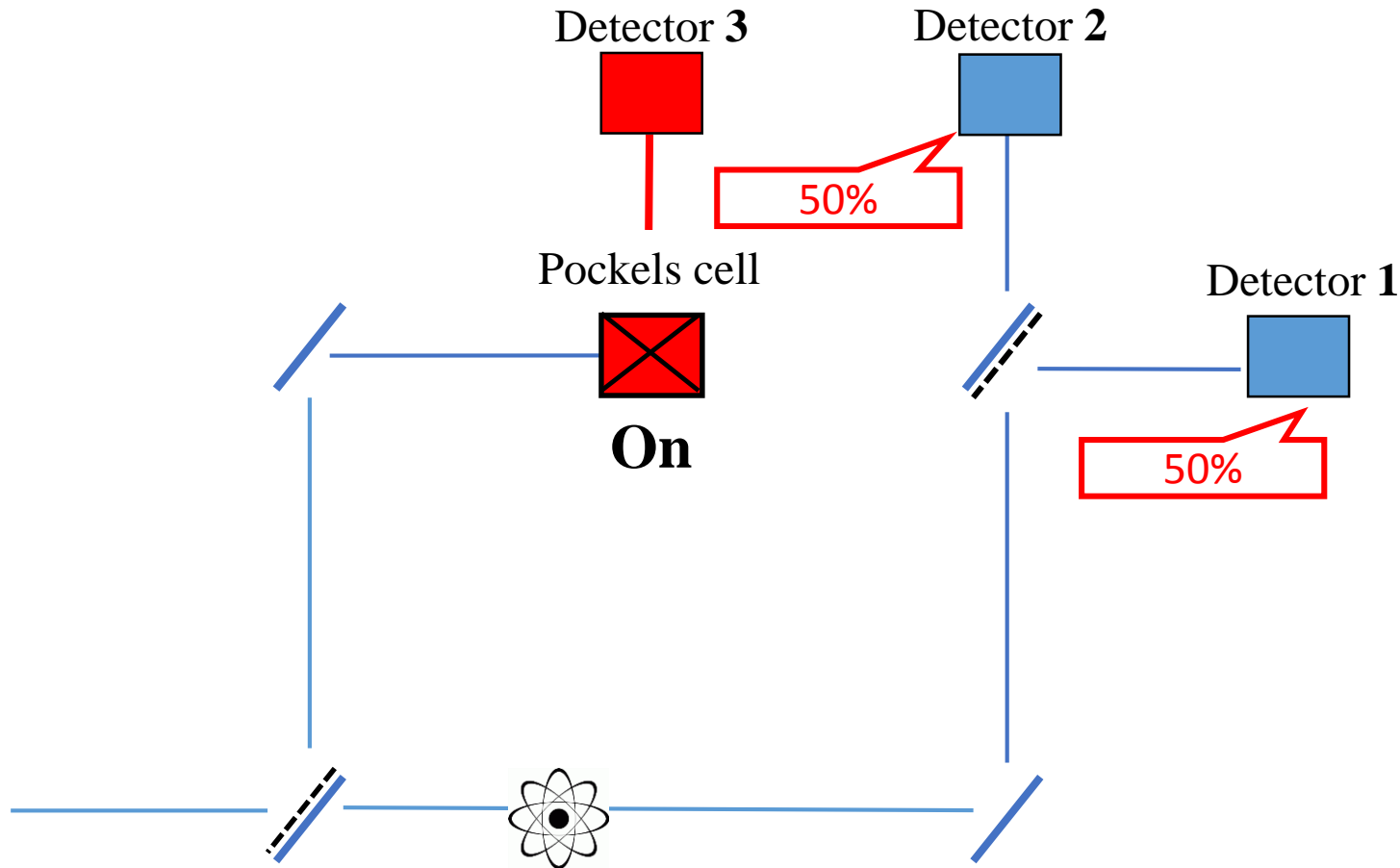
Delayed-choice experiment



If the PC is **set to *transmit***, then we get no photons at D2 and all of them at D1.

The device can be set to allow photons to pass through (it is OFF)

Delayed-choice experiment

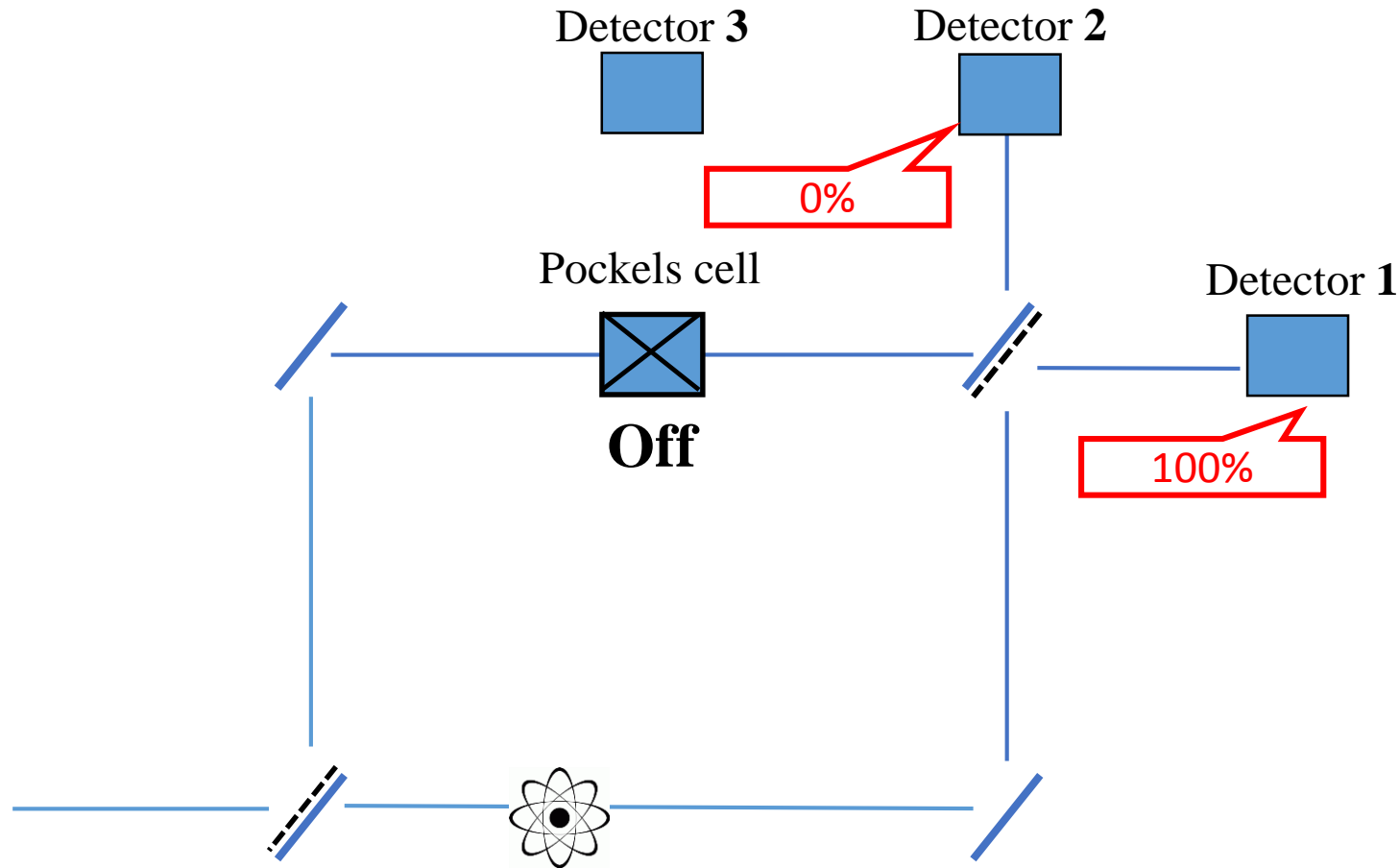


First scenario

Considering one individual photon...

- ❑ Suppose we set the PC **to divert** and the photon goes through the first half-silvered mirror, taking the lower path. **We'll get the photon either D2 or D1**
- ❑ Now, let suppose we set the PC **to transmit** photon and the photon goes through the first half-silvered mirror, taking the lower path. **We'll get the photon at D1.**

Delayed-choice experiment

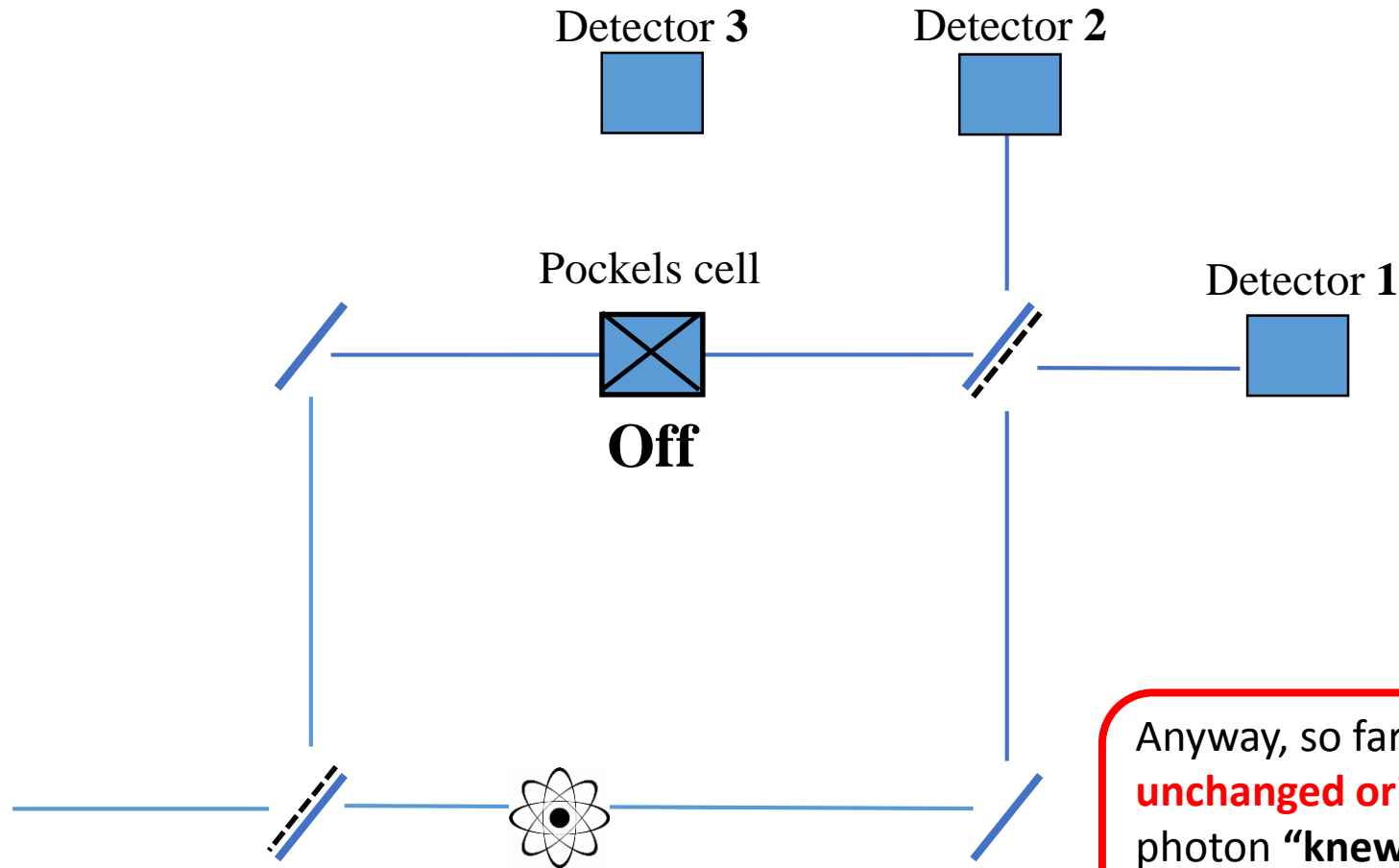


Second scenario

Considering one individual photon...

- ❑ Suppose we set the PC to **divert** and the photon goes through the first half-silvered mirror, taking the lower path. We'll get the photon either D2 or D1
- ❑ Now, let suppose we set the PC to **transmit** photon and the photon goes through the first half-silvered mirror, taking the lower path. **We'll get the photon at D1.**

Delayed-choice experiment

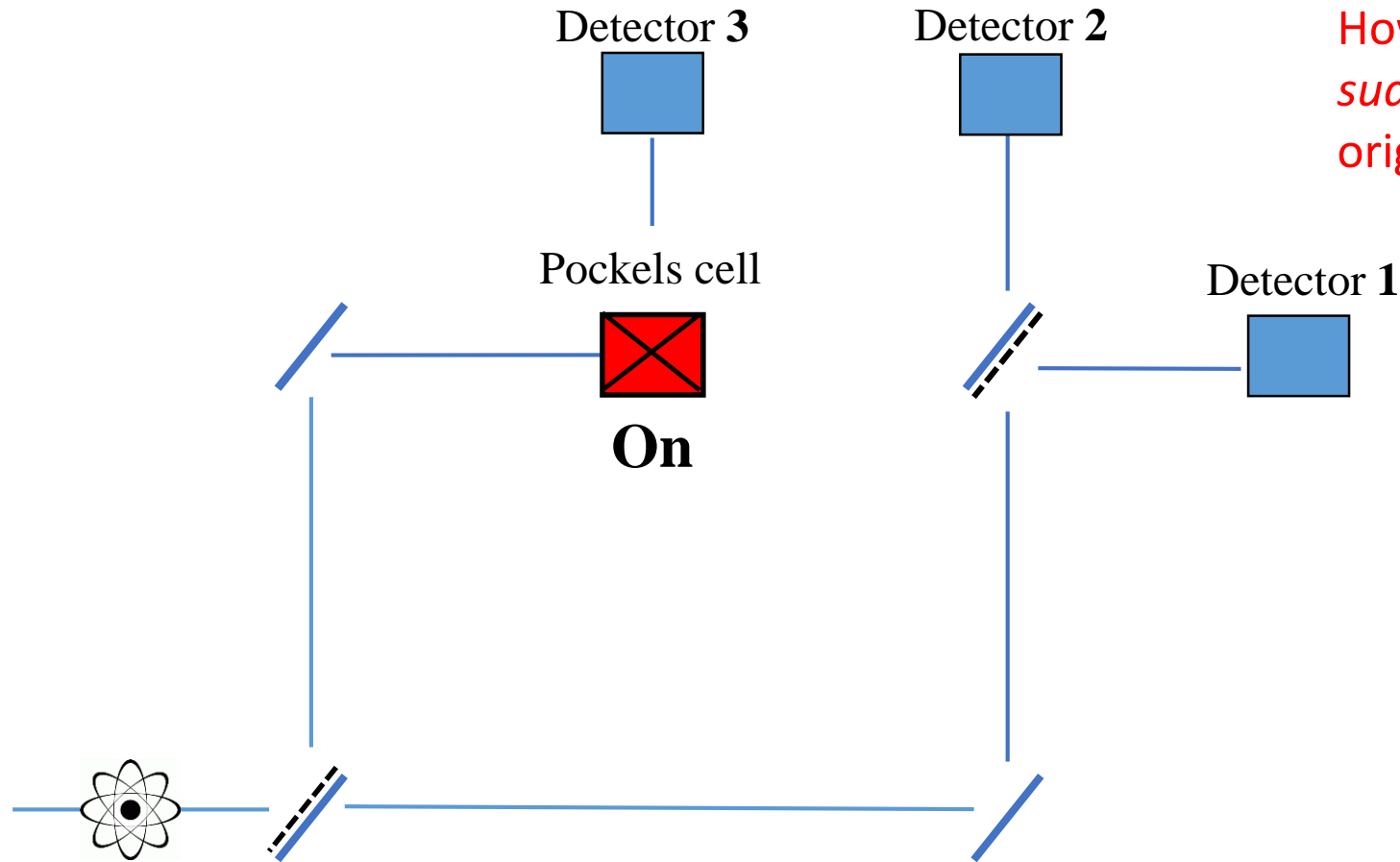


Some questions...

- How does the photon *know* that the PC was set to divert or to transmit photon if it took the lower path?
- How can the setting of that device affect the behavior of the photon?

Anyway, so far so good as long as we are dealing with an **unchanged original configuration**. We could say that the photon "**knew**" the initial configuration of the interferometer and it behaved according to that original configuration.

Delayed-choice experiment

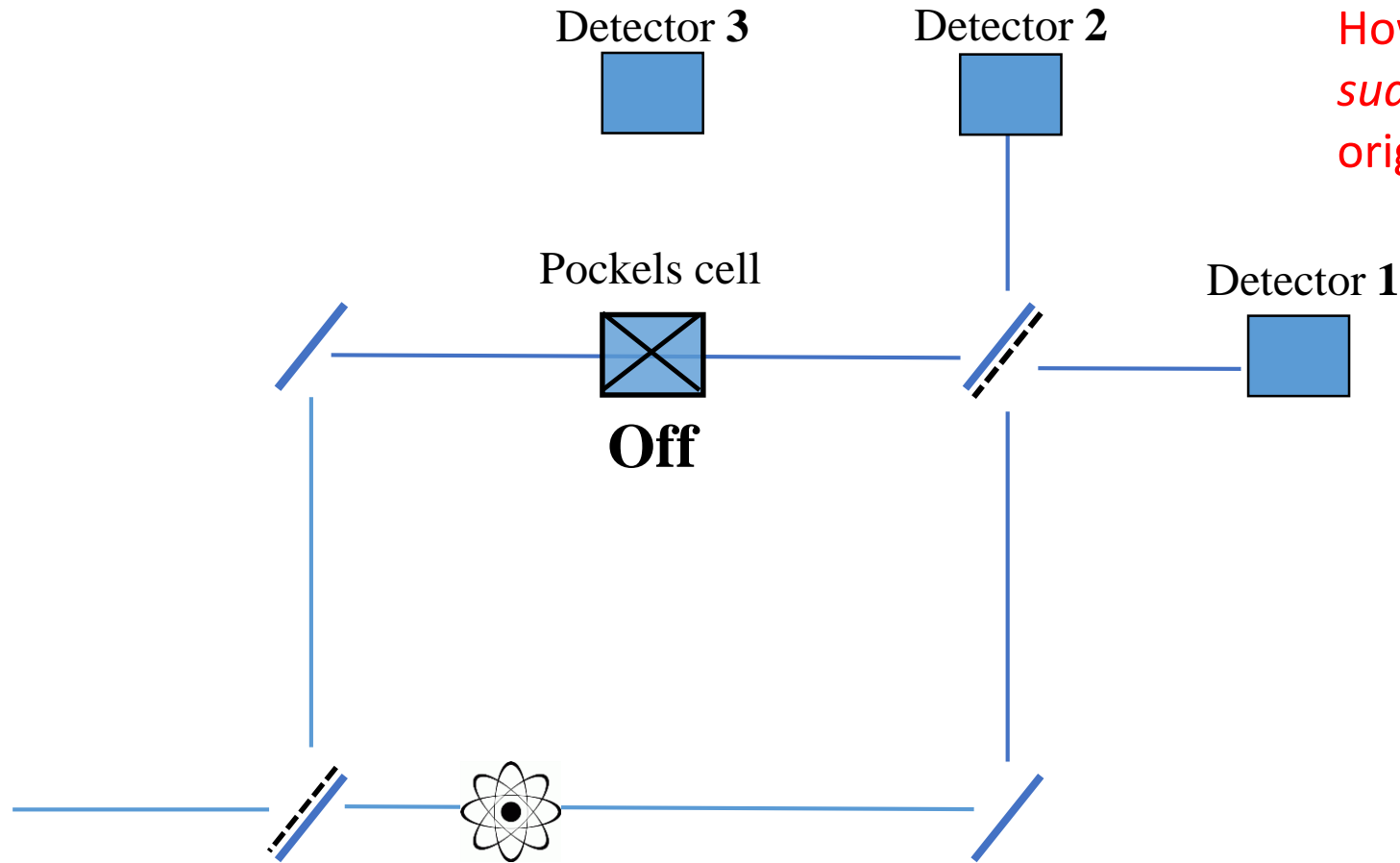


However, we can get things devious as we *suddenly switch the cell over changing the original configuration...*

Time 1

- the photon starts out its trip.
- The PC is set **to divert** photon.
- The photon has not reached the first half-silvered mirror yet.

Delayed-choice experiment

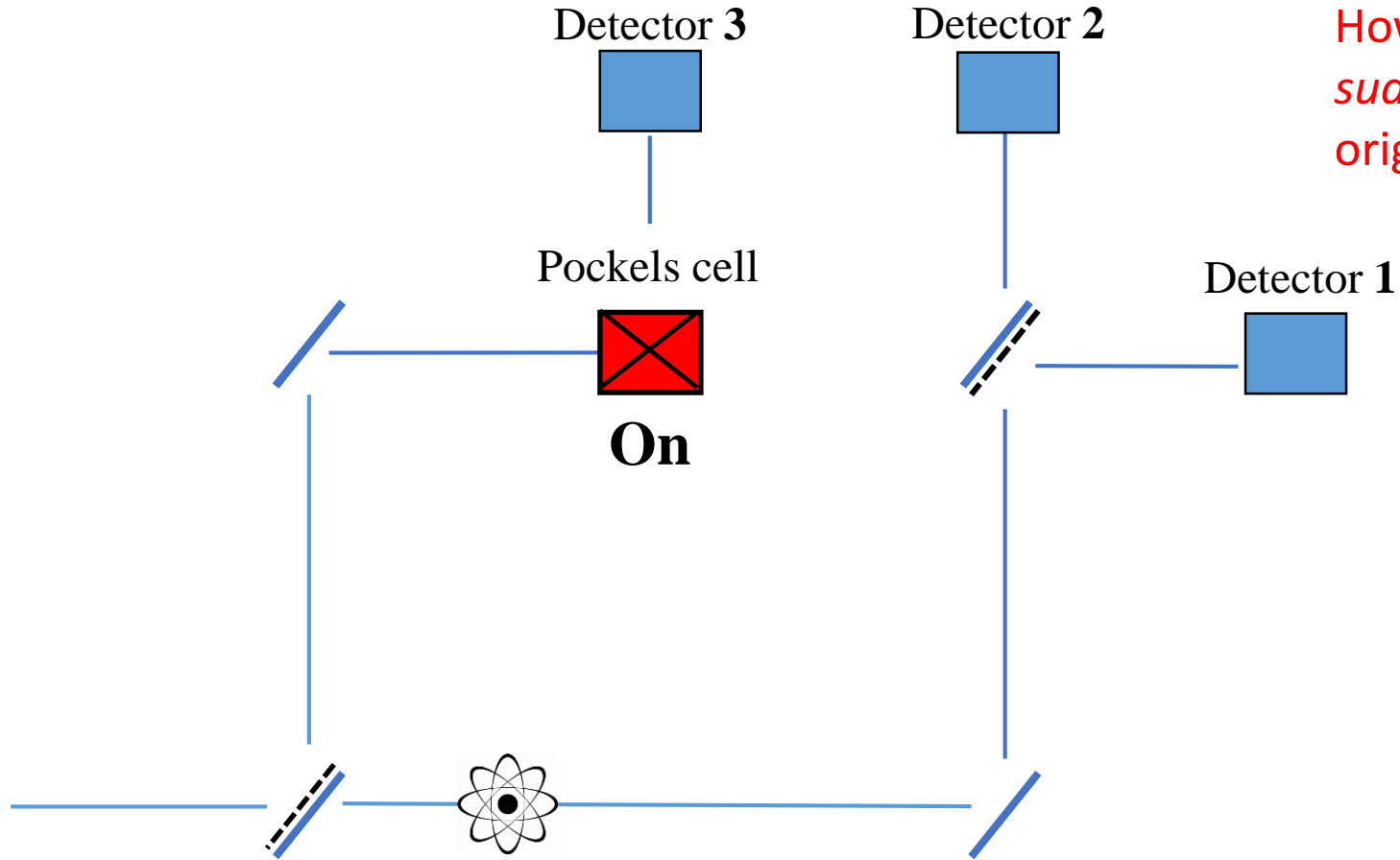


However, we can get things devious as we **suddenly switch the cell over changing the original configuration...**

Time 2

- ☐ the photon has already passed through the first half-silvered mirror and let suppose it took the lower path.
- ☐ We **suddenly change** the original configuration **turning the PC off.**

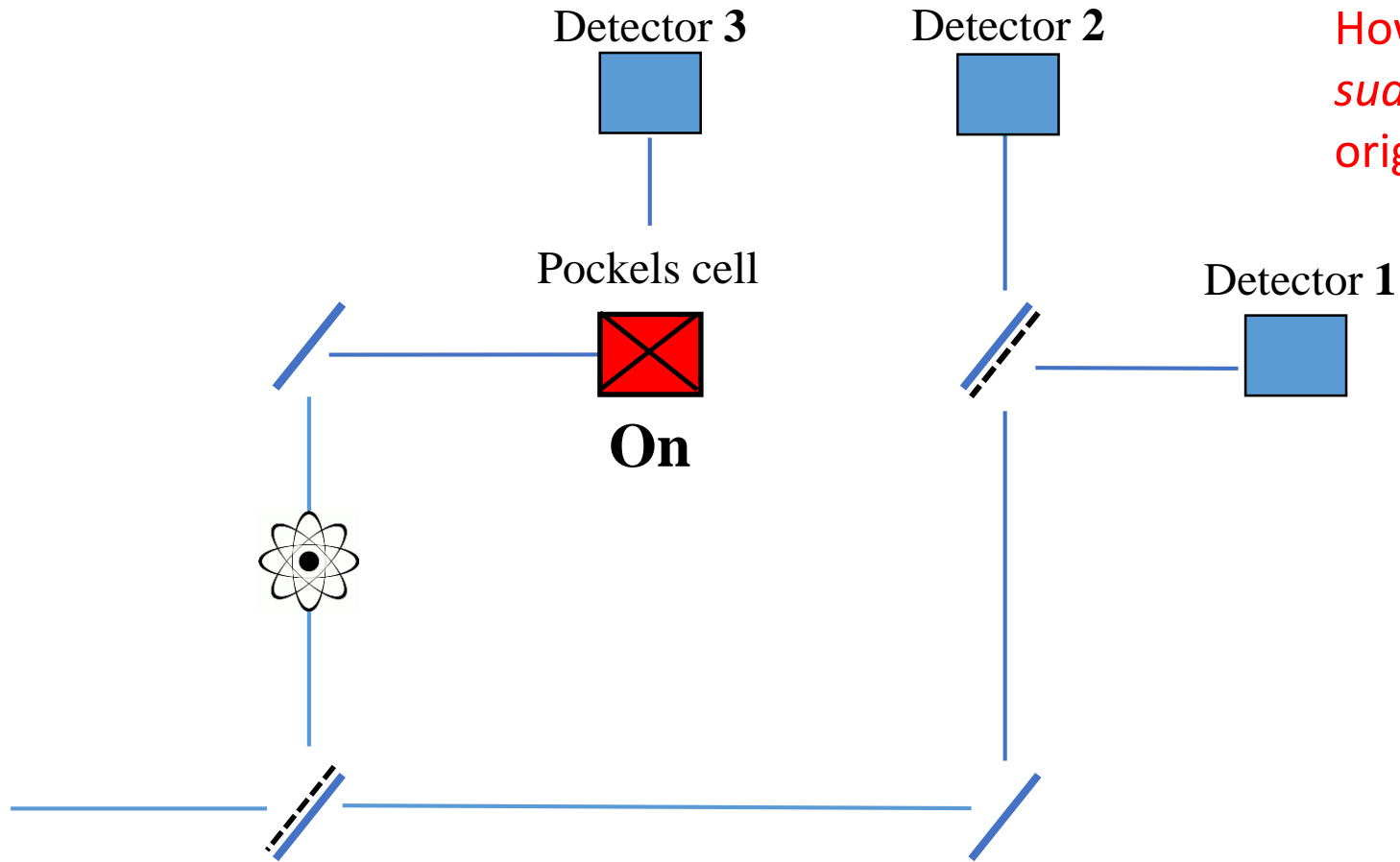
Delayed-choice experiment



However, we can get things devious as we suddenly **switch the cell over** changing the original configuration...

And then, we repeat the experiment many times, **turning the PC off** randomly and recording their arrival at the detectors

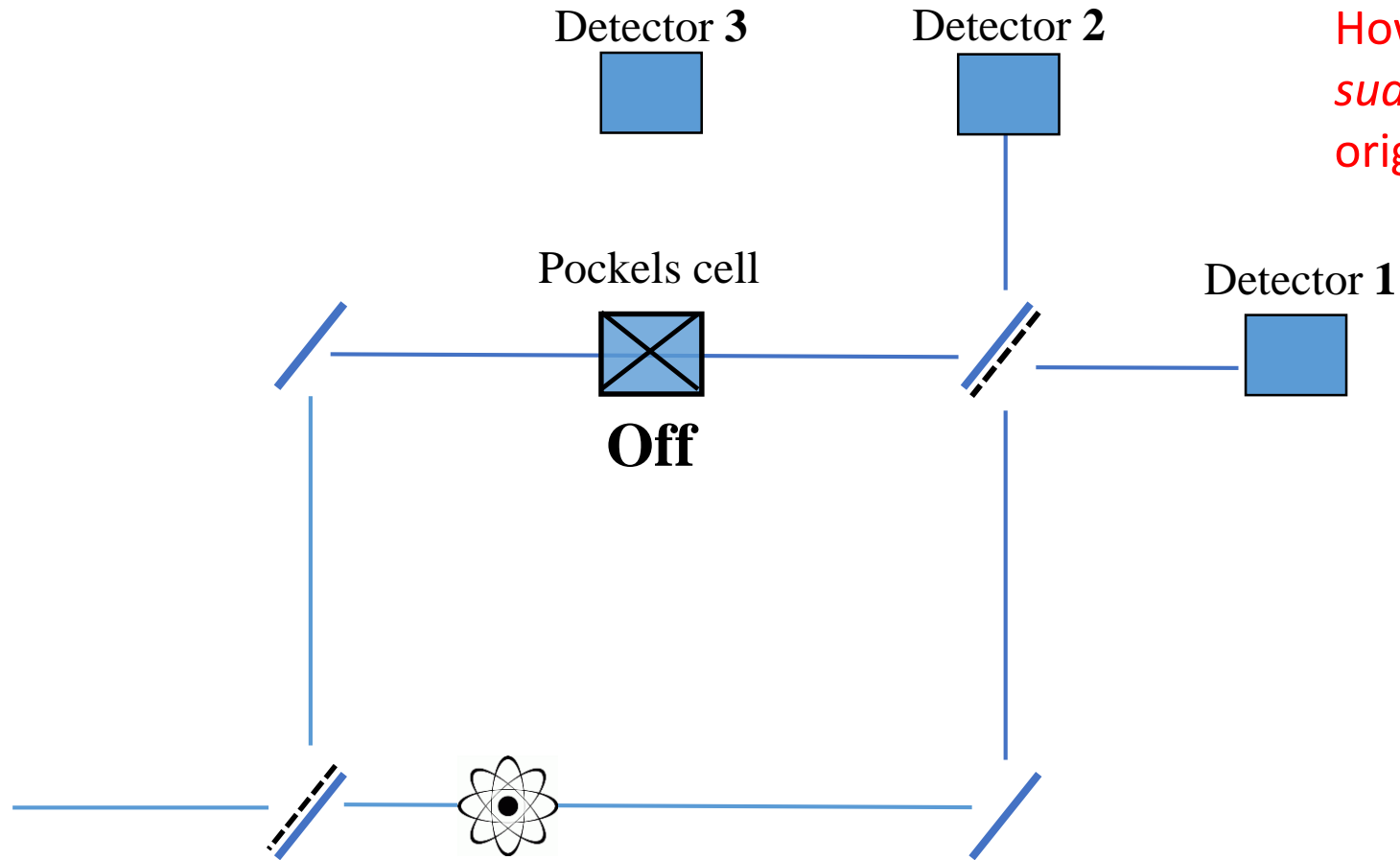
Delayed-choice experiment



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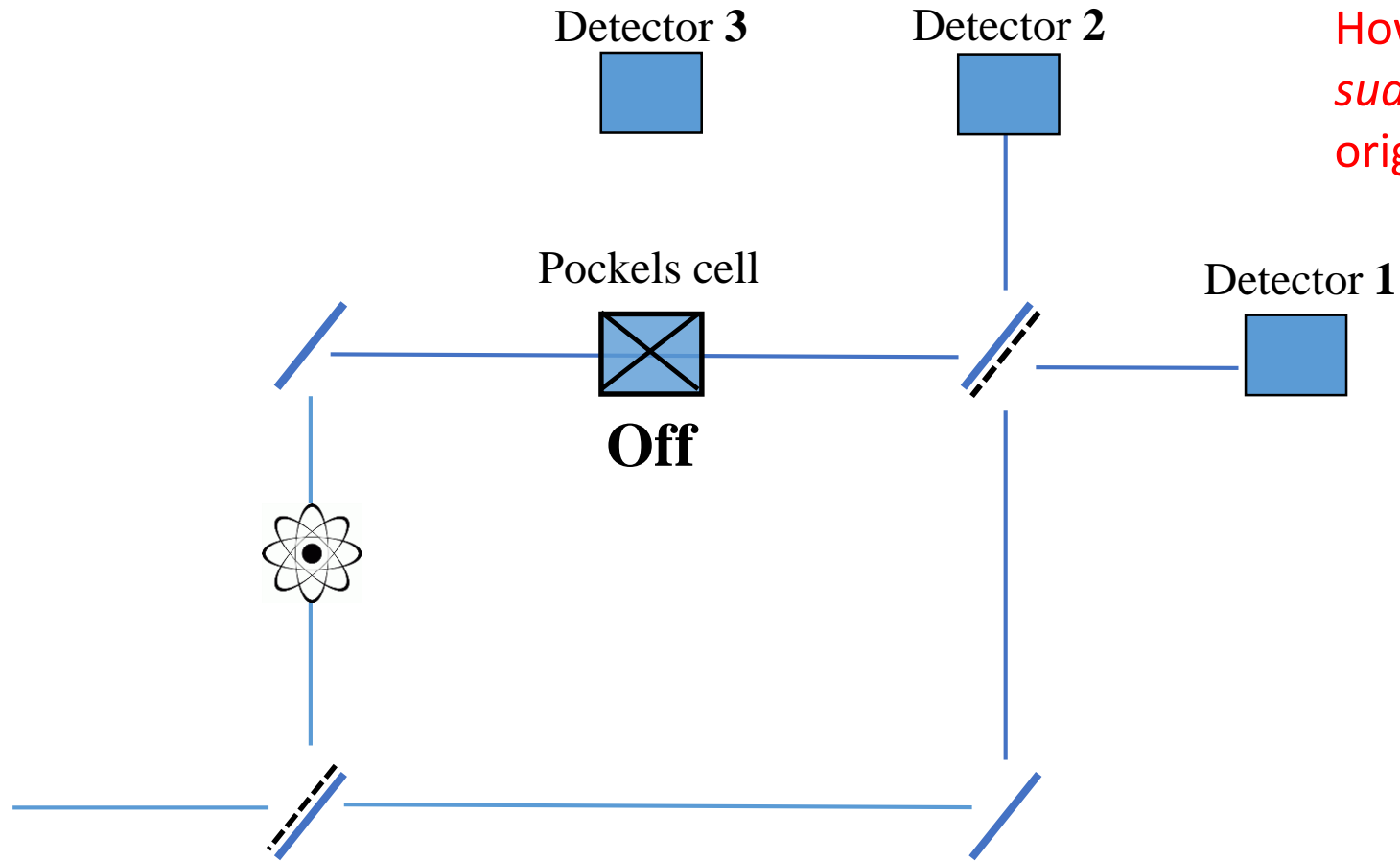
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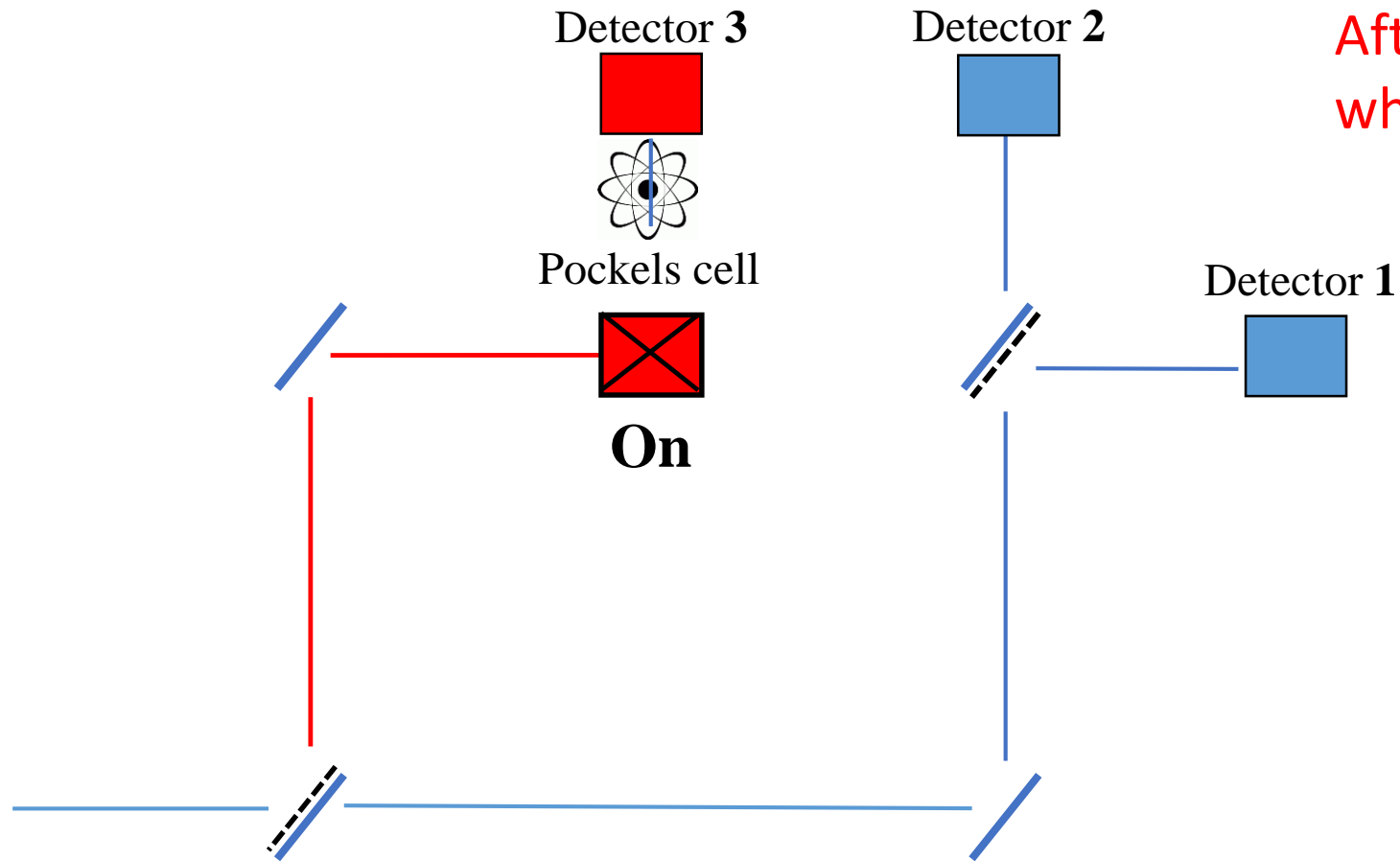
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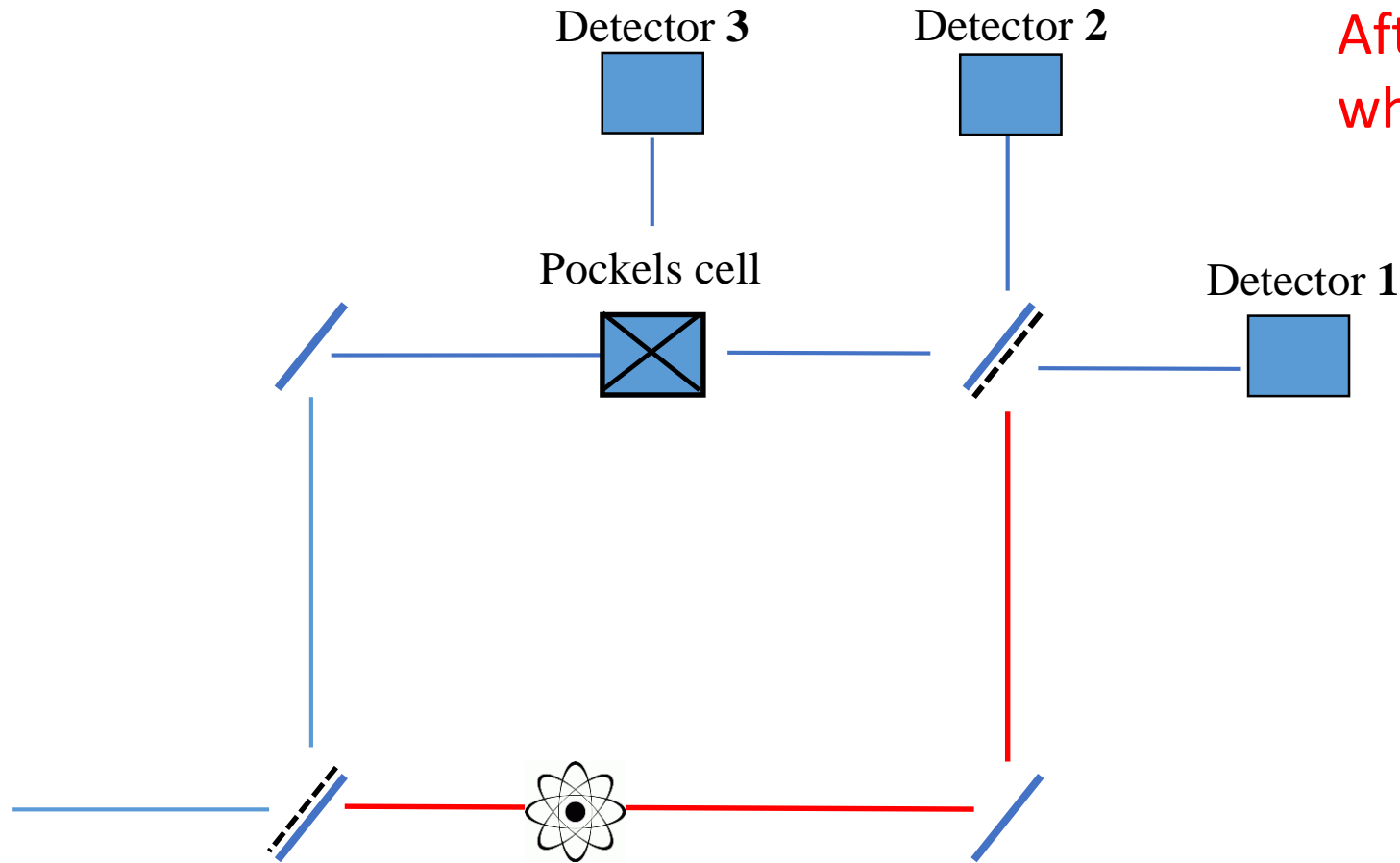
Delayed-choice experiment



After the experiment has run for a while, we get...

- ☐ Some photons arrived at the PC and then at **D3**, always when the **PC was set to divert.**

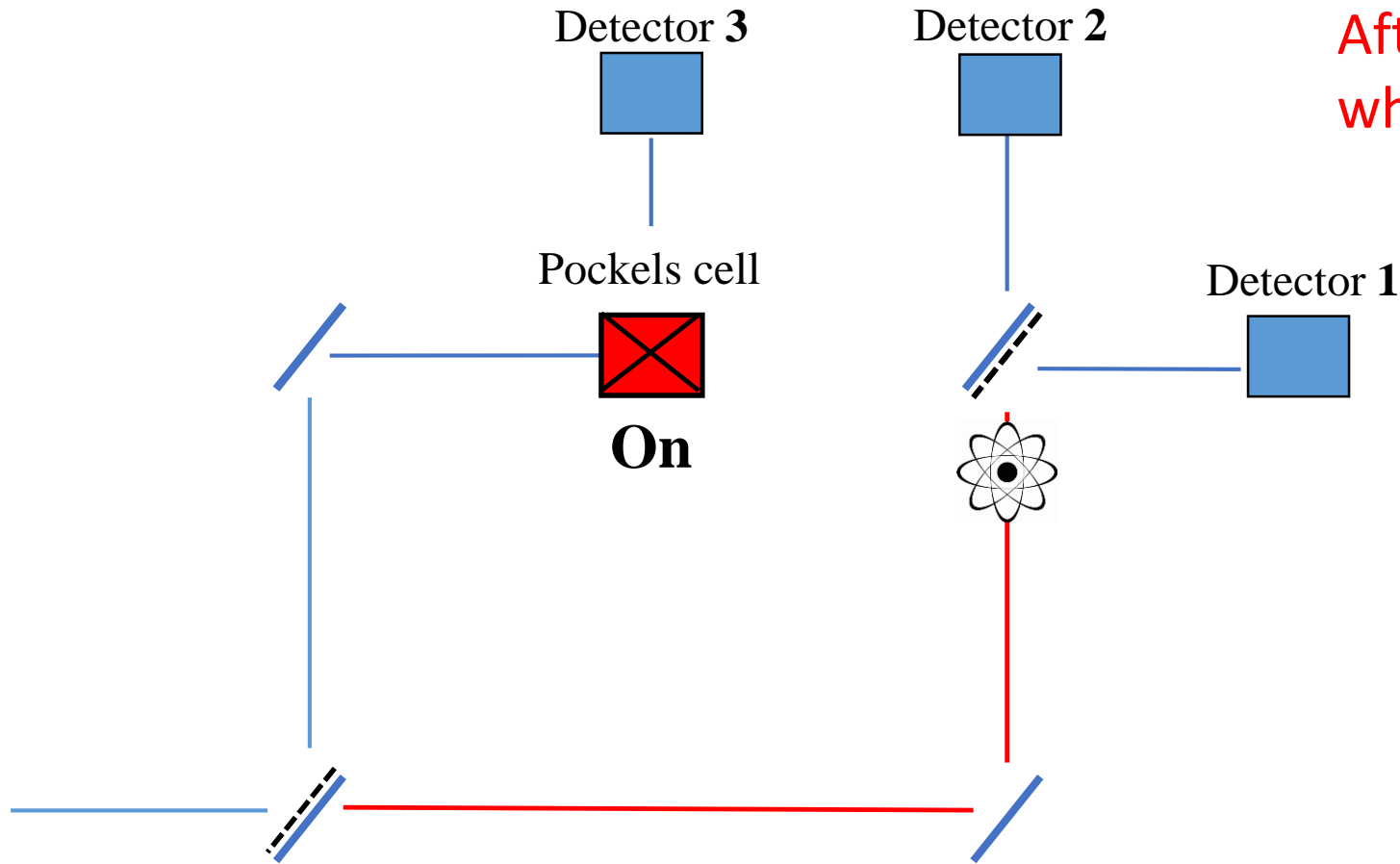
Delayed-choice experiment



After the experiment has run for a while, we get...

- Some photons arrived at the PC and then at D3, always when the PC was set to divert.
- Some photons arrived **at the end of the experiment**, which can be sorted out into....

Delayed-choice experiment

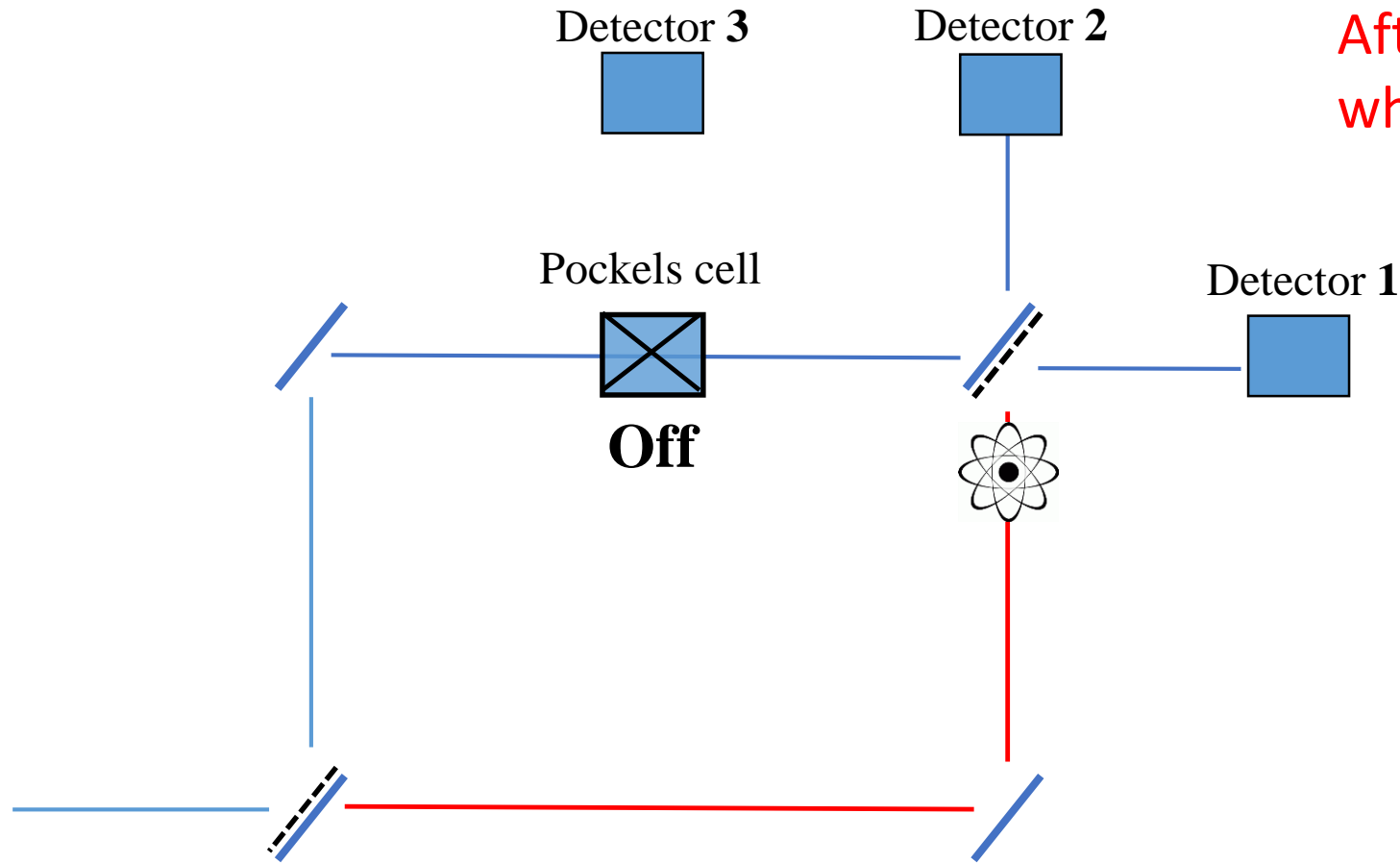


After the experiment has run for a while, we get...

(A) Those that arrived when de
PC was set to divert

(B) Those that arrived when de
PC was set to transmit

Delayed-choice experiment

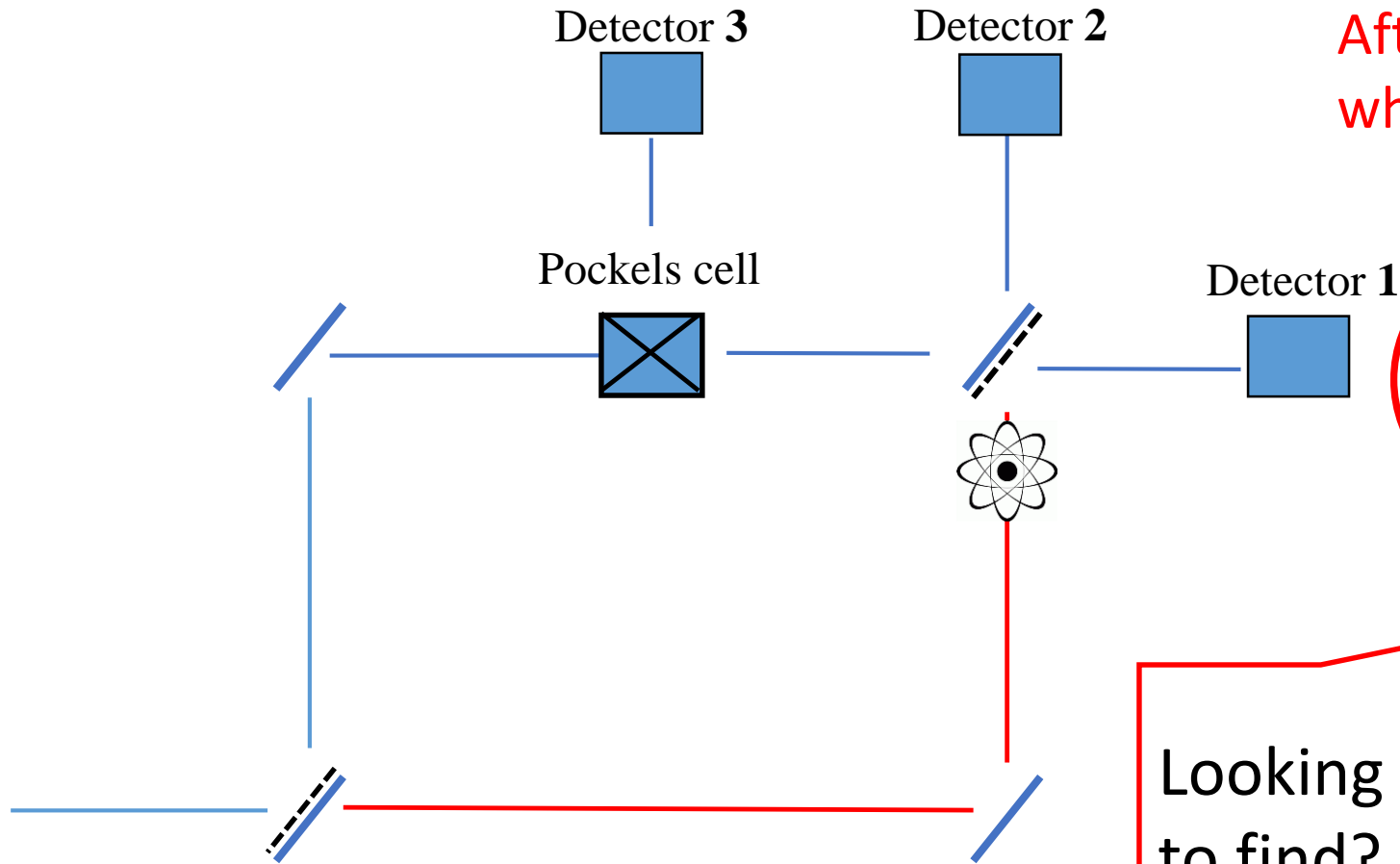


After the experiment has run for a while, we get...

(A) Those that arrived when the PC was set to divert

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Delayed-choice experiment

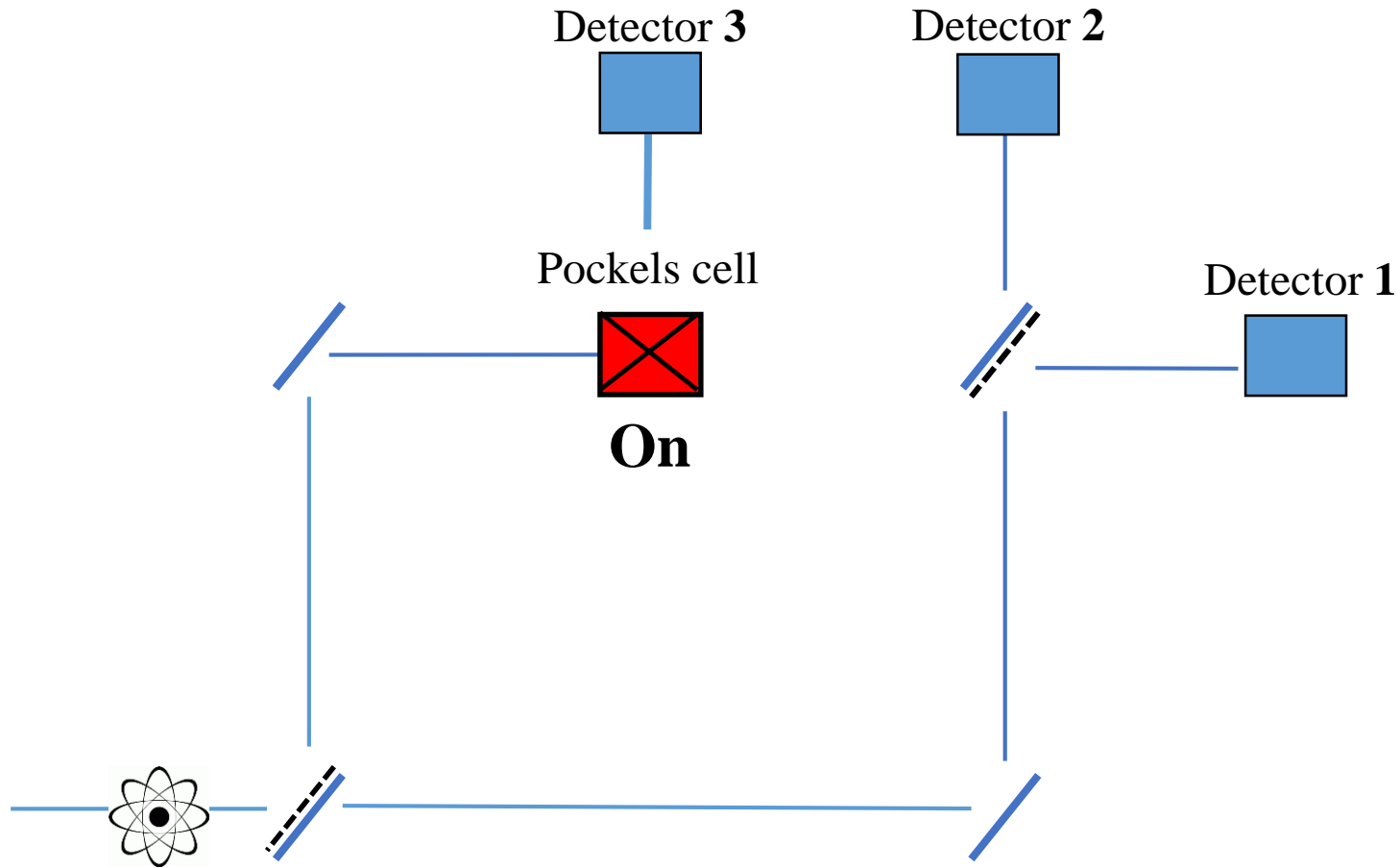


After the experiment has run for a while, we get...

- (A) Those that arrived when de
PC was set to divert
- (B) Those that arrived when de
PC was set to transmit

Looking at data, what do we expect to find?

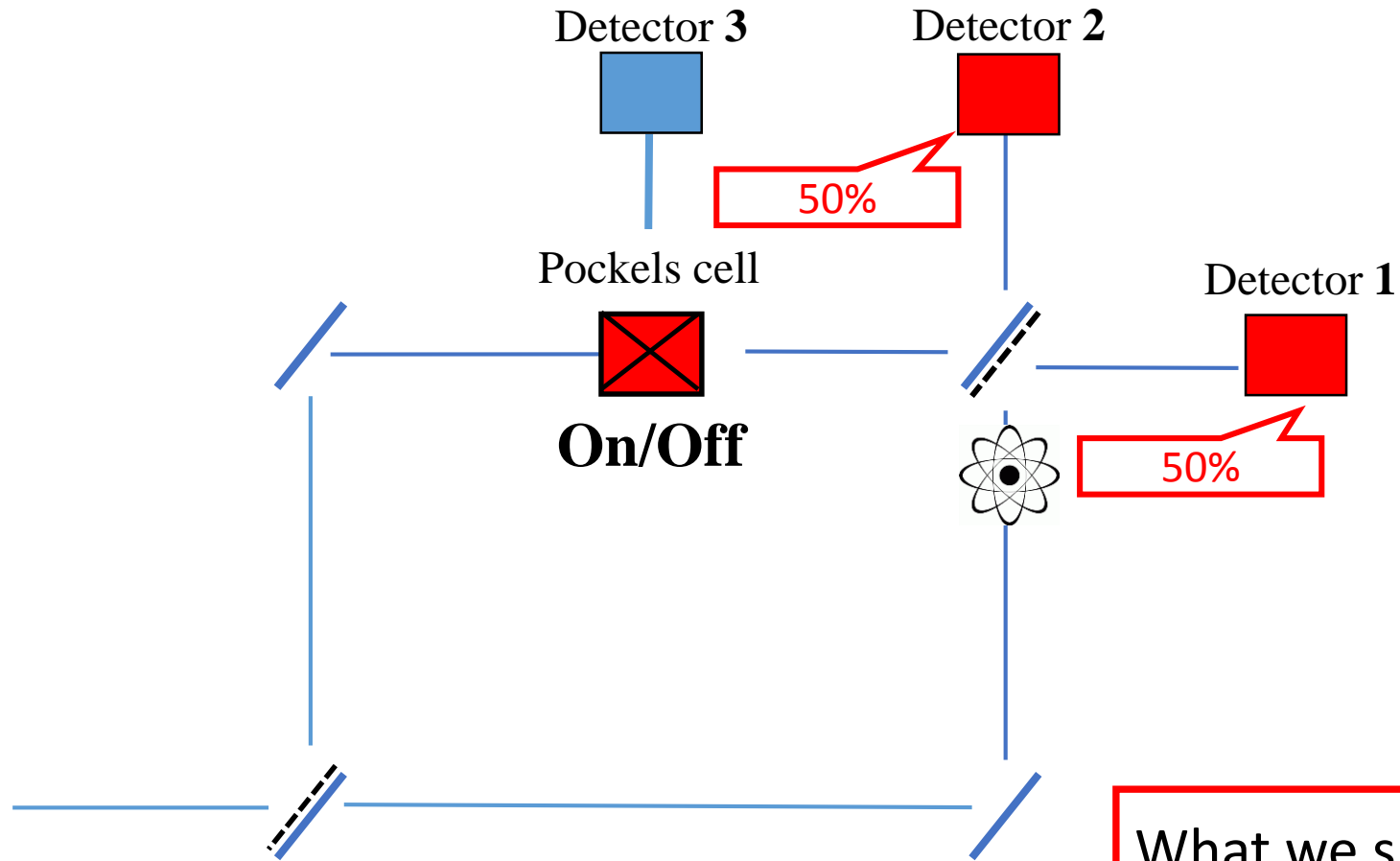
Delayed-choice experiment



Give us pause...

- In every case, the PC was *initially* set to divert photons, that is, it was set to know which path the photon took (**particle-like behavior**)
- We knew that photons mysteriously noticed how the interferometer is *at the beginning of the experiment* set and they behave according to that.

Delayed-choice experiment

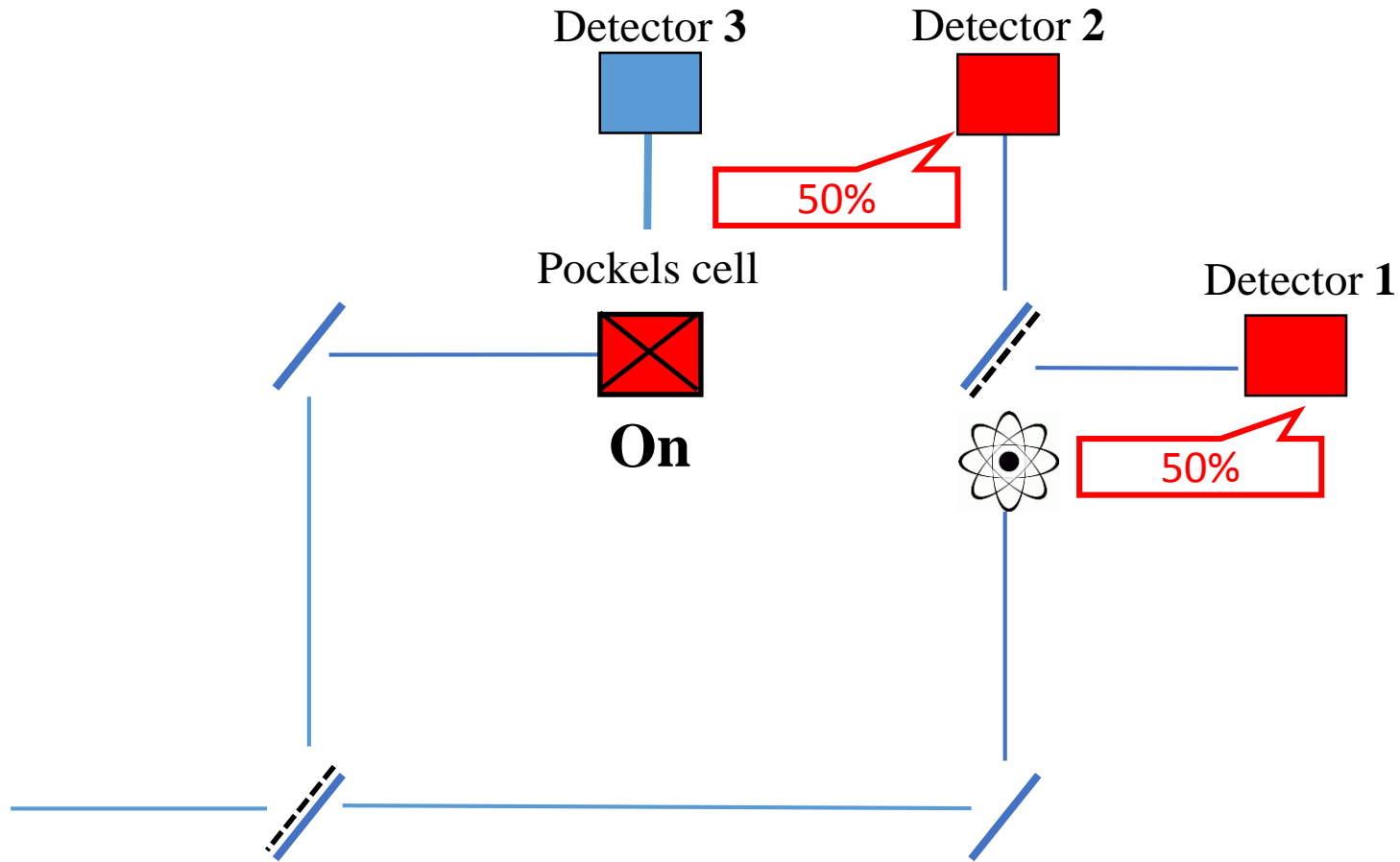


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- ❑ We knew that photons mysteriously noticed how the interferometer is *at the beginning of the experiment* set and they behave according to that.

What we should expect is the half of the photons at D2 and the other half at D1.

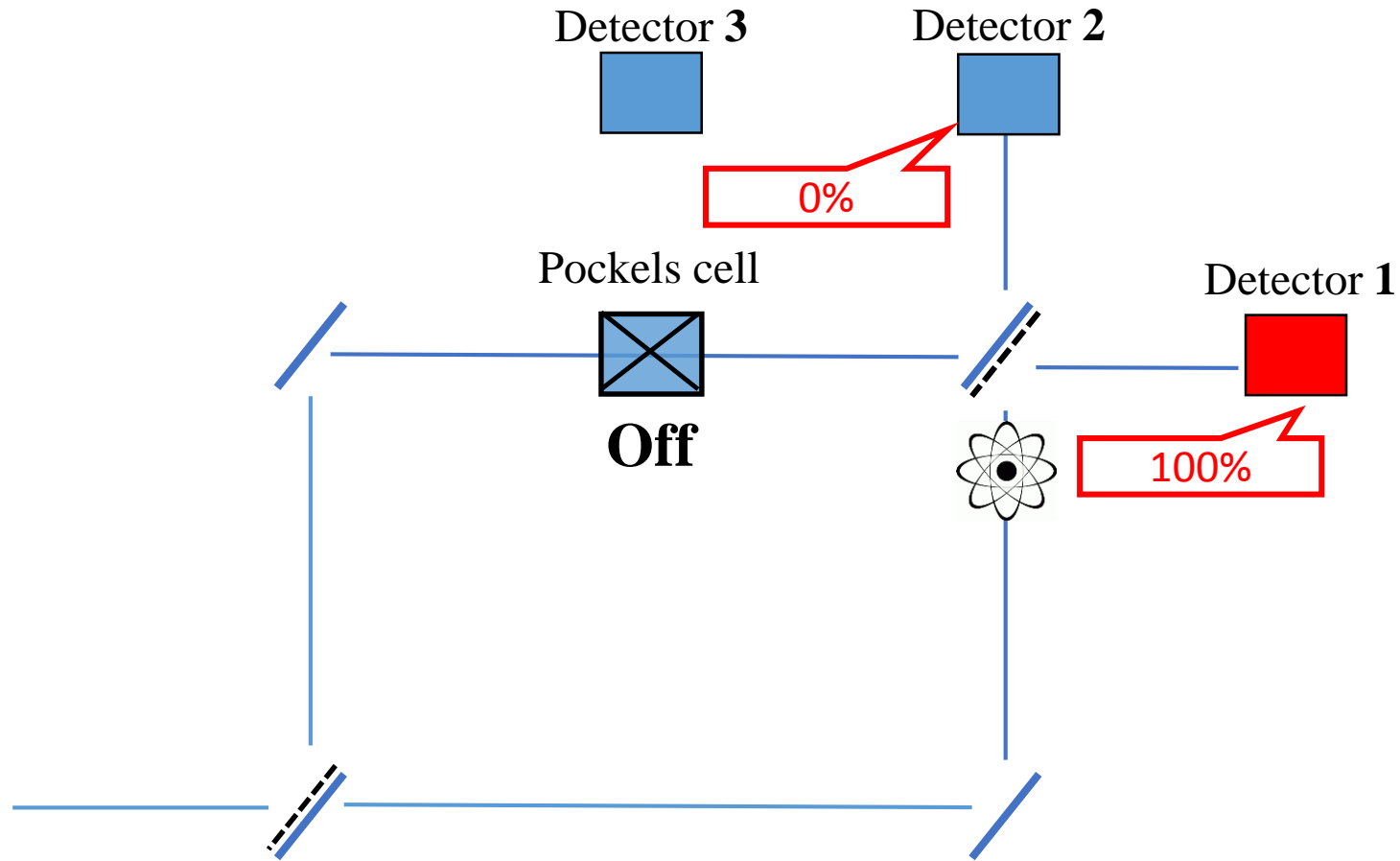
Delayed-choice experiment



However, what we really find is...

- ☐ Those photons, that arrived at the far end of the experiment when the cell was set to divert, don't produce an interference pattern.
- ☐ But those photons that arrived when the cell was switch over do produce an interference pattern!

Delayed-choice experiment



However, what we really find is...

- ☐ Those photons, that arrived at the far end of the experiment when the cell was set to divert, don't produce an interference pattern.
- ☐ But those photons that arrived when the cell was switch over **do produce an interference pattern!**

Delayed-choice experiment

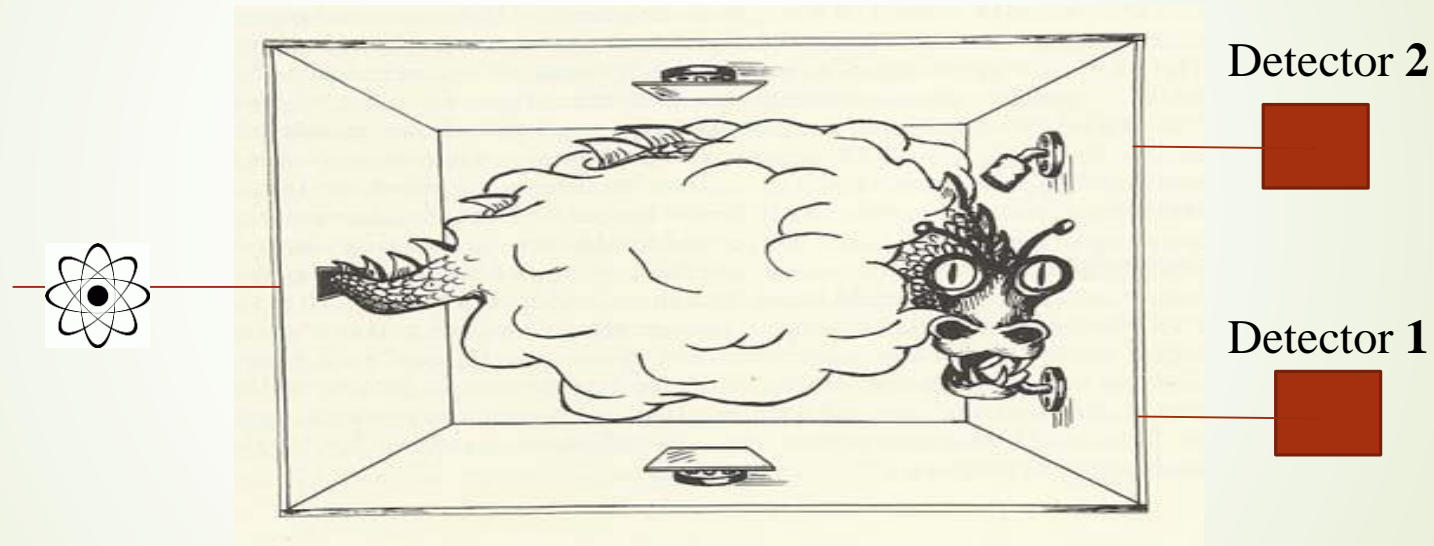
So, facts are...

- The **original configuration** is not the only factor affecting the nature of the quantum system: **any delayed choice** made after that the photon interacted with the first half-silvered mirror and before that that reach detectors will do that as well.
- The nature of the quantum system (particle-like or wave-like) is determined by the **original and delayed** interferometer configuration.

And questions are...

- How does the photon travelling on the lower path **know** that we switched the cell over on the upper path?
- Is there some kind of influence backward in time to when the photon reaches the mirror? Is delayed-choice experiment an instance of “**retro-causation**”?

What is there inside of “*the great smoky dragon*”?



Cristian López

31th of March

Second Part

Interpreting the experiment

How does the paradox arise?

- ❑ How does the photon *know* how to behave if the observer has not yet decided yet whether the PC will finally be on or off?
- ❑ how does the photon on the lower path *know* that a modification was performed on the upper path and that it then must change its particle-like behavior into a wave-like one?
- ❑ The paradox crops up when **we ask about the nature of the photon before it is measured**: what is there inside the “great smooky dragon”?
- ❑ **What is the nature** of the photon during the very short time interval between it is reflected off by the first half-mirror and our last-minute decision?
- ❑ **When we want to know what is the particle’s past!**

Anti-realism reloaded - Complementarity

As we try to describe the **lifetime** of a single real particle (**tracing its past**), the paradox crops up!

REVIEWS OF MODERN PHYSICS, VOLUME 88, JANUARY–MARCH 2016

“Wheeler’s delayed-choice experiments challenge a realistic explanation of the wave-particle duality. In such an explanation every photon is assumed to behave either definitely as a wave (traveling both paths in an interferometer) or definitely as a particle (traveling only one of the paths), by adapting a priori on the experimental situation” (Xiao-so Ma, Kofler and Zeilinger, 2015)

“the delayed-choice entanglement-swapping experiment reinforces the lesson that quantum states are neither descriptions nor representations of physical reality” (Haley 2012)

Delayed-choice gedanken experiments and their realizations

Xiao-song Ma^{*}

Institute for Quantum Optics and Quantum Information (IQOQI), Austrian Academy of Sciences, Boltzmannngasse 3, 1090 Vienna, Austria, Department of Electrical Engineering, Yale University, 15 Prospect Street, New Haven, Connecticut 06520, USA, and National Laboratory of Solid State Microstructures, School of Physics, Collaborative Innovation Center of Advanced Microstructures, Nanjing University, Nanjing 210093, China

Johannes Kofler[†]

Max Planck Institute of Quantum Optics (MPQ), Hans-Kopfermann-Straße 1, 85748 Garching, Germany

Anton Zeilinger[‡]

Vienna Center of Quantum Science and Technology (VCQ), University of Vienna, Boltzmannngasse 5, 1090 Vienna, Austria

Anti-realism reloaded - Complementarity

Delayed-choice experiment as a confirmation of Principle of Complementarity

nature
physics

LETTERS

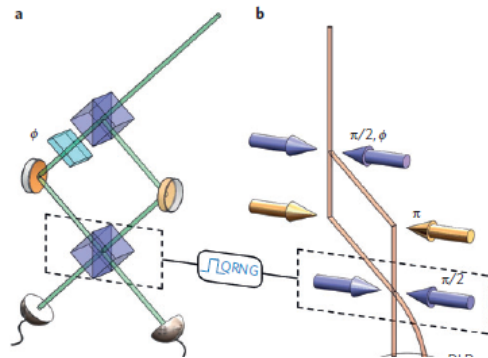
PUBLISHED ONLINE: 25 MAY 2015 | DOI: 10.1038/NPHYS3343

Wheeler's delayed-choice gedanken experiment with a single atom

A. G. Manning, R. I. Khakimov, R. G. Dall and A. G. Truscott*

The wave-particle dual nature of light and matter and the fact that the choice of measurement determines which one of these two seemingly incompatible behaviours we observe are examples of the counterintuitive features of quantum mechanics. They are illustrated by Wheeler's famous 'delayed-choice' experiment¹, recently demonstrated in a single-photon experiment². Here, we use a single ultracold metastable helium atom in a Mach-Zehnder interferometer to create an atomic analogue of Wheeler's original proposal. Our experiment confirms Bohr's view that it does not make sense to ascribe the wave or particle behaviour to a massive particle before the measurement takes place³. This result is encouraging for current work towards entanglement and Bell's theorem tests in macroscopic systems of massive particles³.

The question of whether light behaves like a particle or wave had a long and strongly contested history until the advent of quantum mechanics when it was established that it could indeed



*“Our experiment confirms Bohr’s view that it does not make sense to ascribe the wave or particle behaviour to a massive particle before the measurement takes place”
(Manning et al. 2015)*

Anti-realism reloaded - Complementarity

We should say nothing about what there is inside of “great smoky dragon”!

“we are not dealing with contradictory but **complementary pictures** of the phenomena” (Bohr 1928)

“Consequently, evidence obtained under different experimental conditions **cannot be comprehended within a single picture**, but **must be regarded as complementary** in the sense that only the totality of **phenomena** exhausts the possible information about the objects” (Bohr 1949)



“As a more appropriate way of expression I advocated the application of the word **phenomenon** exclusively to refer to **the observations obtained under specified circumstances**, including an account of the whole experimental arrangement” (Bohr 1949)

Lev Vaidman – We can trace the particle's past!

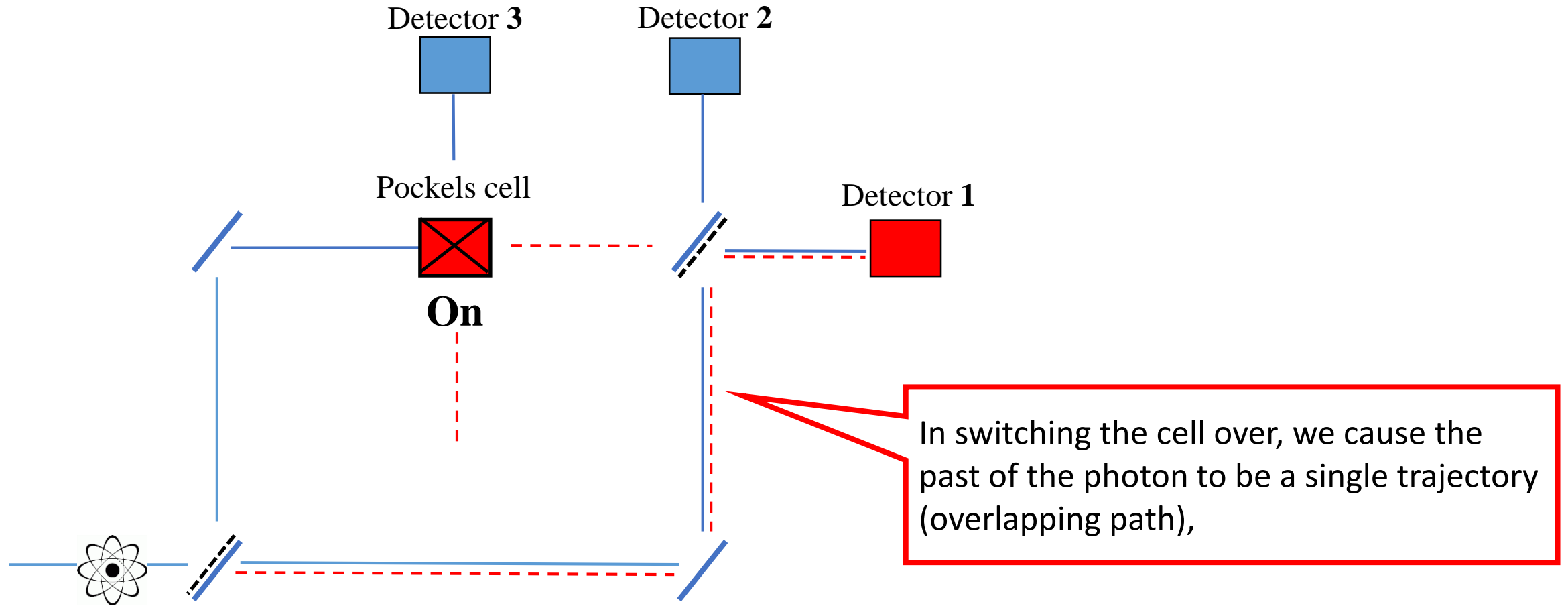
- ❑ “The experiment demonstrated the bizarre feature of a quantum particle that a choice of measurement performed now **determines its behavior in the past**” (Vaidman 2014)
- ❑ In order to explain that we need a new formalism: “the two-state vector formalism”

$$\langle \Phi | \Psi \rangle$$

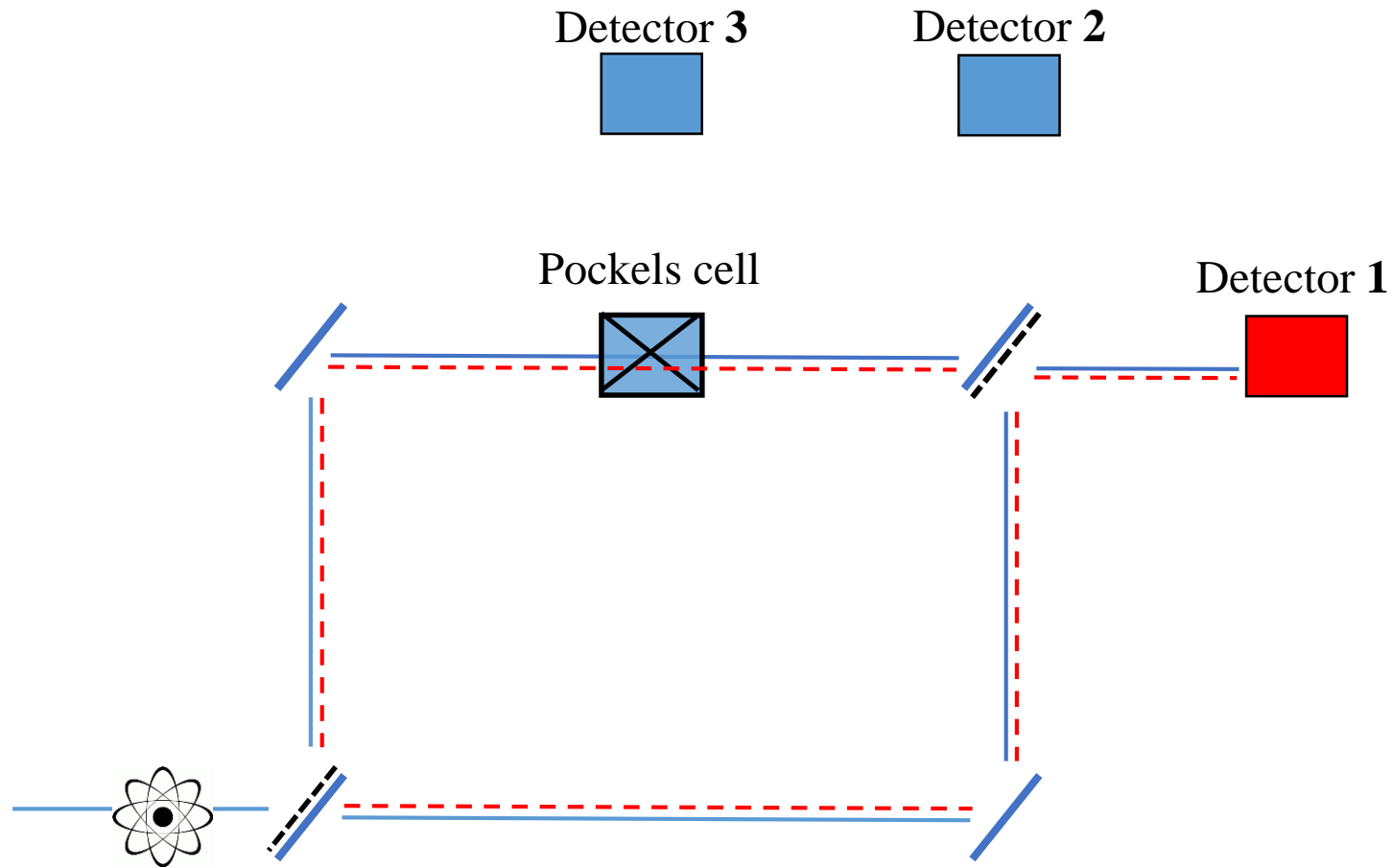
*“The **usual quantum** state **evolving forward in time**, defined by the results of a complete measurement at the earlier time, and by a quantum state **evolving backward in time**, defined by the results of a complete measurement at a later time” (Vaidman 2013)*

- ❑ The particle was in the **overlap** of the forward and backward evolving quantum state
- ❑ The wave-function of the particle can be affected by objects placed in any point where at least one of the waves is present.

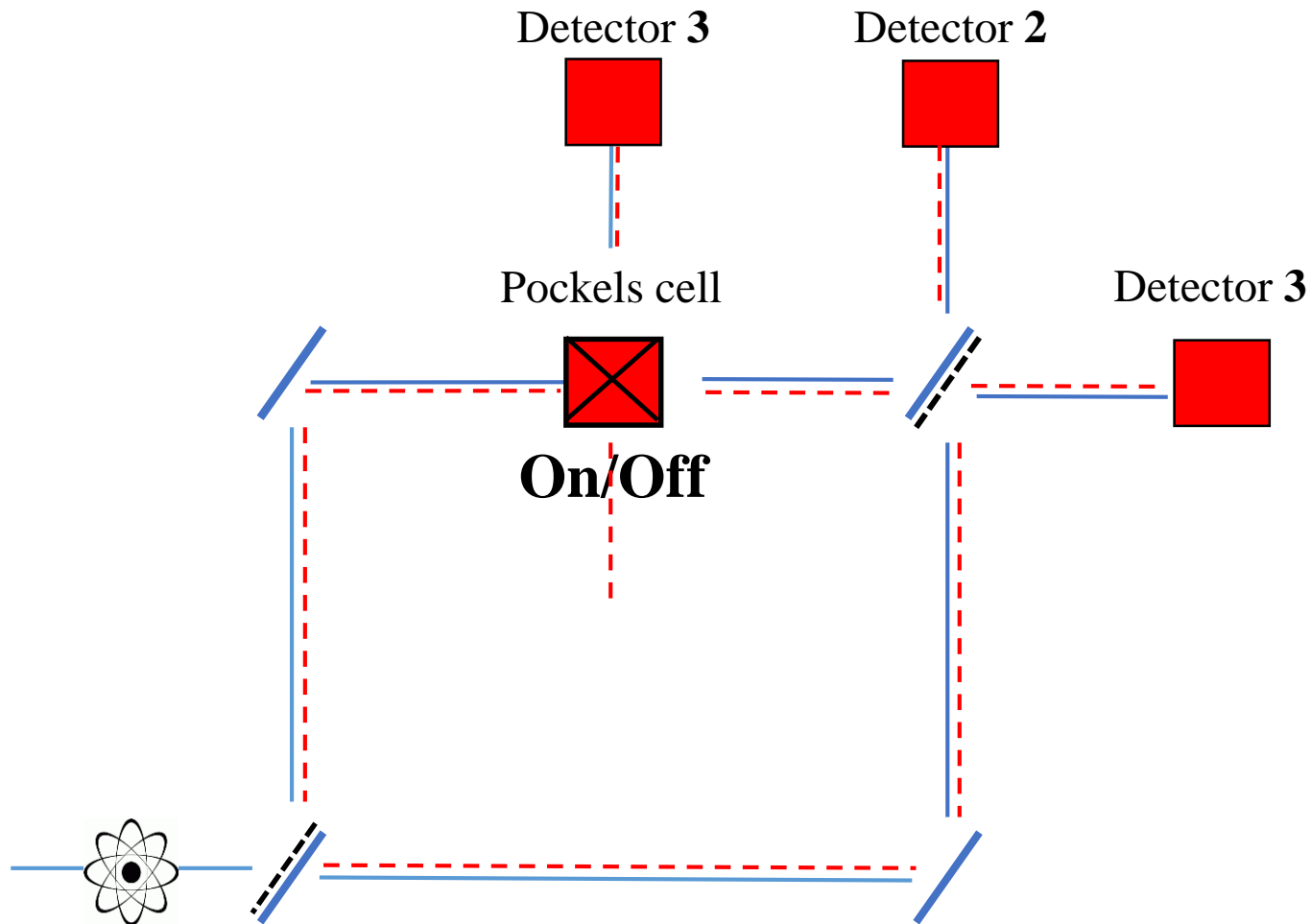
Lev Vaidman – We can trace the particle's past!



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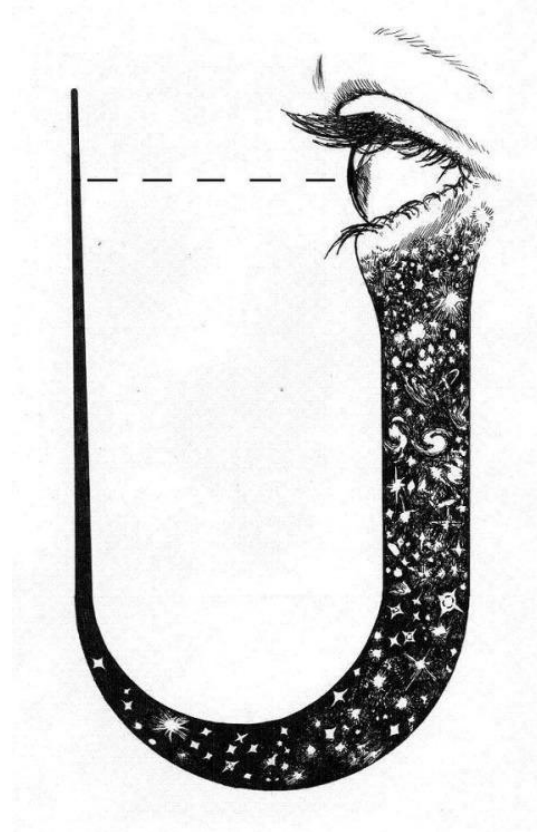
Lev Vaidman – We can trace the particle's past!



- ❑ Lev Vaidman says that TSVF finds a natural place within the framework of **Many-World Interpretation**
- ❑ Naturally, we are seeing what happens **in one world**, but from the point of view of the Universe (incorporating all the worlds), we get...
- ❑ “Secondary presence”

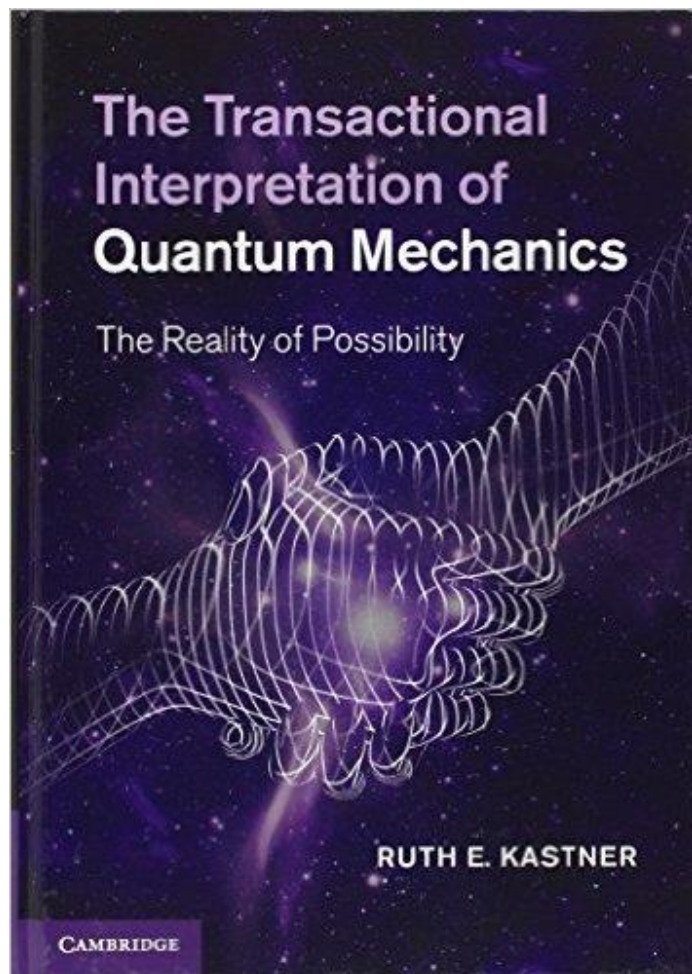
John Wheeler– Participatory Universe

Only **we can speak** about the past of the particle after it has completely finished its travel and has been registered. In doing that, we create the past of the particle.



- ❑ “We have a **strange inversion of the normal order of time**. We, now, by moving the mirror in or out have an unavoidable effect on what we have a right to say about the already **past history** of that photon” (Wheeler 1984)
- ❑ “**One decide** whether the photon ‘shall have come by one route or by both routes’ after it has already done its travel” (Wheeler 1984)
- ❑ “the **past has no existence except as it is recorded in the present** (...) [t]he universe does not ‘exist, out there,’ independent of all acts of observation” (Wheeler 1978)

Transactional Interpretation – Handshake!



The Transactional Interpretation of Quantum Mechanics

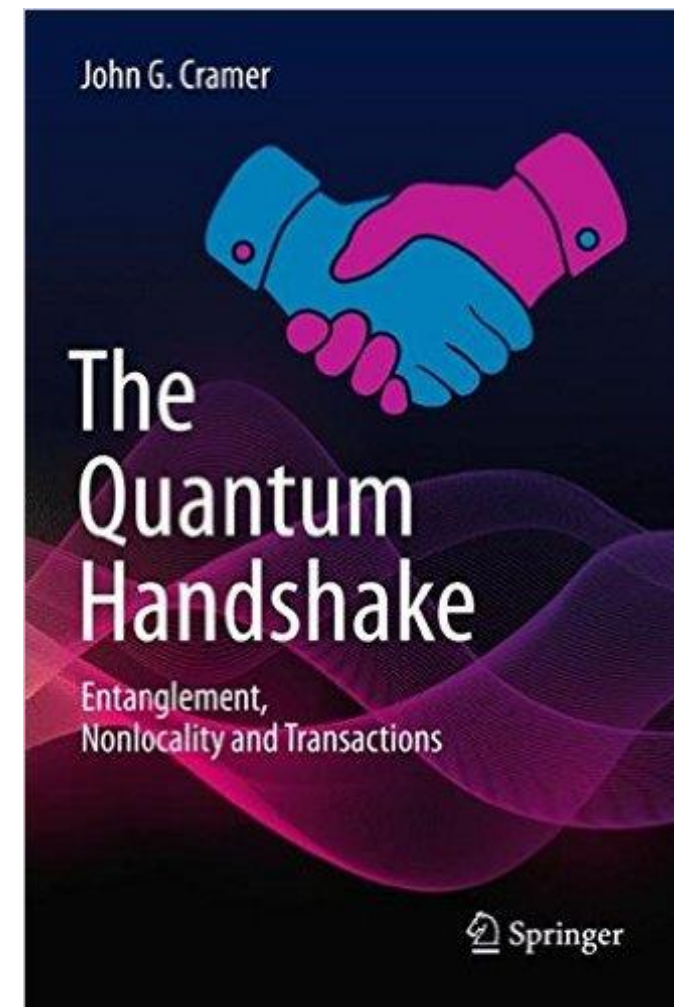
The Reality of Possibility

RUTH E. KASTNER

CAMBRIDGE

Ruth Kastner (2014)

John Cramer (2016)



John G. Cramer

The Quantum Handshake

Entanglement,
Nonlocality and Transactions

Springer


Transactional Interpretation – Handshake!

“The emphasis is on a clear understanding of how the instantaneous “collapse” of the wave function due to a measurement at a specific time and place may be reinterpreted as a relativistically well-defined collapse over the entire path of the photon and over the entire transit time from slit to detector. This is made possible by the use of a **retarded offer wave**, which is thought to travel from the slits (or rather the small region within the parametric crystal where down-conversion takes place) to the detector and an **advanced counter wave traveling backward in time** from the detector to the slits” (Fearn 2016)

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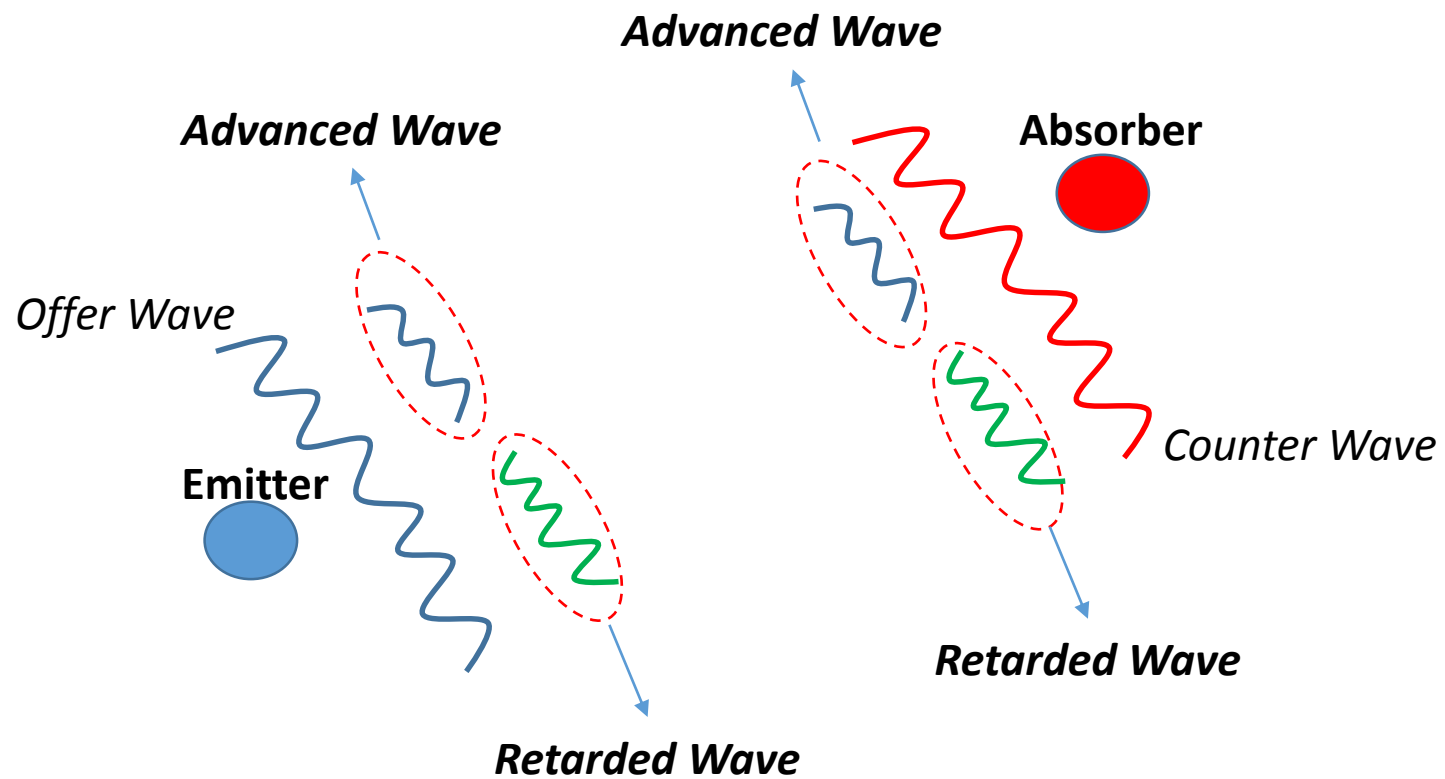
A Delayed Choice Quantum Eraser Explained by the Transactional Interpretation of Quantum Mechanics

H. Fearn¹ 

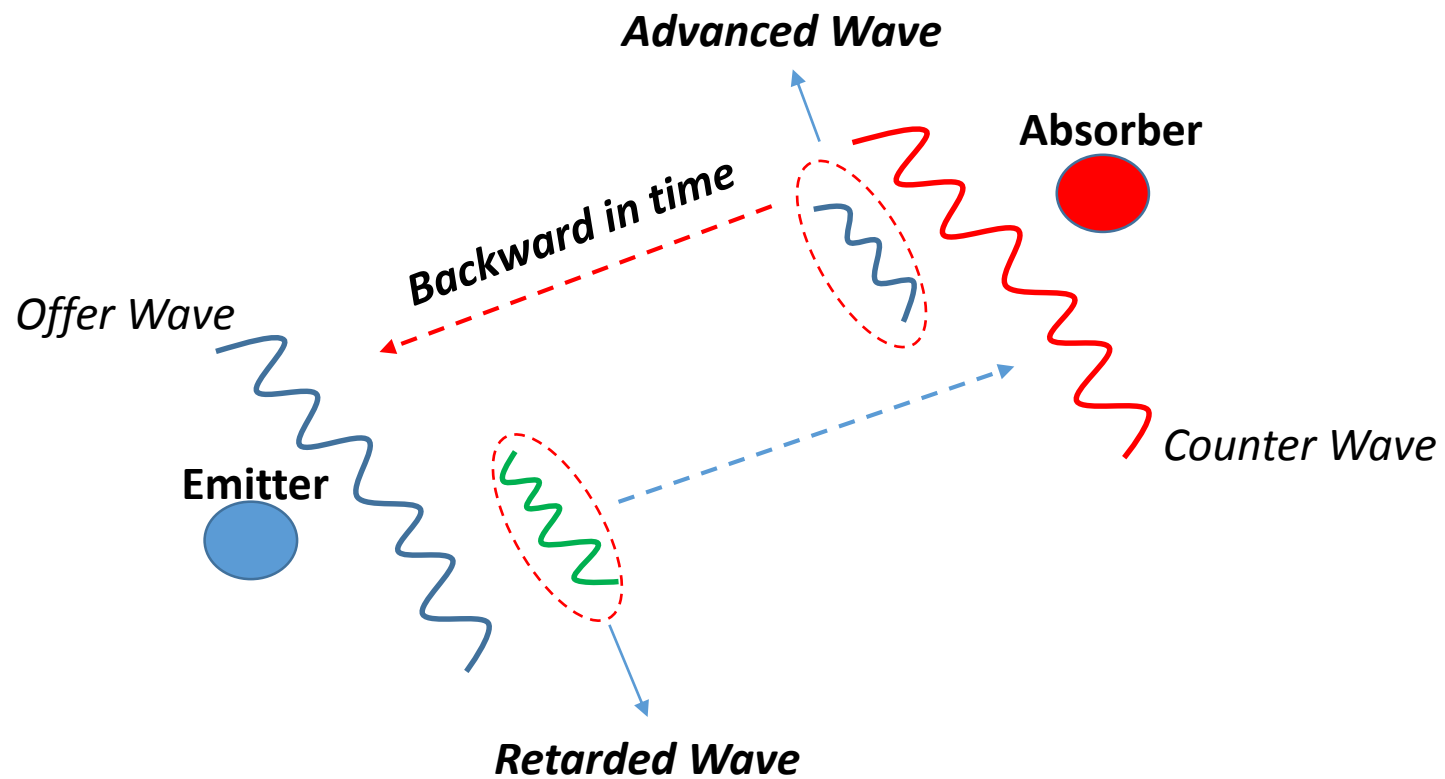
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Abstract This paper explains the delayed choice quantum eraser of Kim et al. (A delayed choice quantum eraser, 1999) in terms of the transactional interpretation (TI) of quantum mechanics by Cramer (Rev Mod Phys 58:647, 1986, The quantum handshake, entanglement, nonlocality and transactions, 1986). It is kept deliberately

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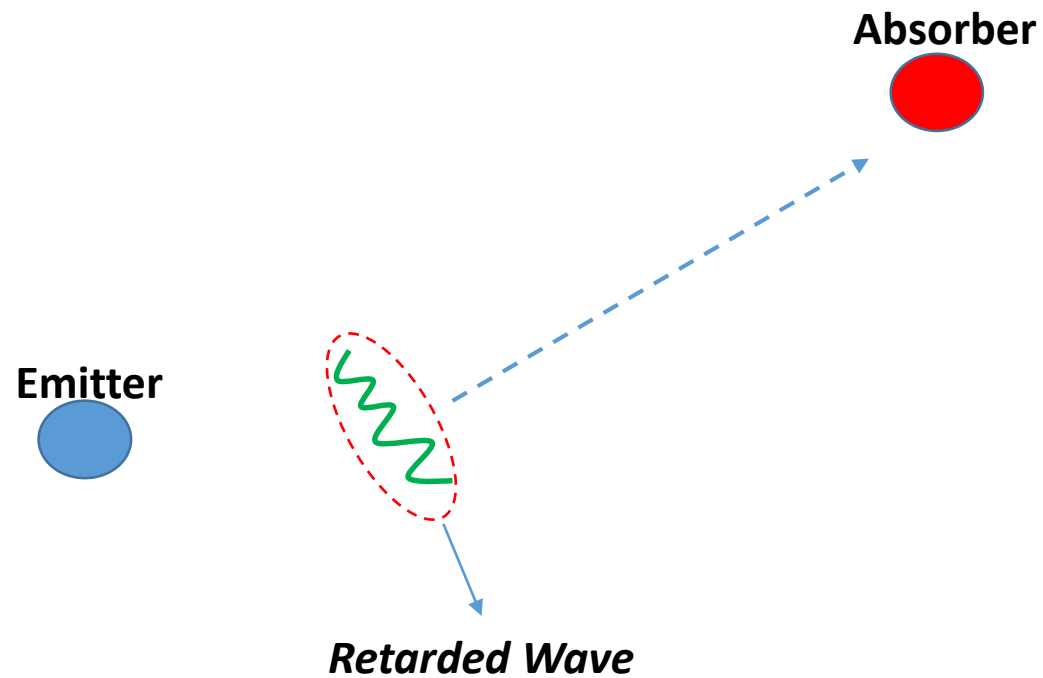


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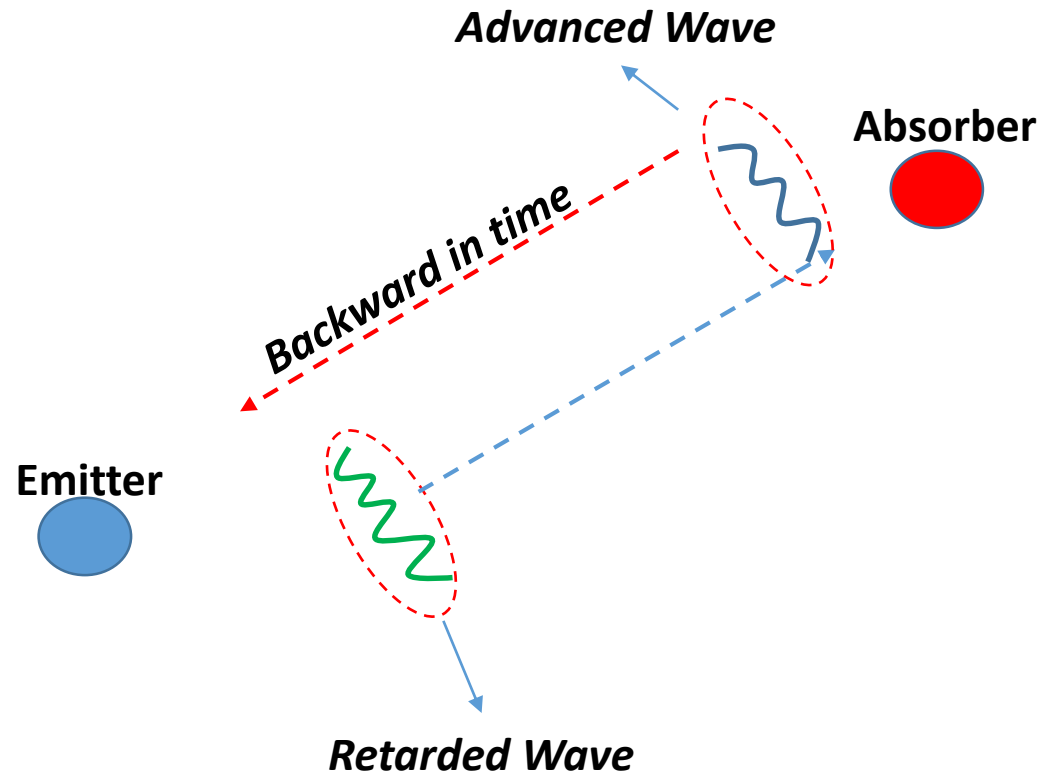
What is an interaction?

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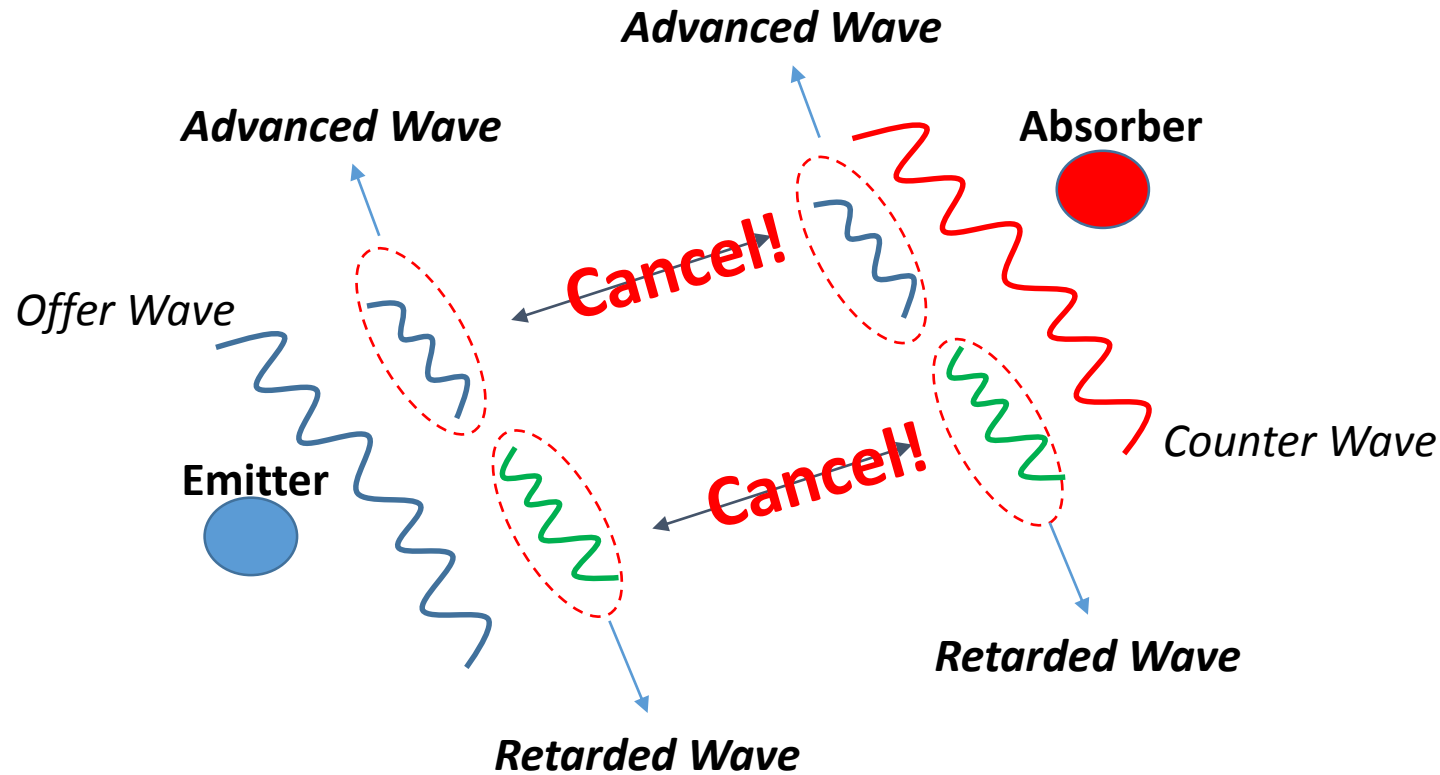
- The **retarded offer wave** reaches the absorber (particle 2)
- When the retarded offer wave reaches the absorber, it sends out a counter wave
- The **advanced counter wave** would travel backward in time along the same path of the **retarded offer wave**.

Transactional Interpretation – Handshake!



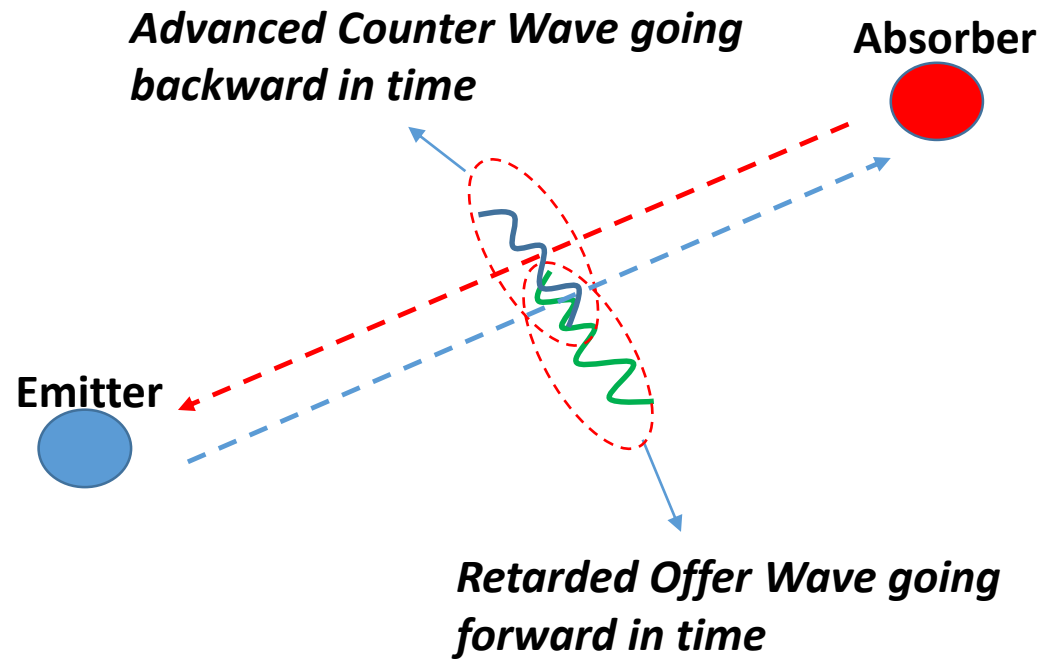
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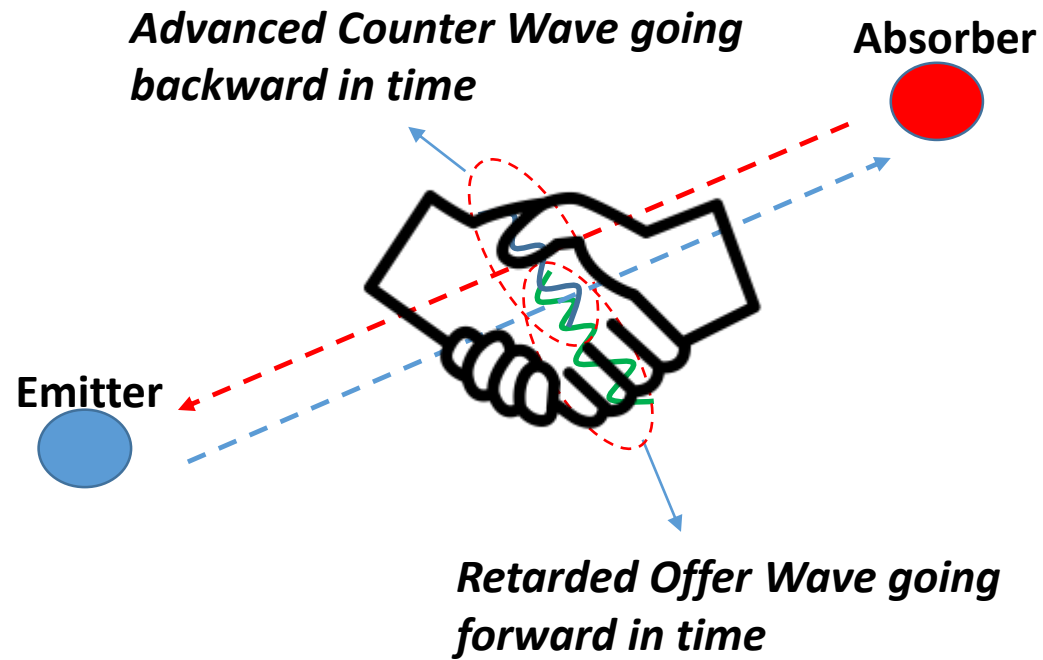
- ❑ **Retarded offer wave – Retarded counter wave** = cancel at the location of the absorber
- ❑ **Advanced offer wave – Advanced counter wave** = cancel at the location of the emitter.

Transactional Interpretation – Handshake!



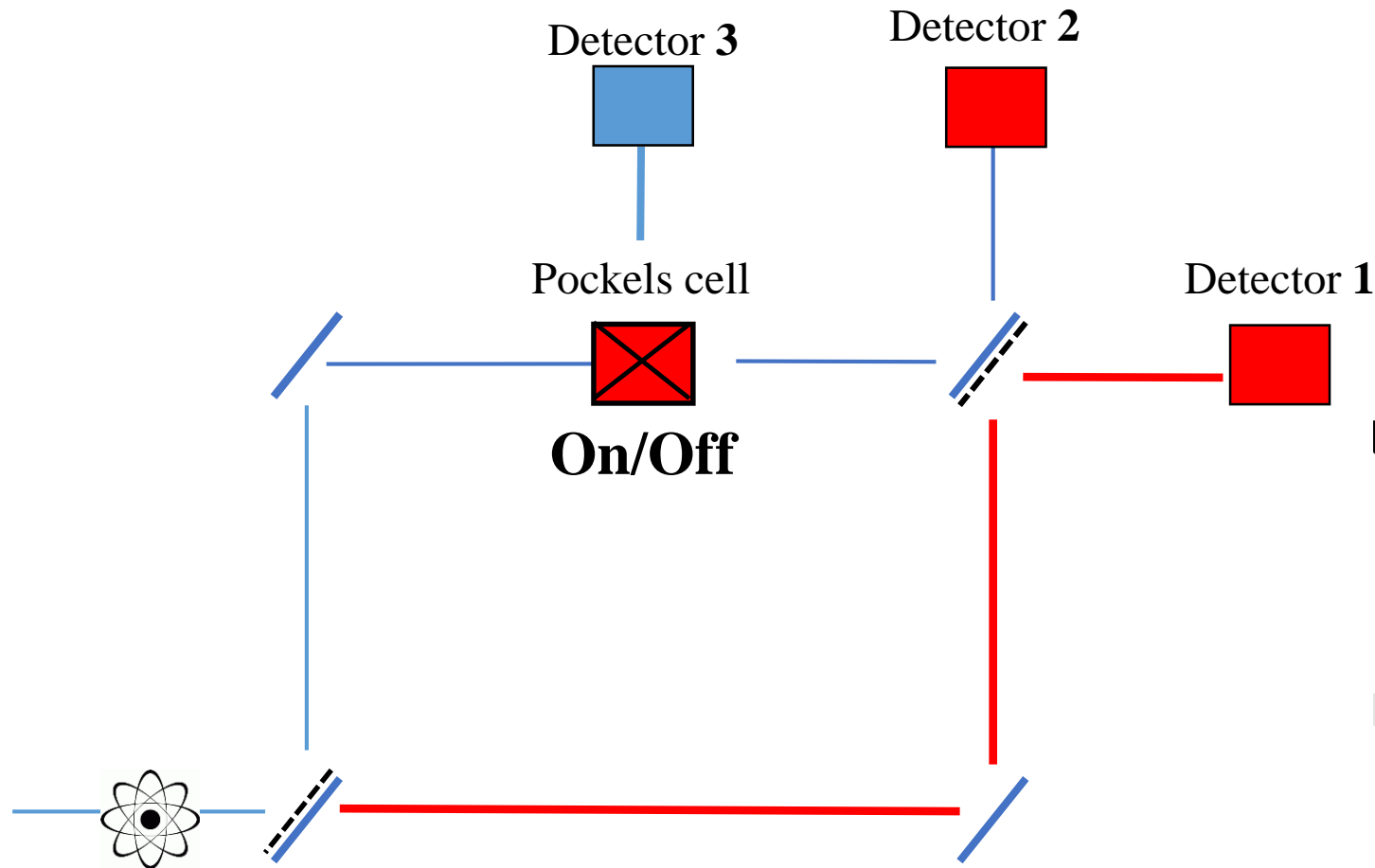
- These waves represent the interaction between the particles
- Constructive interference
- Interaction = Quantum Handshake!

Transactional Interpretation – Handshake!



- These waves represent the interaction between the particles
- Constructive interference
- Interaction = **Quantum Handshake!**

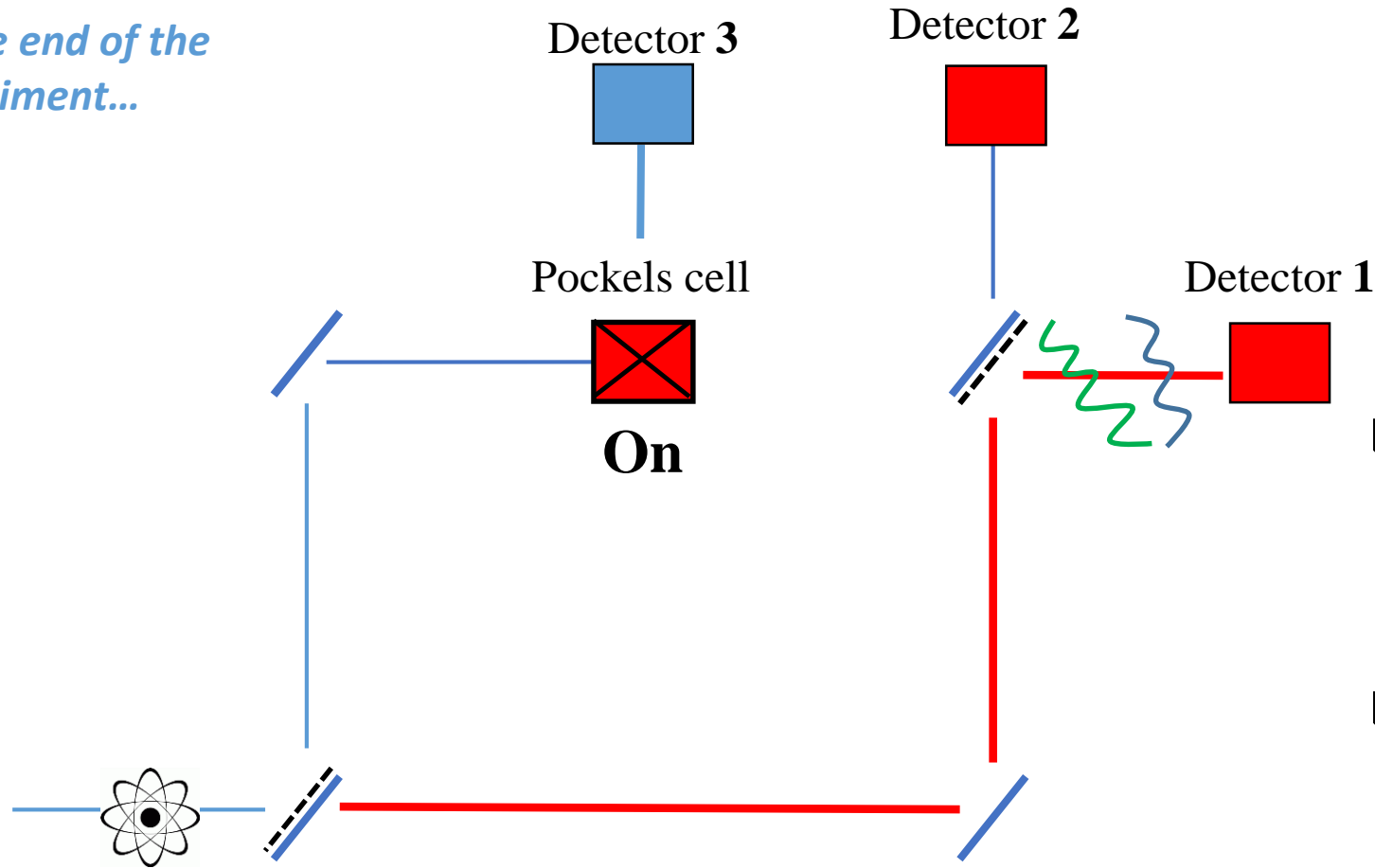
Transactional Interpretation – Handshake!



- ❑ The wave function would **collapse along the entire paths** between the laser and the detector
- ❑ When the **advanced counter wave** is sent out from the detector 1, the PC is turn on!

Transactional Interpretation – Handshake!

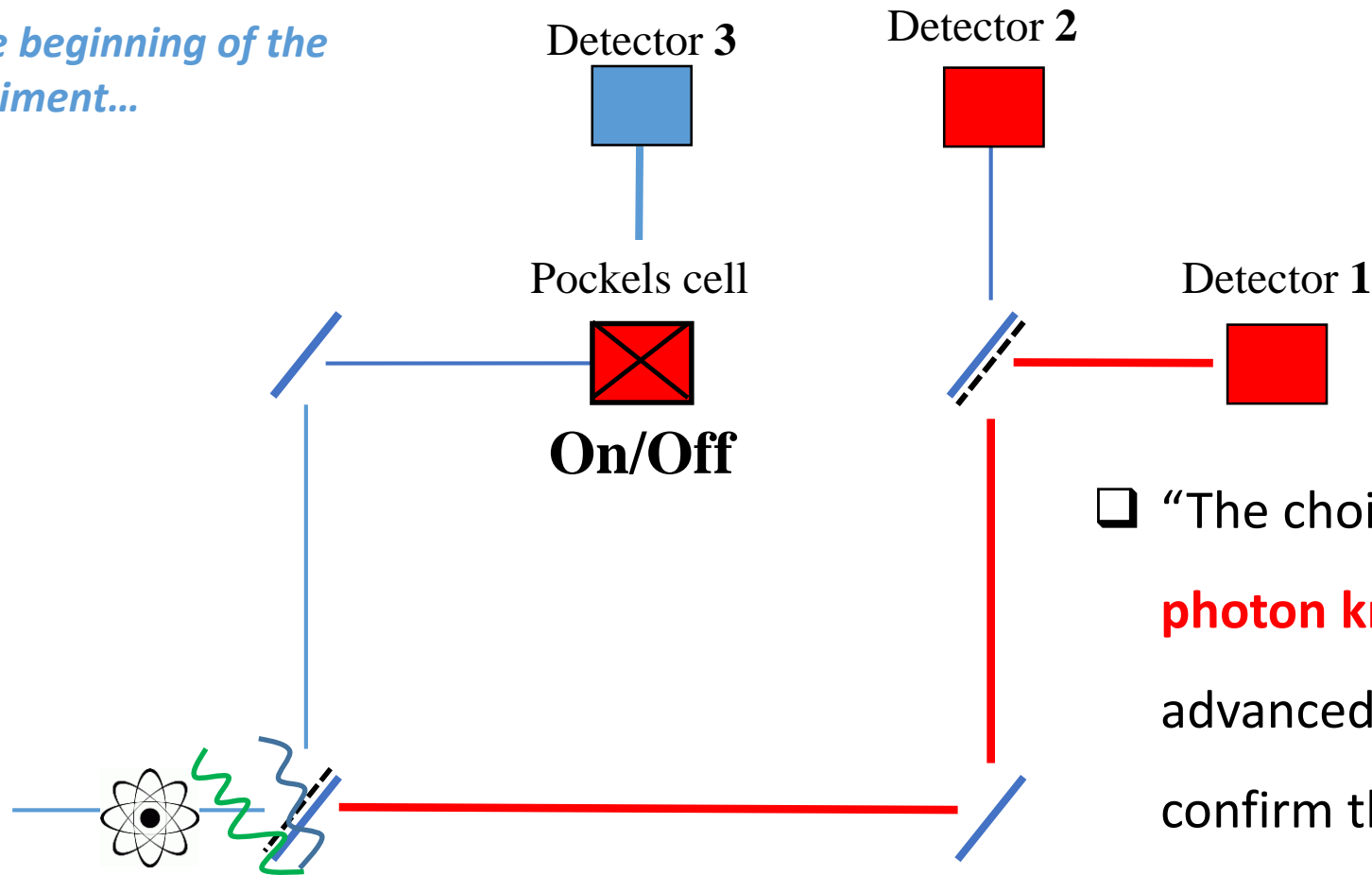
At the end of the experiment...



- ❑ The wave function would **collapse along the entire paths** between the laser and the detector
- ❑ When the **advanced counter wave** is sent out from the detector 1, **the PC is turn on!**

Transactional Interpretation – Handshake!

At the beginning of the experiment...



- “The choice is really no longer delayed since the **photon knows** where it will end up because the advanced wave coming backward in time to confirm the interaction or quantum handshake” (Fearn 2016)

Final Remarks

- ❑ Some authors interpret delayed-choice experiment as a **strong argument against** any realist interpretation of quantum mechanics.
- ❑ Realist interpretations appeal to (a) some kind of retro-causation or (b) waves going backward in time.
- ❑ All realist interpretations suppose an ***ontology of individuals according to which particles are substances + properties***
- ❑ ***What happens if we turn the ontology around and properties are grasped as fundamental entities?***