How to Test Quantum Causality with the Neutron Interferometer

Richard Wagner

Neutrons for Europe
USER MEETING
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Outline

- Motivation
- Preliminaries
- Quantum Causality:
  Delayed Choice Cheshire Cat Experiment

Motivation

- <u>Causality</u>

  Relationship between cause and effects

  Classically an effect cannot occur before the cause.

  In QM this fixed order is loosened as can be demonstrated in an experiment with a delayed choice setting

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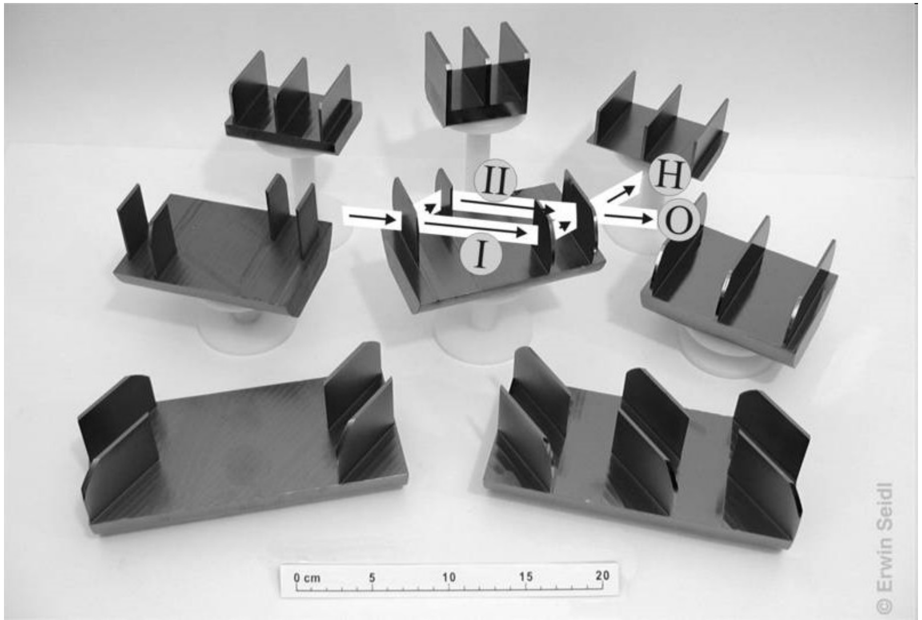
Delayed Choice Cheshire Cat Experiment

Neutron Interferometry

- Neutrons have wave and particle properties
  $p = mv = h/\lambda$ (L. De Broglie)
- Perfect Silicon Crystals can be utilized to build interferometer for neutrons
- Can be used to demonstrate fundamental laws of quantum mechanics
  (e.g. 4π symmetry of the wave function)



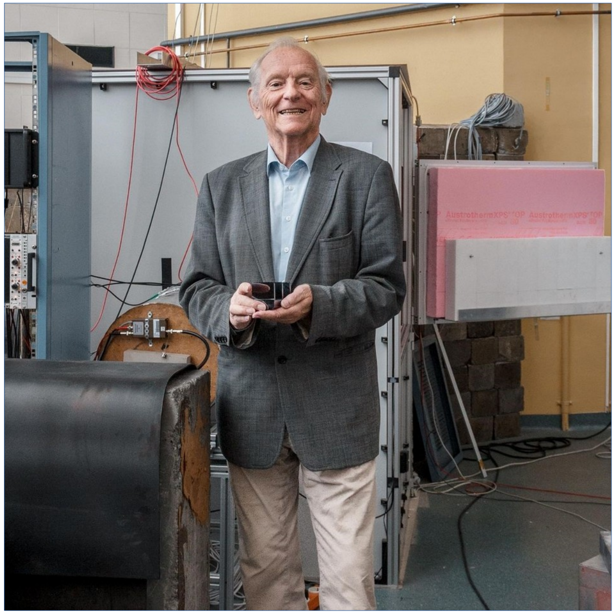
Self-interference

Neutron Interferometry

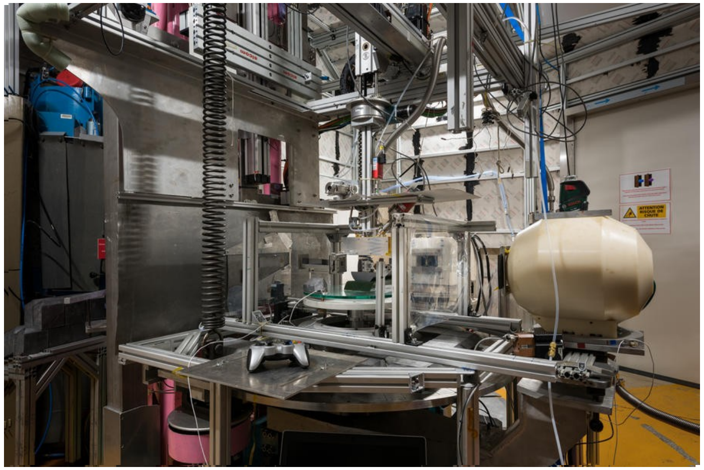
- Demonstrated successfully in 1974 by Helmut Rauch et al. at the Atominstitut Vienna, Austria

- Due to this the Atominstitut was granted 2019 the status of an EPS (European Physical Society) Historic Site

- Soon afterwards plans for experiments at the ILL
  - ➔ today the instrument S18



H.Rauch 1939-2019



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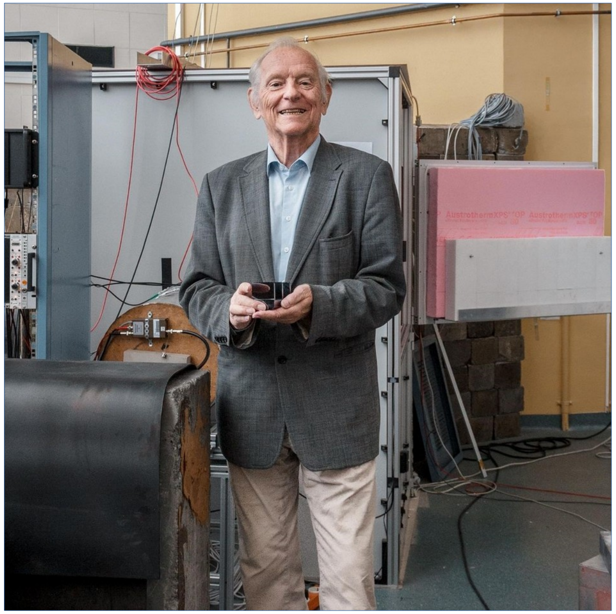
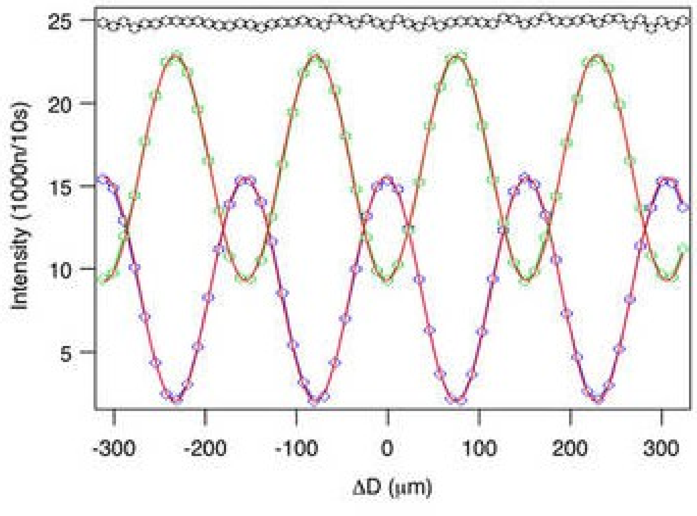


H.Rauch 1939-2019

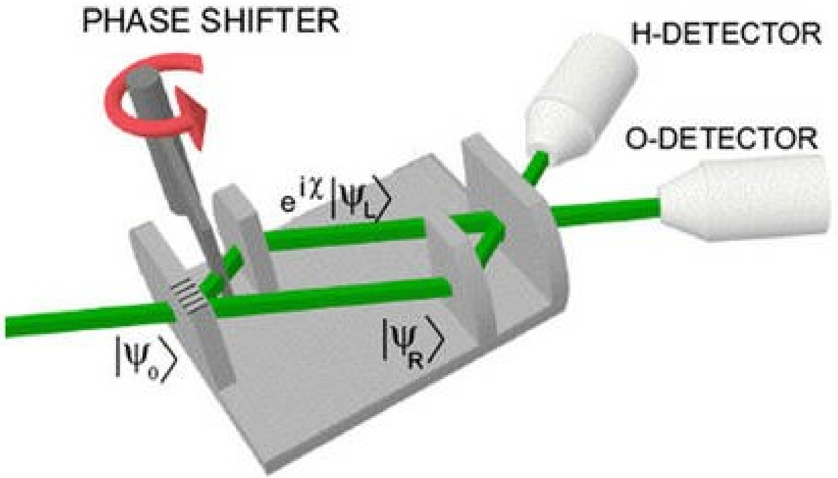
Trivia

Anton Zeilinger made his PhD Thesis under Rauch;
worked on neutron interferometry (at ILL) before moving on to photons

Basic Measuring Principle



Standard interferogram



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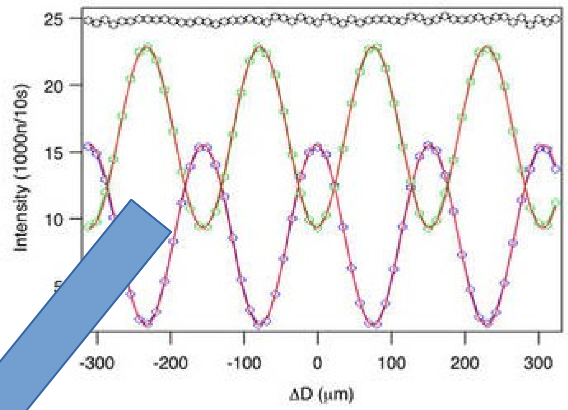

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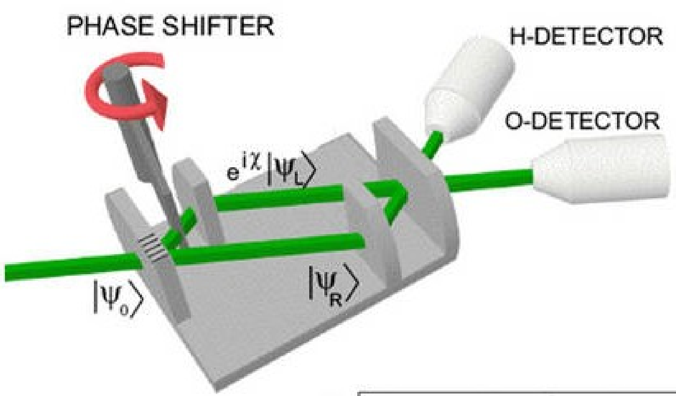
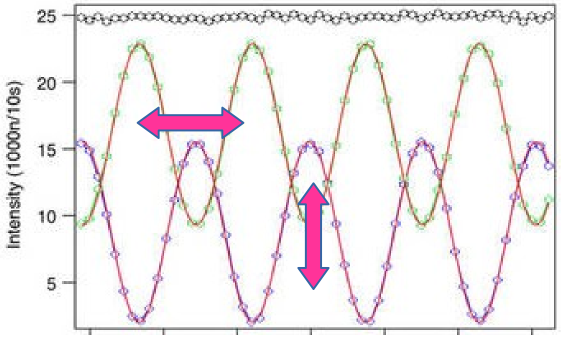


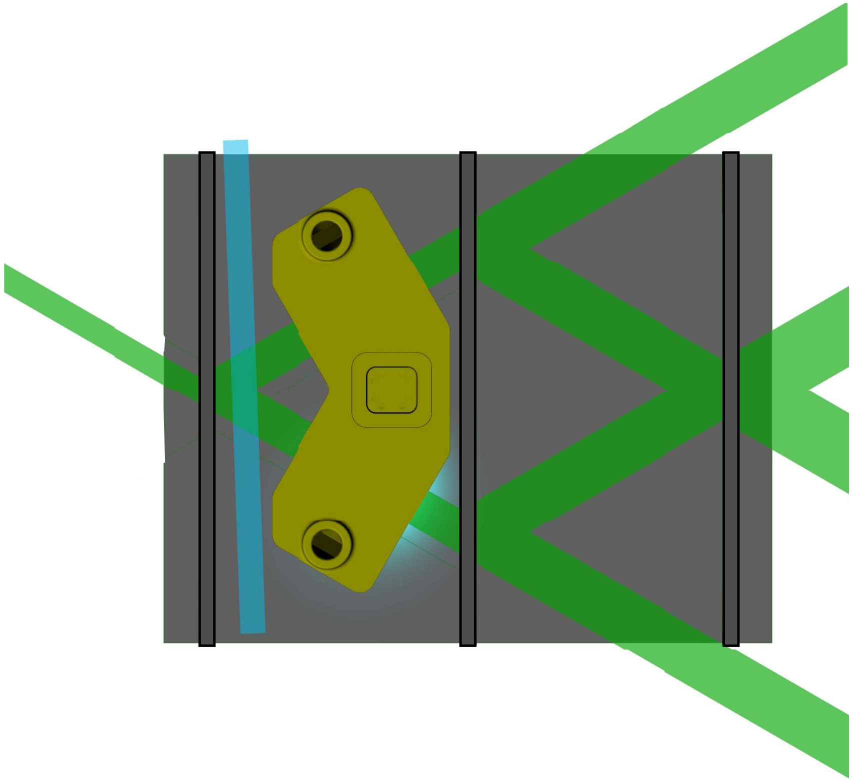
Manipulate beam paths:
e.g. magnetic fields; spin
flipper coils, insertion of probes

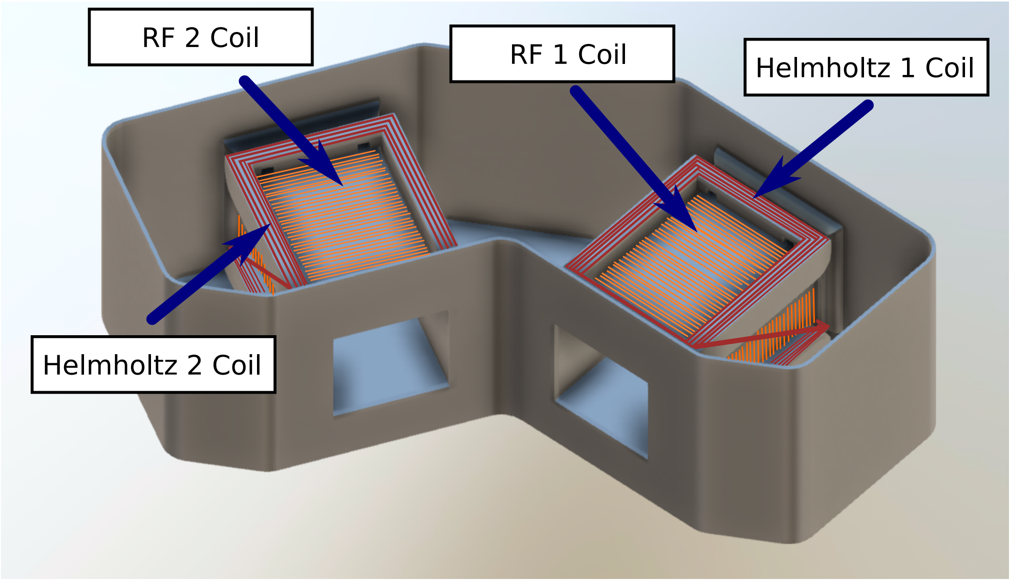


Observe/Measure shifts in interferogram

Spin Manipulation

Separate manipulation of neutron wave function in the individual paths of the interferometer

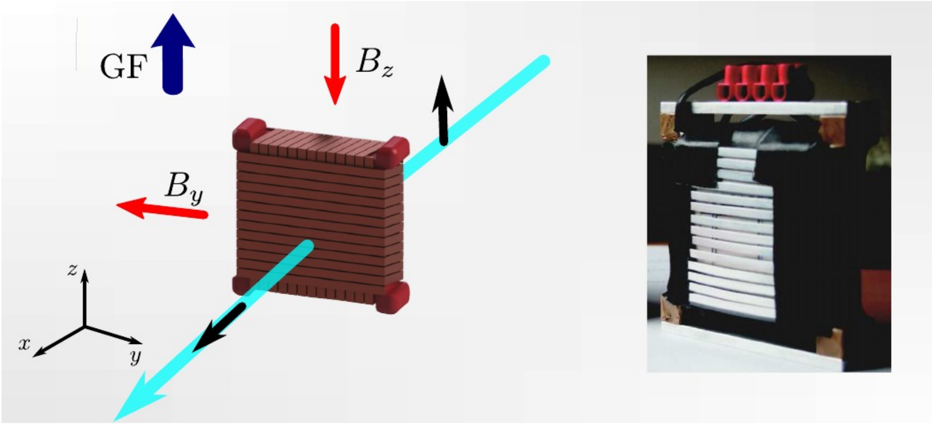




Spin Manipulators

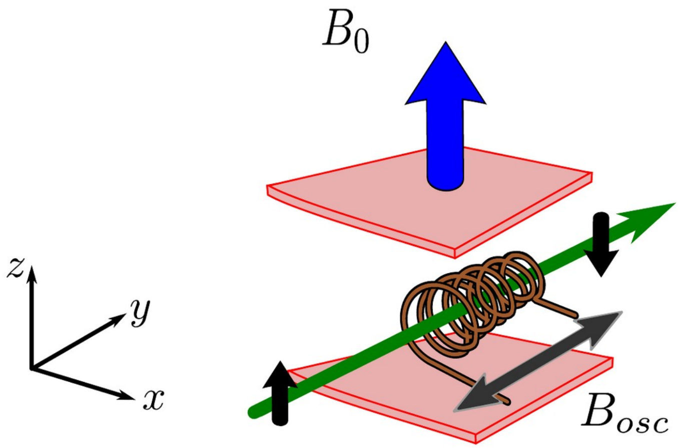
Direct Current (DC) Spin Rotator

- Change direction of the neutron spin
- Utilizing Larmor precession
- Rotation of Spin around perpendicular magnetic field



Radio Frequency (RF) Spin Rotator

- Small oscillation field B_{osc} at resonance frequency ω of guide field B_0
- Neutrons end up rotated with changed energy
  $\Delta E = \pm \hbar\omega$

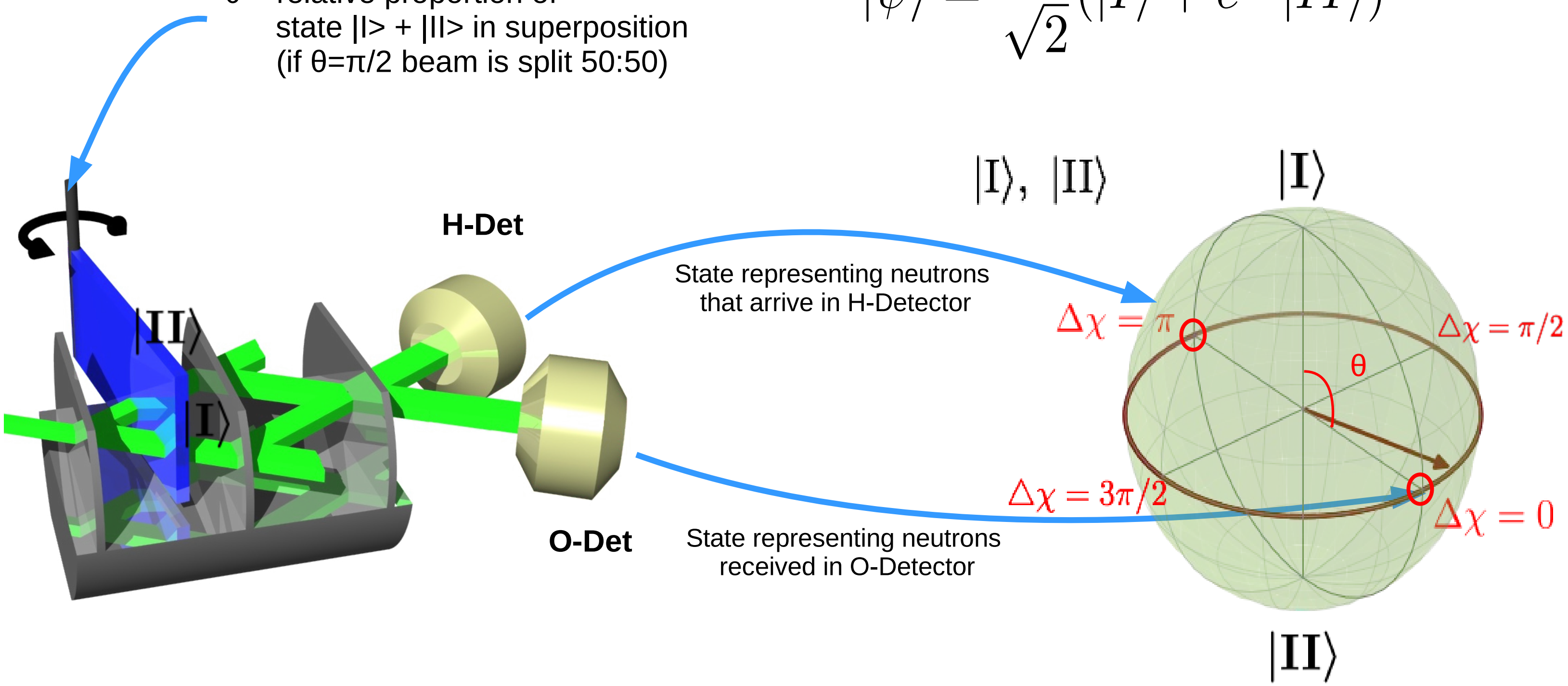


Neutron Interferometry

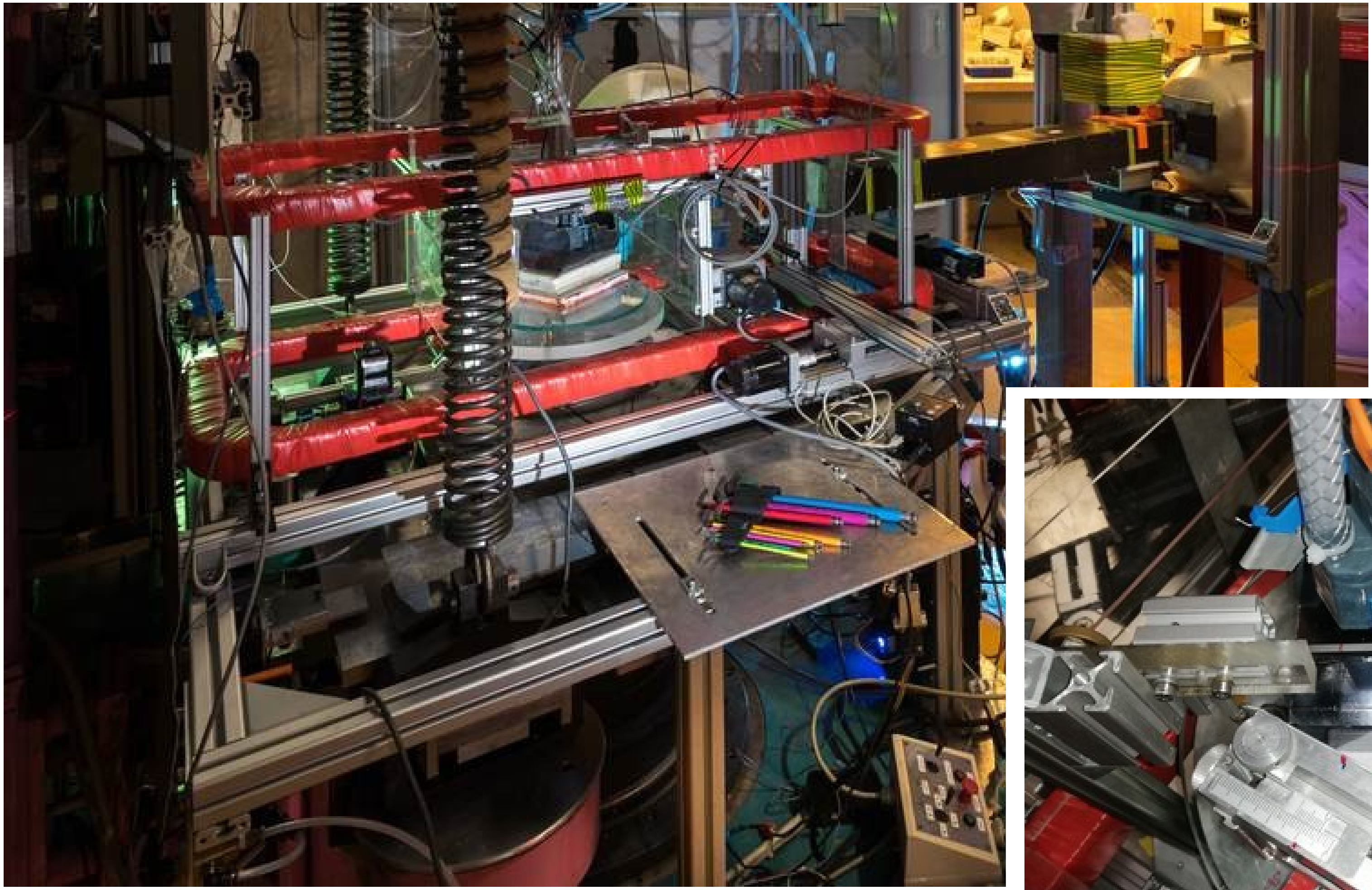
- For the following experiments we utilize the properties of the interferometer as a two level system

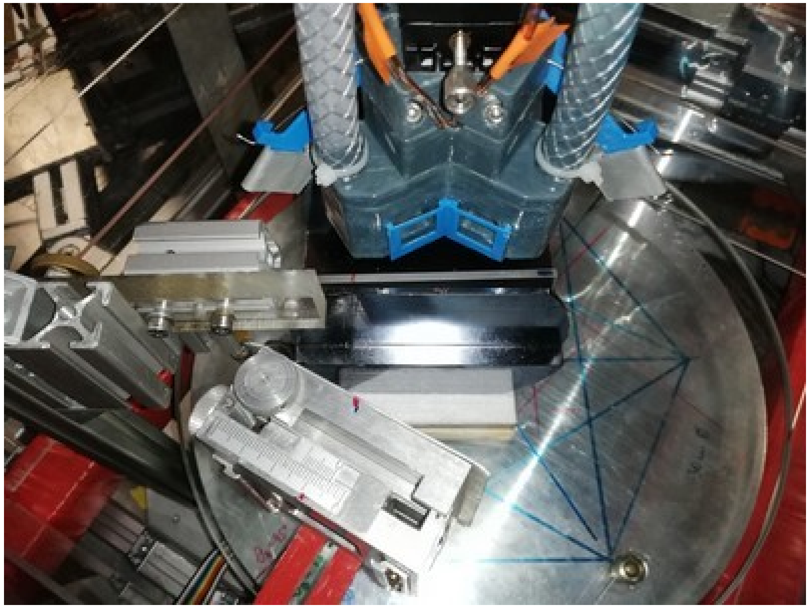
χ = Phase Shift
θ = relative proportion of state |I> + |II> in superposition (if θ=π/2 beam is split 50:50)

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|I\rangle + e^{i\chi}|II\rangle)$$



Typical Experimental Setup at the S18





Weak Measurement - Weak Value

- Proposed by Yakir Aharonov, David Z. Albert and Lev Vaidman (AAV) (1988)
- Describes the effect a quantum system has on a measuring device (probe system) when weakly interacting
- Coupling with minimal disturbance

Definition: $\langle \hat{A} \rangle_w = \frac{\langle \psi_f | \hat{A} | \psi_i \rangle}{\langle \psi_f | \psi_i \rangle}$

$$|\phi_{\mathrm{f}}\rangle \simeq \int dp\, e^{-\triangle^2 (p - \langle A \rangle_{\mathrm{w}})^2} |p\rangle$$

WV appears shift in the gaussian of the meter system during a weak measurement

Weak Value – Weak Measurement

- Properties of Weak Value

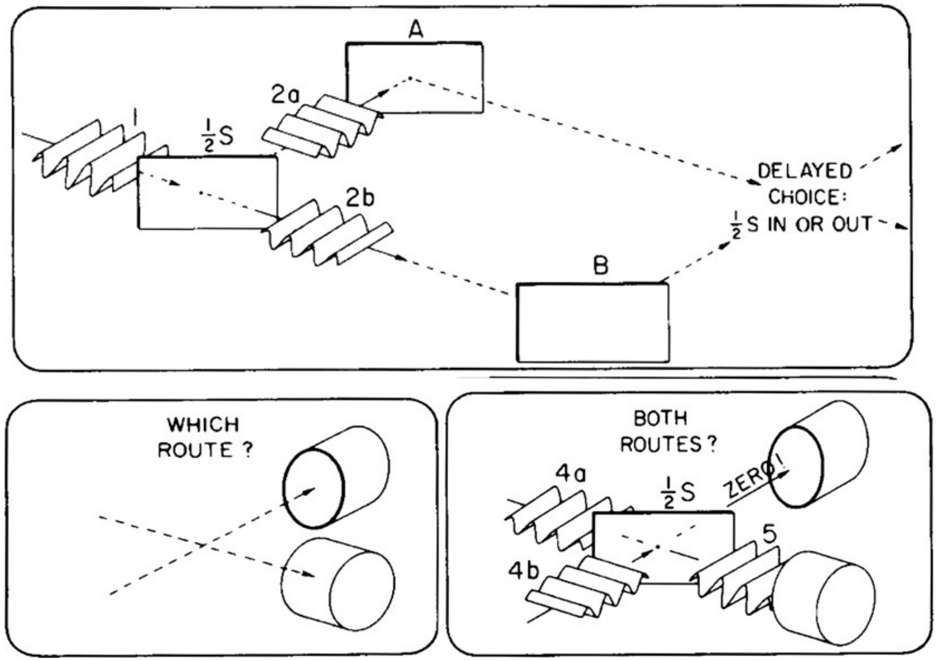
$\langle \hat{A} \rangle_w \in \mathbb{C}$	in general the weak value is a complex number
$\Re \langle \hat{A}_w \rangle$	real part: • may lie (far) outside the range of usual expectation values of an observable • can be interpreted as a conditioned average associated with an observable

- Weak measurement in neutron interferometer
  - Induce path (I and II) dependent spin rotations α
  - ➻ Coupling of path and spin
  - If α small ➻ weak measurement criteria fulfilled

Quantum Causality

Delayed Choice Cheshire Cat Experiment

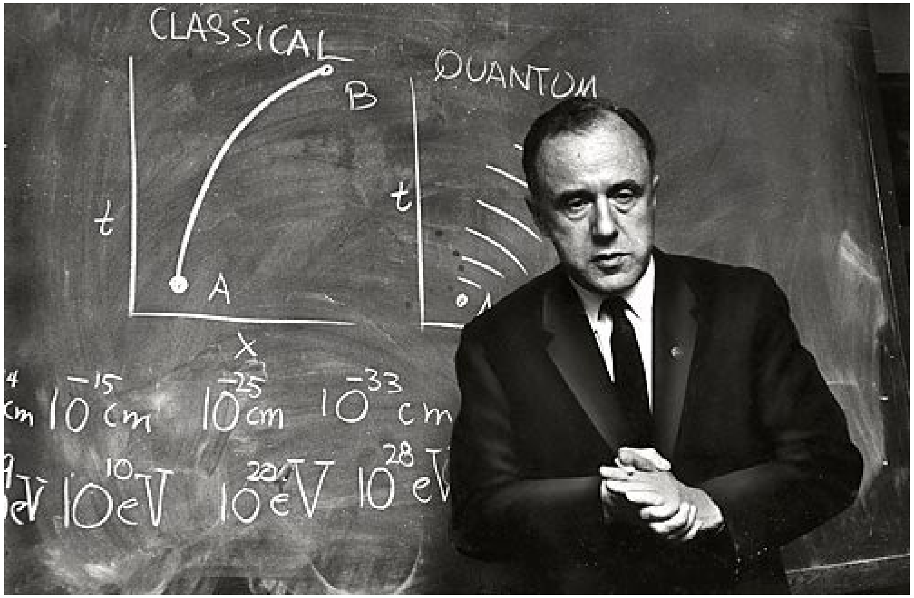
Delayed Choice Experiment I



(Wheeler, 1984 – Law without Law)

- Interference or Which-Way (path taken) information depends whether beam splitter (BS) is inserted or not
- Delay Choice whether to insert BS until particle has entered interferometer
- But: ➸ delayed choice is not altering result of measurement
- By putting in the BS we have an effect on an event in the past
- Retro causal effect

Delayed Choice Experiment II



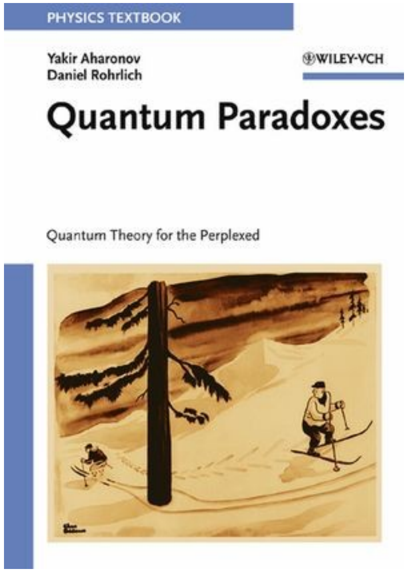
- Wheeler: "No phenomenon is a phenomenon until it is an observed phenomenon."

- Delayed Choice Experiments have been realized with photons
- Only known delayed choice experiment with Neutrons:
  Kawai et. al. (1998) “Realization of a delayed choice experiment using a multilayer cold neutron pulser”

Quantum Cheshire Cat

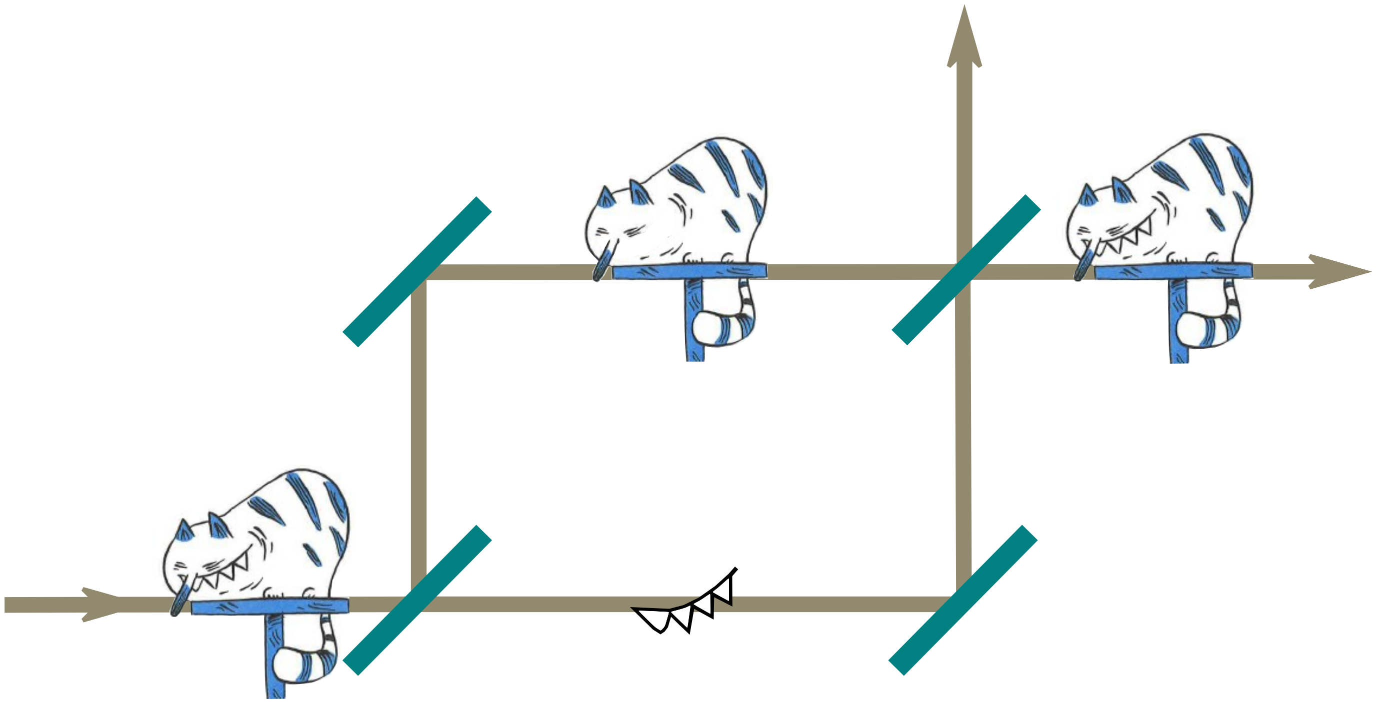
- Cheshire cat is a character from Lewis Carrols novel ’Alice‘s Adventures in Wonderland’
  - Cat leaves the scene but grin stays behind

- Aharonov and Rohrlich (2005) asked the question: Can a property be separated (‘disembodied‘) from an object?
- For classical systems impossible
- But in the quantum realm
  - ➔ Formulation of the Quantum Cheshire Cat (qCC)



Quantum Cheshire Cat

- In an interferometer experiment the cat is represented by the neutron and the grin by its magnetic moment/spin (property).
- qCC is realized if neutron and spin take different paths in the interferometer and hence are spatially separated



Quantum Cheshire Cat

Pre- and Post-selection

$$\psi_i = \frac{1}{\sqrt{2}}\left(|\uparrow_x\rangle\,|I\rangle + |\downarrow_x\rangle\,|II\rangle\right)$$

$$\psi_f = \frac{1}{\sqrt{2}}|\downarrow_x\rangle\left(|I\rangle + |II\rangle\right)$$

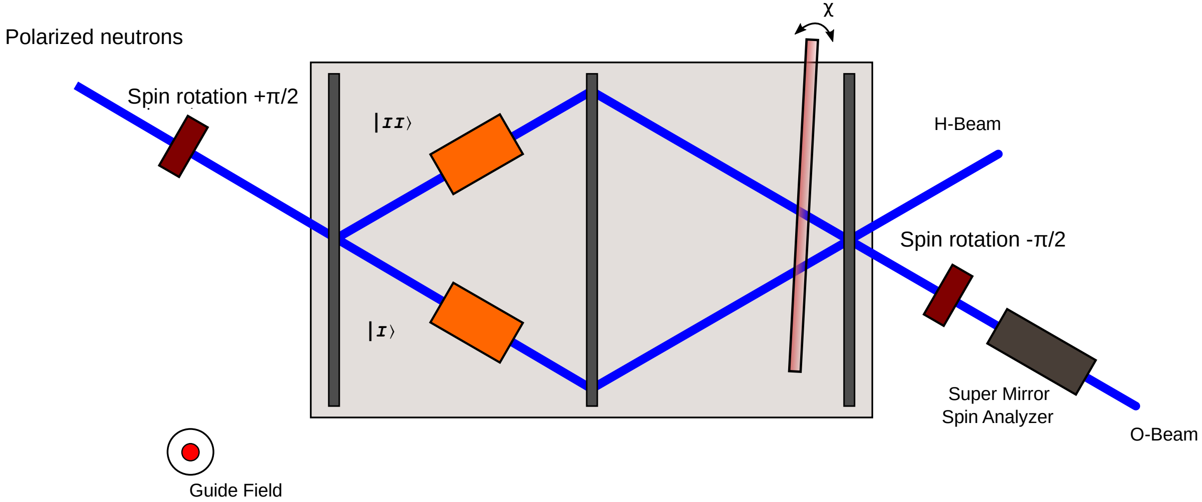
$$\langle\hat{A}\rangle_w = \frac{\langle\psi_f|\,\hat{A}\,|\psi_i\rangle}{\langle\psi_f|\psi_i\rangle}$$

Classification with weak values

$$\hat{\Pi}_I = |I\rangle\langle I| \quad \text{and} \quad \hat{\Pi}_{II} = |II\rangle\langle II|$$

Cat

$$\left\langle\hat{\Pi}_I\right\rangle_w = 0 \quad \text{and} \quad \left\langle\hat{\Pi}_{II}\right\rangle_w = 1$$



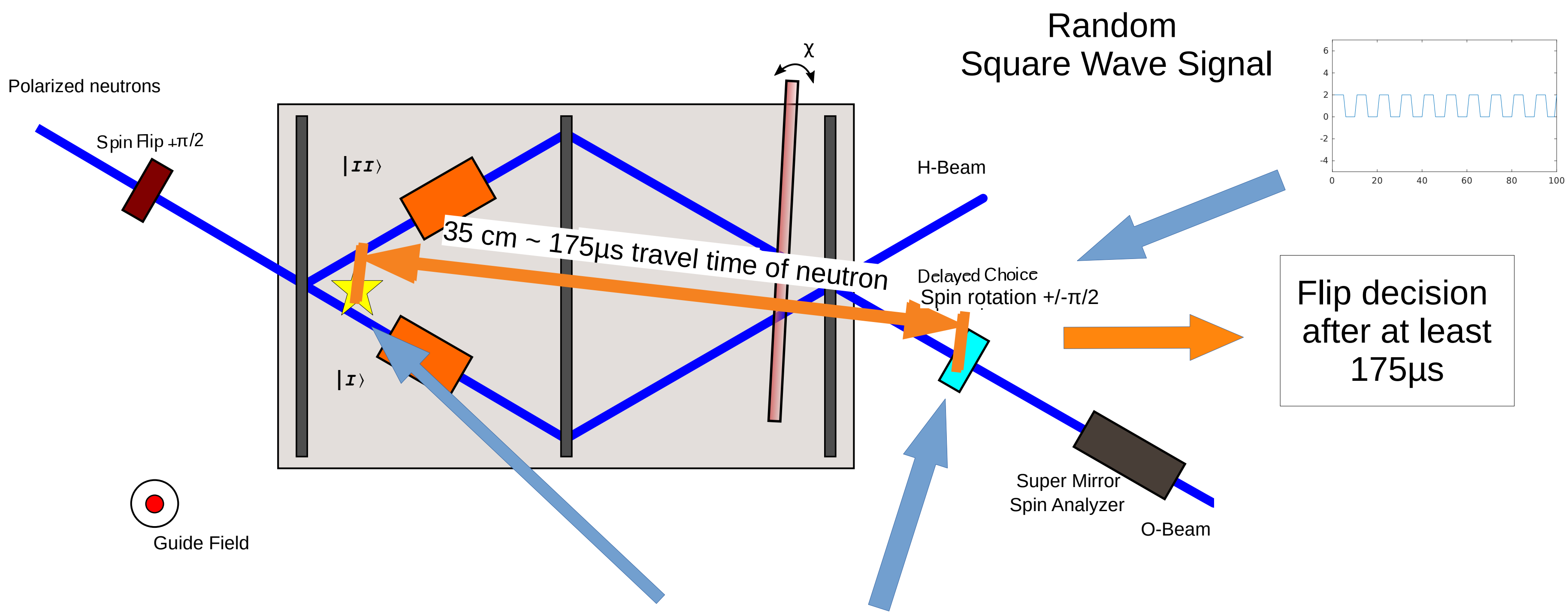
Grin of cat

$$\left\langle\hat{\sigma}_z\hat{\Pi}_I\right\rangle_w = 1 \quad \text{and} \quad \left\langle\hat{\sigma}_z\hat{\Pi}_{II}\right\rangle_w = 0$$

Denkmayr, T. et al., Nature Communications 5, 4492 (2014).

Delayed Choice Cheshire Cat

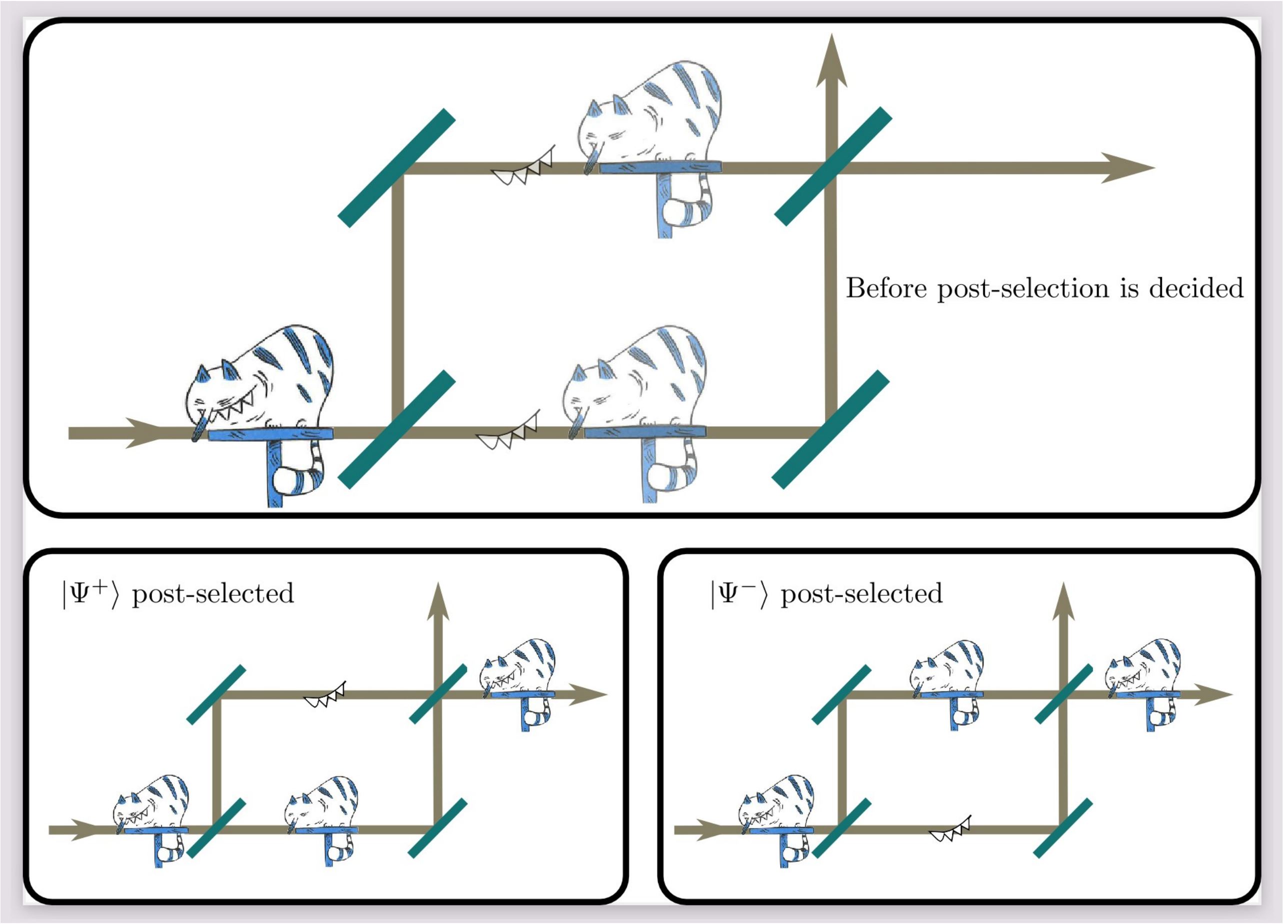
- Delayed Choice Extension (“delayed post-selection“)



Choice of spin analysis direction randomly after neutron entered IFM

- Behavior of qCC is switched with state of Delayed Choice Coil
- Separation of neutron and its property occurs at the moment of post-selection

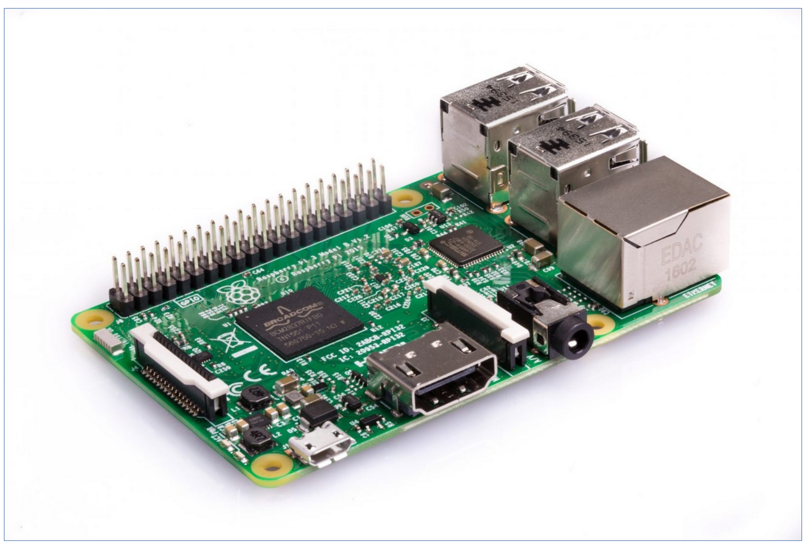
Delayed Choice Cheshire Cat



Delayed Choice Cheshire Cat

Random Number Generator

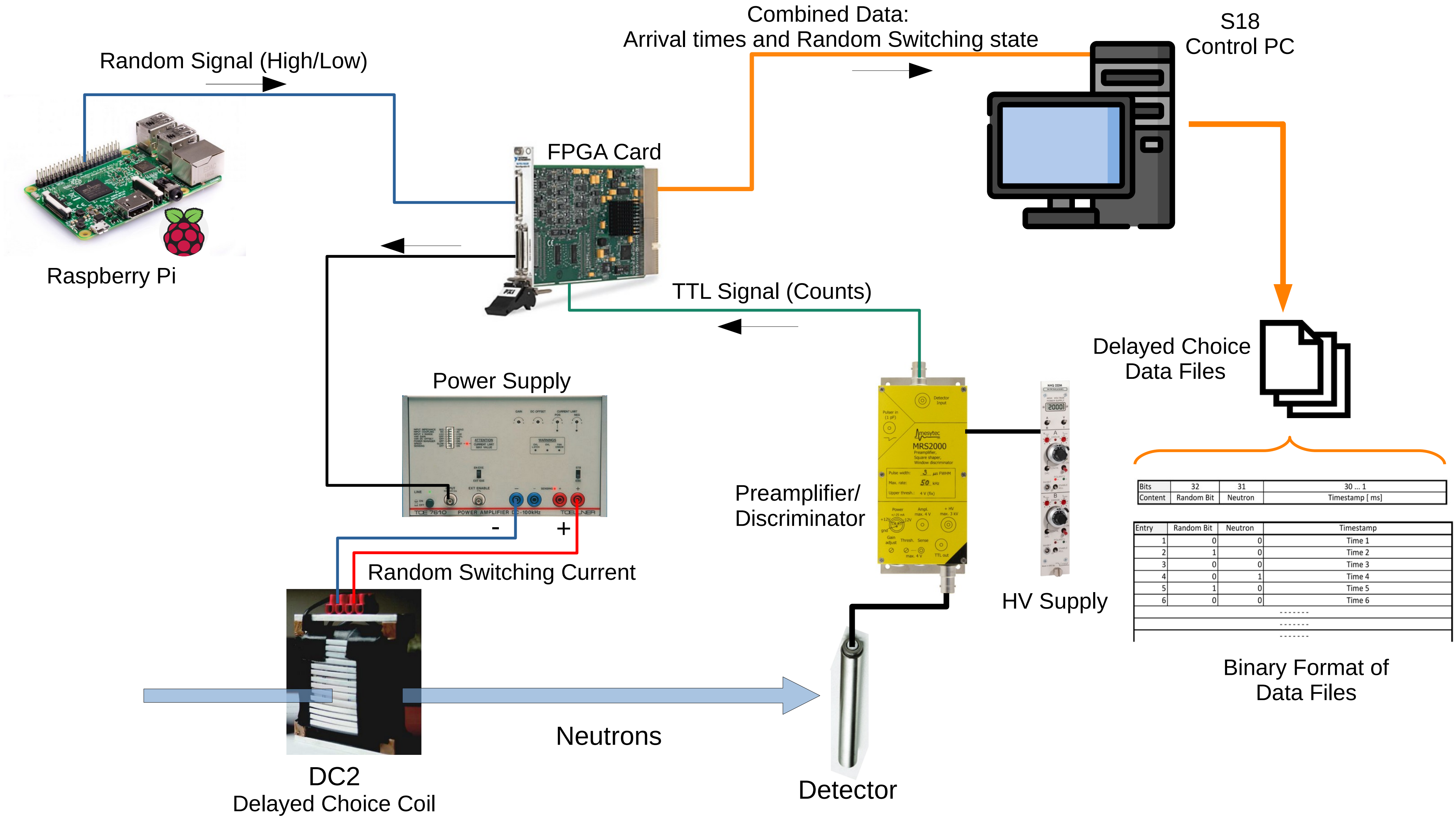
- Realization with Raspberry Pi HWRNG on Pi's SoC
- With rng-tools-package
  → True Random (!)



s18_hwrng.py

```python
#!/usr/bin/env python
#
import RPi.GPIO as GPIO
import time
import sys
import random
import os
import wiringpi

GPIO.setmode(GPIO.BOARD)
#OutputPin 11 == GPIO 17
GPIO.setup(11, GPIO.OUT)

#use hardware random generator
#rnd = random.SystemRandom()
f = os.open('/dev/hwrng', os.O_RDONLY)
#print(os.read(f,1))
#define delay time of (endless) while loop
delay_microseconds = 33 # equals 50 µs
                        # together with while loop execution time

while True:
    #read 1 byte from hardware-rng-device
    #test on first bit -> our random bit
    random_bit = (ord(os.read(f,1)) & 1)
    #set output pin to random bit state
    GPIO.output(11, bool(random_bit))
    #waitwiringpi.delayMicroseconds(delay_ms) for delay_microseconds
    wiringpi.delayMicroseconds(delay_microseconds)

f = os.close()
```

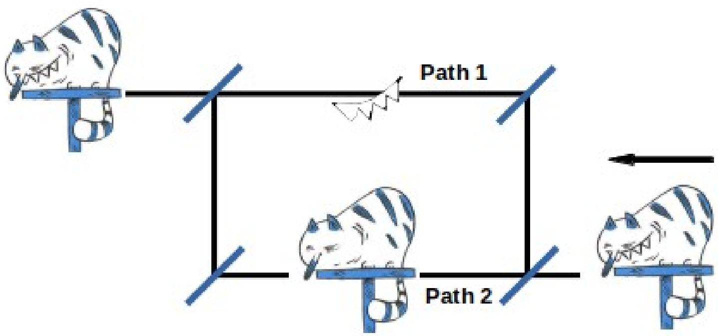
Schematic Overview – Time resolved measurement

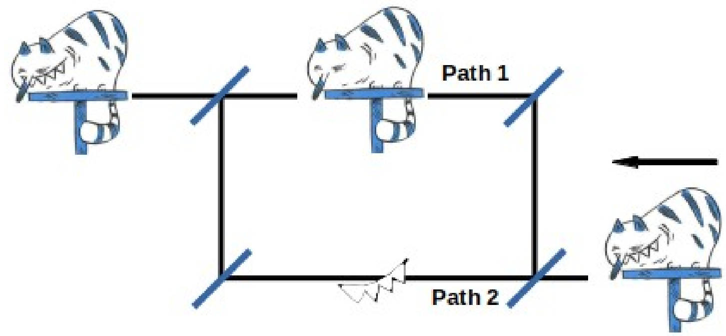


Bits	32	31	30 ... 1
Content	Random Bit	Neutron	Timestamp [ms]

Entry	Random Bit	Neutron	Timestamp
1	0	0	Time 1
2	1	0	Time 2
3	0	0	Time 3
4	0	1	Time 4
5	1	0	Time 5
6	0	0	Time 6

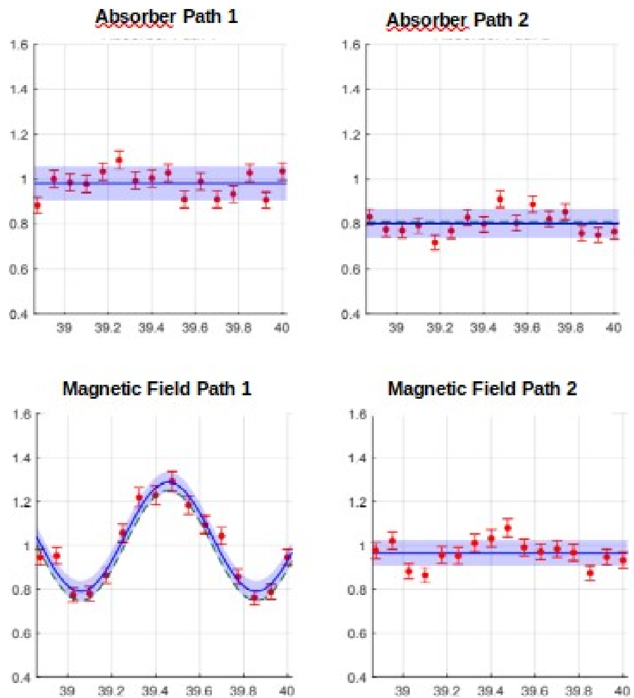
Delayed Choice Cheshire Cat



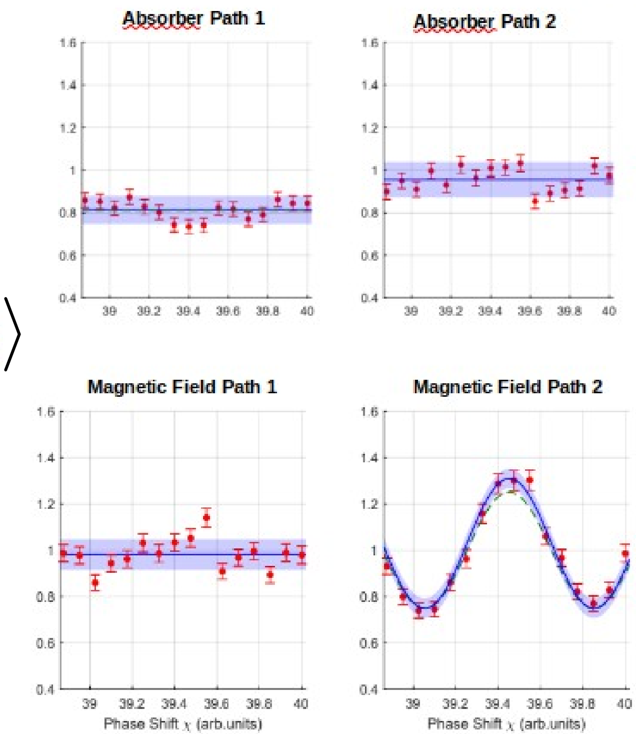


Cat © N.Mahler

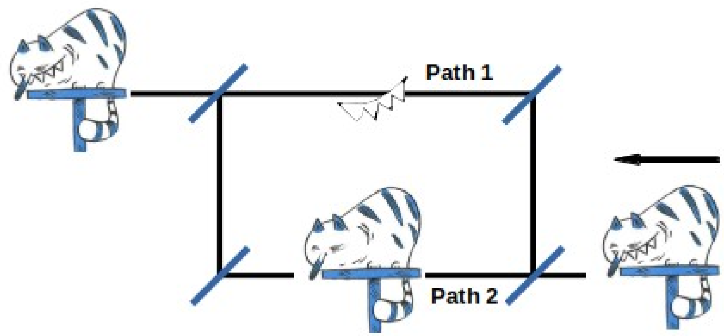
$|+x\rangle$

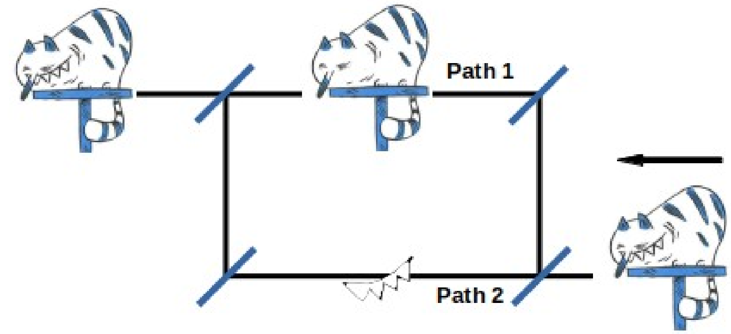


$|-x\rangle$



Delayed Choice Cheshire Cat

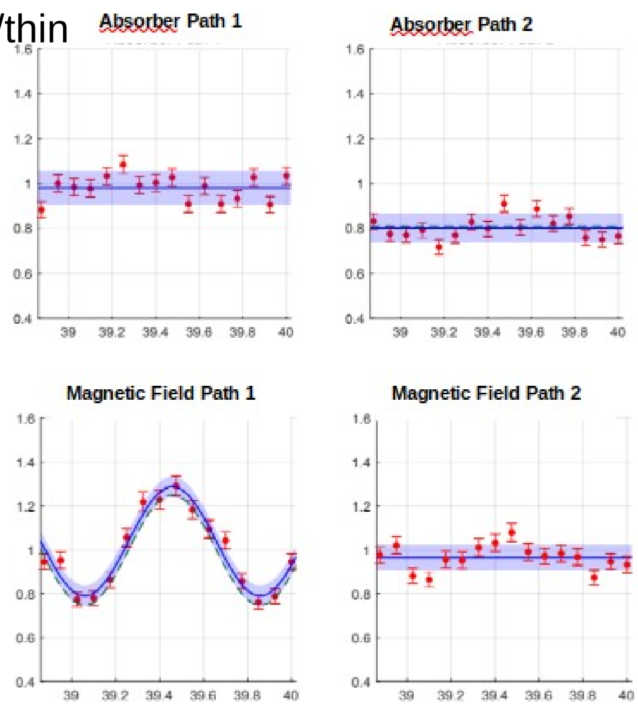




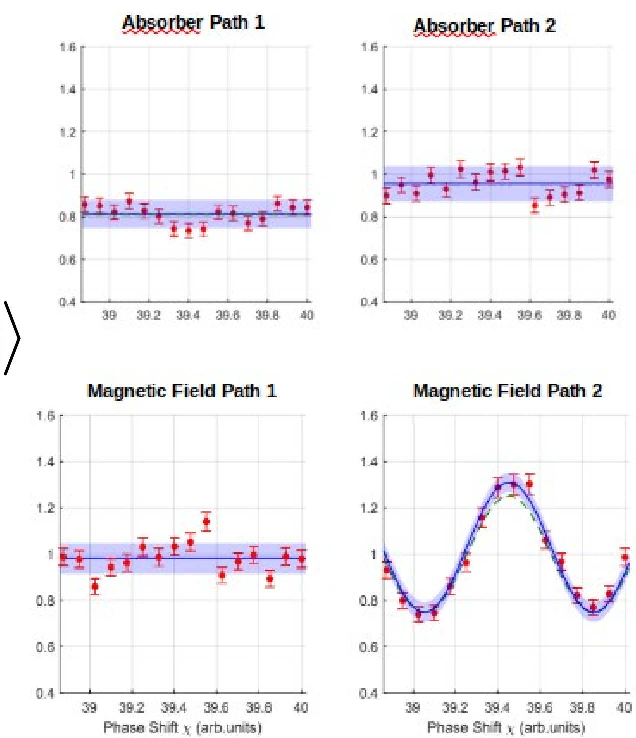
Cat © N.Mahler

Probing for the neutron i.e. effect of weak/thin absorber

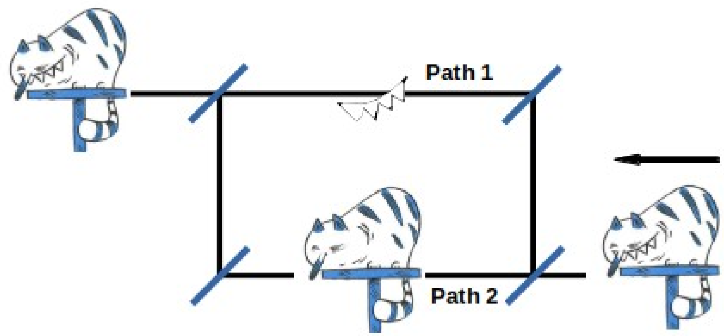
$|+x\rangle$

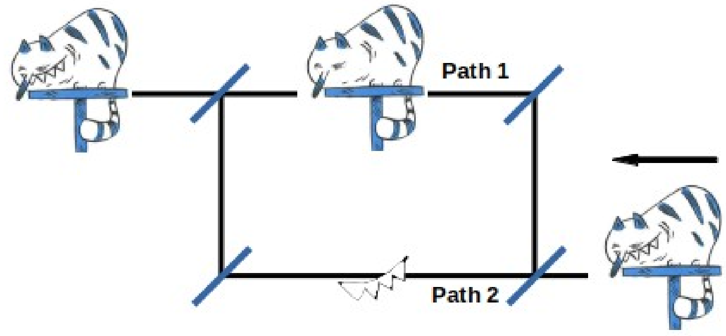


$|-x\rangle$



Delayed Choice Cheshire Cat





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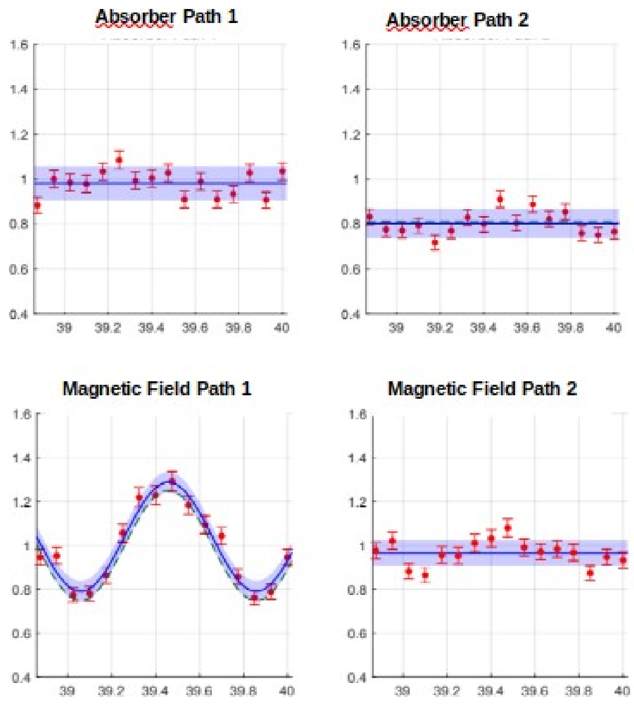
$|+x\rangle$



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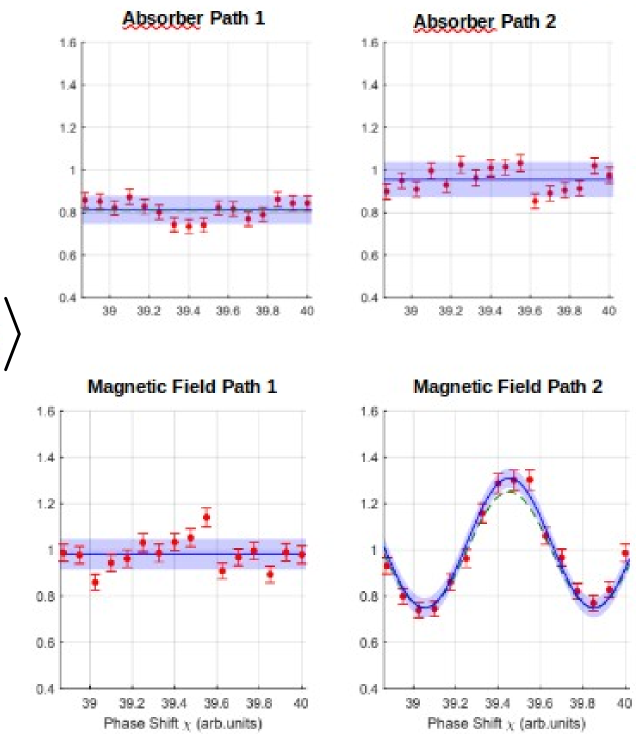
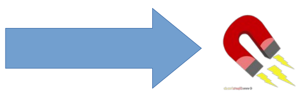
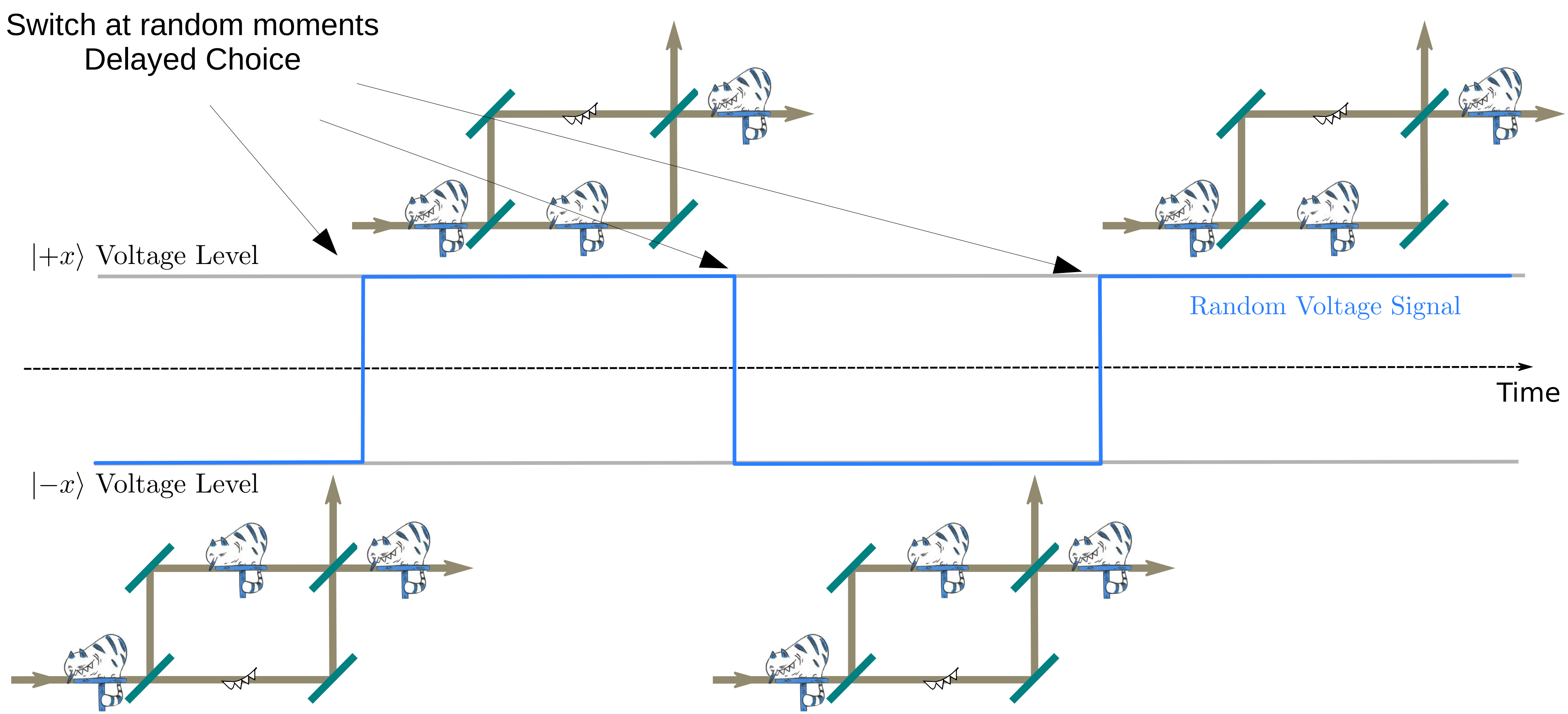


Probing for spin: applying a weak magnetic field



Evolvement of the qCC state over time



Conclusion

- Realization of a qCC:
neutron and one of its properties are spatially separated inside the interferometer
- Observation of the influence of an in the future lying random delayed choice
- The random selection/choice decides on the location of the neutron and the property
- Demonstration of quantum causality
→ conventional notion of causal order not valid anymore

Soon to be published

Quantum Causality emerging in a Delayed-Choice Quantum Cheshire-Cat Experiment with Neutrons

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Thank you for your attention!