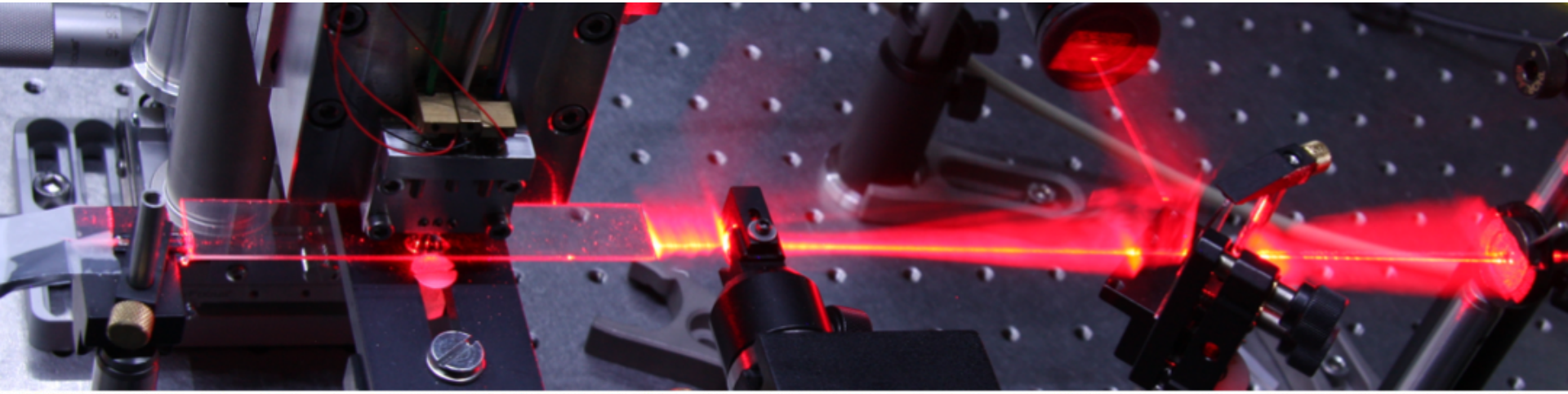
universität innsbruck



Testing Foundations of Quantum Mechanics with Waveguide Interferometers

Sebastian Gstir

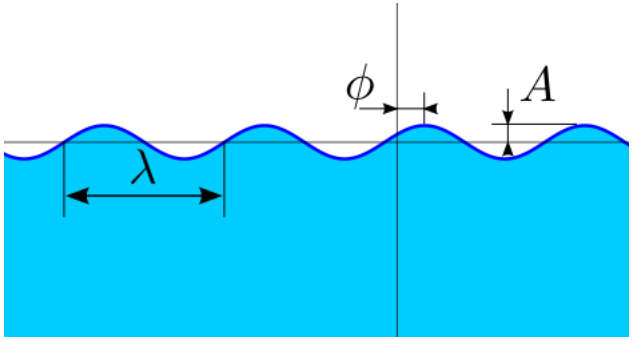
Supervised by Prof. Gregor Weihs

Testing Foundations of Quantum Mechanics with Waveguide Interferometers

Testing Wave Properties of Light using Interference

Background

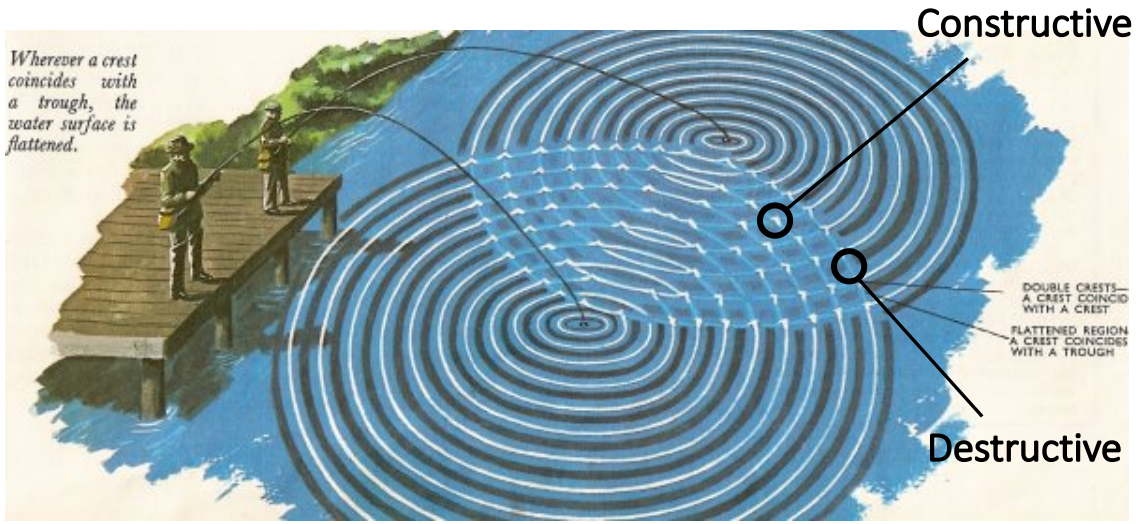
What are Waves?

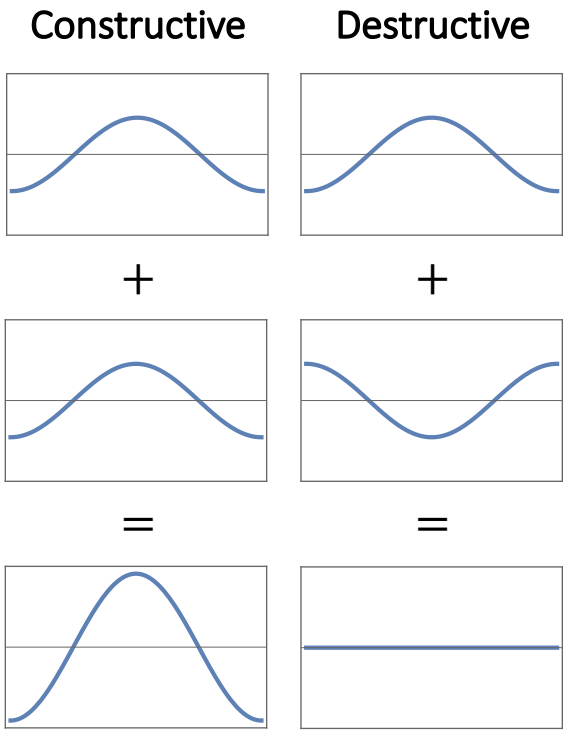


$$\psi(x) = \mathrm{A}\cos\left(\mathrm{x}\cdot\frac{2\pi}{\lambda}+\phi\right)$$

Background

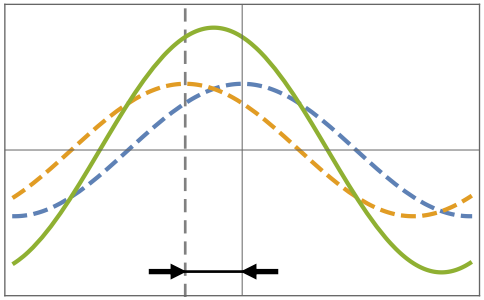
What is Interference?





Superposition Principle:

$$\psi_{12} = \psi_1 + \psi_2$$



$\Delta\phi_{12}$

Background

Wave Properties

Mechanical Waves

- Wavefunction

$$\psi(x) = A\, e^{i\,(x\,2\pi/\lambda+\phi)}$$

- Measurement Parameter

Amplitude $Re(\psi(x))$

Quantum Mechanics (QM)

- Wavefunction

$$\psi(x) = A\, e^{i\,(x\,2\pi/\lambda+\phi)} \in \mathbb{C}$$

- Measurement Parameter

Probability $P(x) = |\psi(x)|^2$

Born's Rule[1]

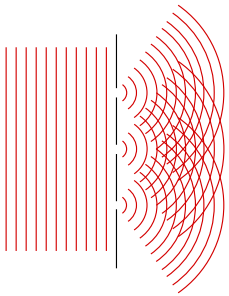
Testing Foundations of Quantum Mechanics with Waveguide Interferometers

[1]M. Born, *Z. Physik* **37**, 863-867 (1926)

Introduction

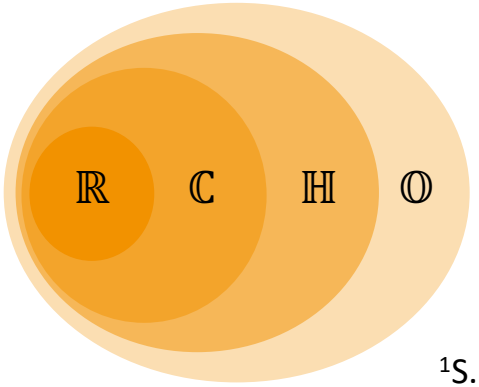
Testing two axioms of Quantum Mechanics

- Born's Rule (Interference)



Higher-order interference?

- Numerical Representation (Wavefunction)



Quaternionic Quantum Mechanics[1]?

$$a + \boldsymbol{i}\, b + \boldsymbol{j}\, c + \boldsymbol{k}\, d \in \mathbb{H}$$

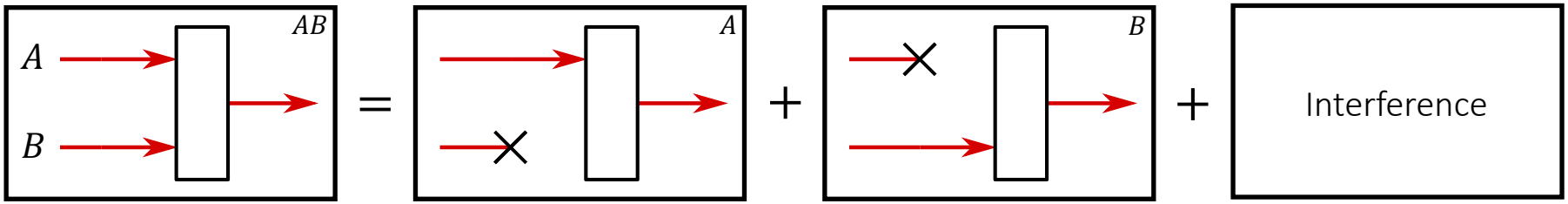
[1]S. Adler, *Quaternionic Quantum Mechanics and Quantum Fields* (1995)

Theoretical Fundamentals

Interference of Quantum Mechanical Waves

$$P(\vec{r},t) = |\psi(\vec{r},t)|^2 \quad \text{Born's Rule}$$

$$P_{\mathrm{AB}} = |\psi_{\mathrm{A}} + \psi_{\mathrm{B}}|^2 = P_{\mathrm{A}} + P_{\mathrm{B}} + \underbrace{2\sqrt{P_{\mathrm{A}}P_{\mathrm{B}}}\cos(\Delta\phi_{\mathrm{AB}})}_{I_{\mathrm{AB}}}$$



P_{AB} $P_{\mathrm{A}} = |\psi_{\mathrm{A}}|^2$ $P_{\mathrm{B}} = |\psi_{\mathrm{B}}|^2$ I_{AB}

$$I_{\mathrm{AB}} = P_{\mathrm{AB}} - P_{\mathrm{A}} - P_{\mathrm{B}} \quad \text{First-order interference}$$

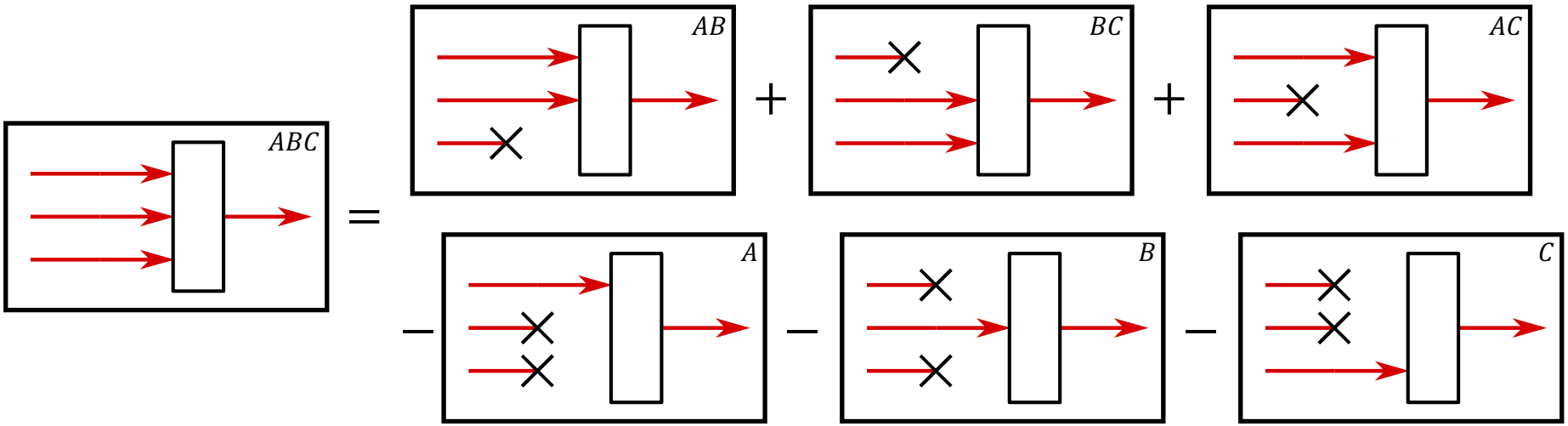
[1]M. Born, *Z. Physik* **37**, 863-867 (1926)

Theoretical Fundamentals

Sorkin Test[1]

Do interferences of higher-order exist? Is Born's Rule valid?

$$P_{\mathrm{ABC}} = |\psi_{\mathrm{A}} + \psi_{\mathrm{B}} + \psi_{\mathrm{C}}|^2 = P_{\mathrm{A}} + P_{\mathrm{B}} + P_{\mathrm{C}} + I_{\mathrm{AB}} + I_{\mathrm{BC}} + I_{\mathrm{AC}} \quad (+ I_{\mathrm{ABC}})\,?$$
$$= P_{\mathrm{AB}} + P_{\mathrm{BC}} + P_{\mathrm{AC}} - P_{\mathrm{A}} - P_{\mathrm{B}} - P_{\mathrm{C}}$$



$I_{\mathrm{ABC}} \overset{!}{=} 0$ Second-order interference

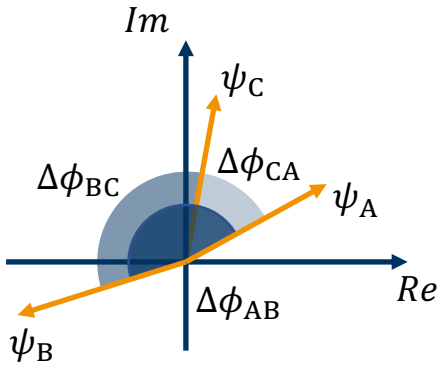
[1]R. D. Sorkin, *Mod. Phys. Lett. A* **8**, 3119-3127 (1994)

Theoretical Fundamentals

Peres Test[1]

Complex or hypercomplex Quantum Mechanical wavefunctions?

One-dimensional or higher-dimensional phase?

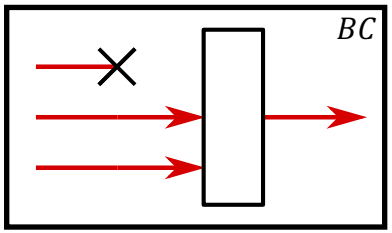


$$\Delta\phi_{AB} + \Delta\phi_{BC} + \Delta\phi_{CA} = 0$$

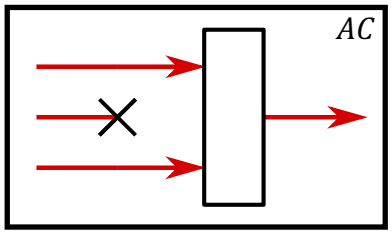
$$\cos(\Delta\phi_{AB} + \Delta\phi_{BC} + \Delta\phi_{CA}) = 1$$

$$\vdots$$

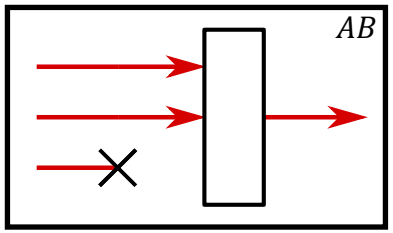
$$F := \alpha^2 + \beta^2 + \gamma^2 - 2\alpha\beta\gamma = 1$$



$$\alpha := \cos(\Delta\phi_{BC})$$



$$\beta := \cos(\Delta\phi_{CA})$$



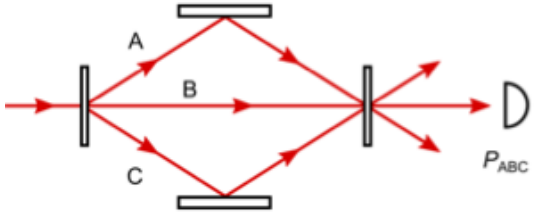
$$\gamma := \cos(\Delta\phi_{AB})$$

[1]A. Peres, *Phys. Rev. Lett.* **42**, 683-686 (1979)

My PhD – Building Interferometers

Task

- Create a waveguide Interferometer
  - three paths
  - paths individually blocked
- Test both axioms (Sorkin & Peres Test)
  - full phase space



Goals

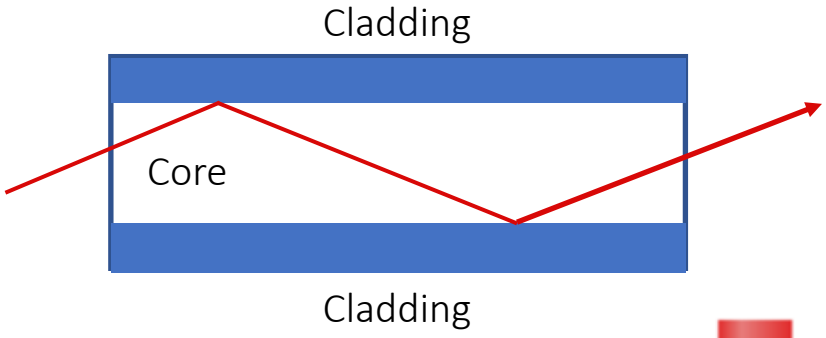
- Sorkin Test: $I_{\mathrm{ABC}} \propto \kappa_3 < (0.0 \pm 3.1) \times 10^{-5}$ [1]
- Peres Test: – (not yet realised!)

[1]T. Kauten et al., *New J. Phys.* **19**, 033017 (2017)

Hardware Platform

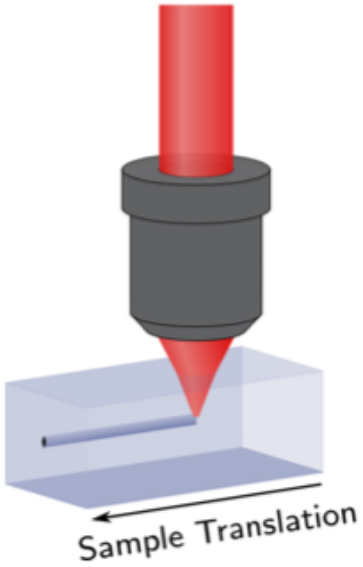
Waveguide Principle

britannica.com



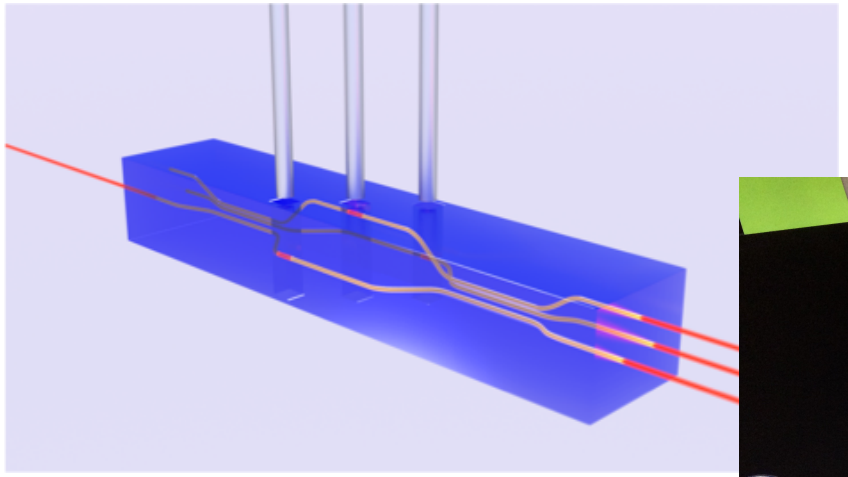
Waveguide Fabrication

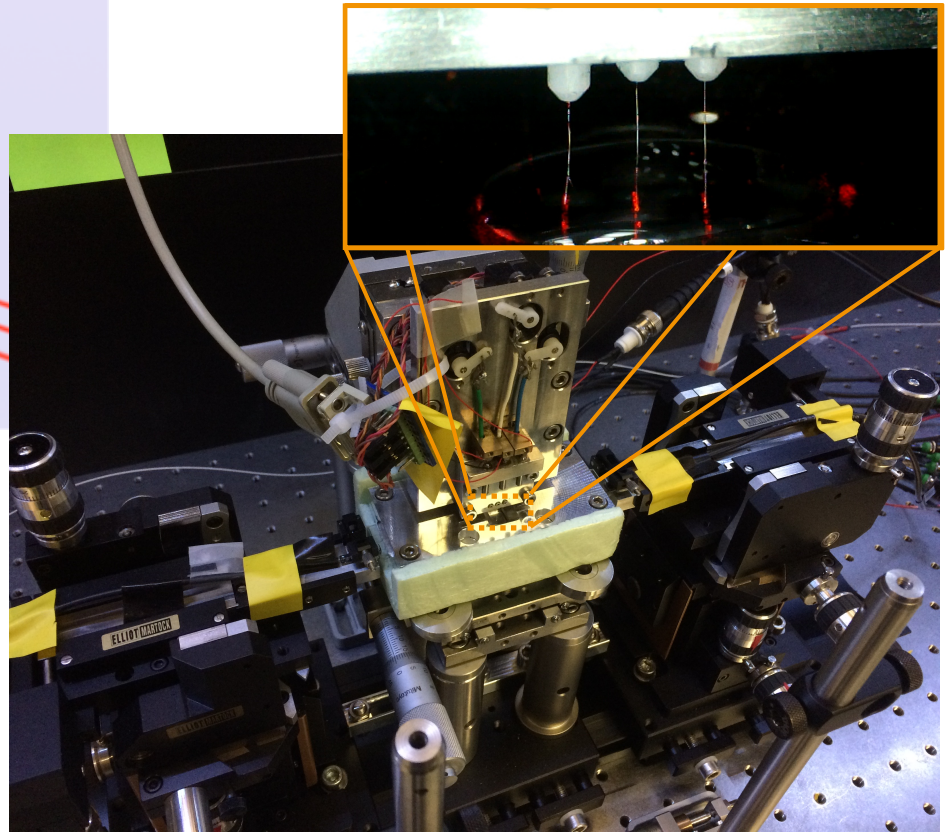
- Femtosecond-laser pulse
- Densification (refractive index increase)
- Sample translation



Hardware Platform

3D Waveguide Structure





- Mechanical shutters
- Fused Silica Chip

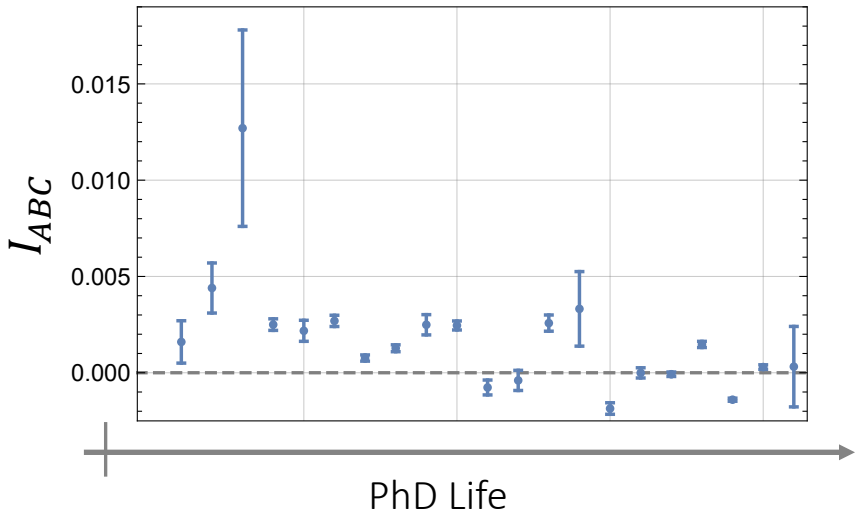
- Temperature stabilised $\Delta T \approx 10^{-3}$°C
- Fiber coupled

Results so far

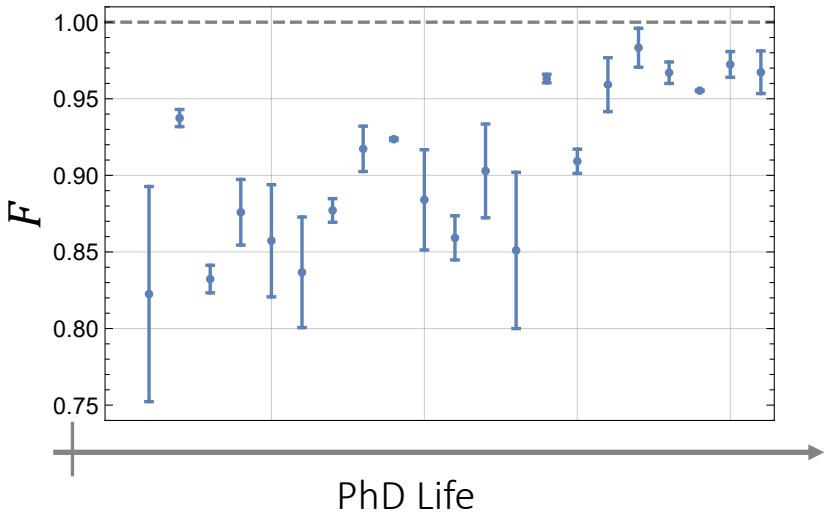
3D Waveguide Sample

using laser (classical regime) → no violation expected: $I_{\mathrm{ABC}} \stackrel{!}{=} 0$ and $\mathrm{F} \stackrel{!}{=} 1$

Sorkin Test

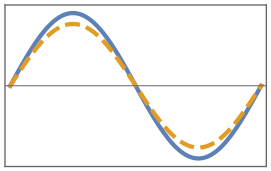


Peres Test



Limitations:

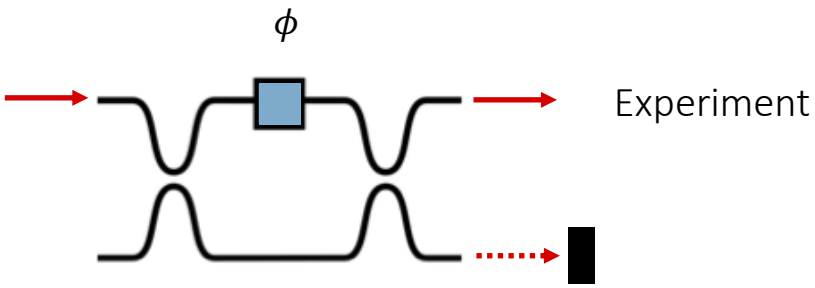
- Shutter cross-talk
- Interference contrast ~97%



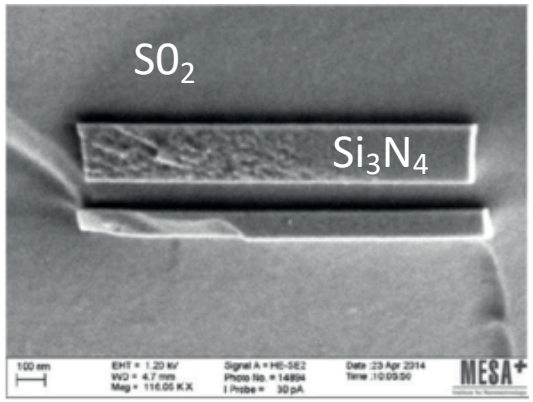
Hardware Platform

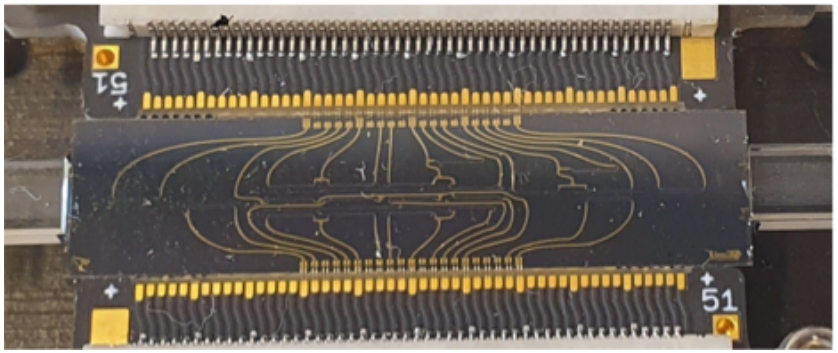
2D Waveguide Structure

- Integrated phase shifters (thermo-optical)
- Integrated shutter
  - faster $\sim 1\text{ms}$
  - less cross-talk
  - less background
- Lower transmission losses



Cross-section

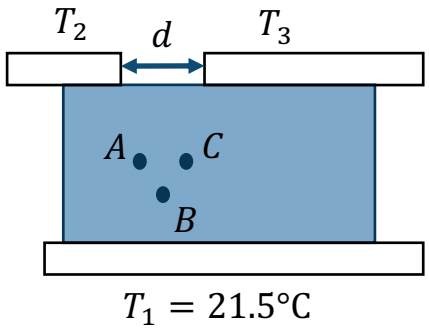




What I did not talk about

- Simulations and error estimations

- Various improvements of the 3D interferometer



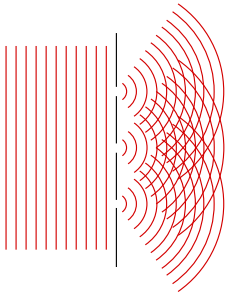
- Measurement Control Software

- Single Photon Sources
- Supervised interns
- Equipment problems

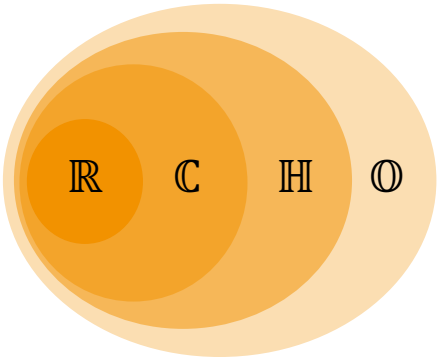
Summary

Testing two axioms of QM

- Born's Rule

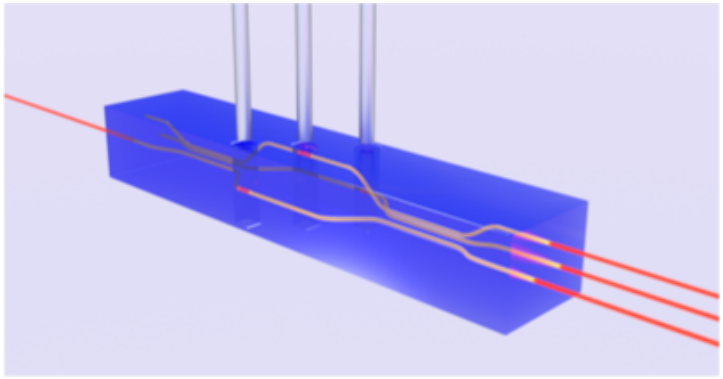


- Numerical Representation of QM Waves



Hardware

- 3D Waveguide Interferometer



- 2D Waveguide Interferometer