Title: The three - slit experiment

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URL: http://pirsa.org/08090082

Abstract: In reference [1] R. D. Sorkin investigated a formulation of quantum mechanics as a generalized measure theory. Quantum mechanics computes probabilities from the absolute squares of complex amplitudes, and the resulting interference violates the (Kolmogorov) sum rule expressing the additivity of probabilities of mutually exclusive events.However, there is a higher order sum rule that quantum mechanics does obey, involving the probabilities of three mutually exclusive possibilities. We could imagine a yet more general theory by assuming that itviolates the next higher sum rule.An experiment is in progress in our laboratory which sets out to test the validity of this second sum rule by measuring the interference patterns produced by three slits and all the possible combinations of those slits being open or closed. We use either attenuated laser light or a heralded single photon source (using parametric down conversion) combined with single photon counting to confirm the single photon character of the measured light. We will show results that bound the possible violation of the second sum rule and will point out ways toobtain a tighter experimental bound.[1] R. D. Sorkin, Quantum Mechanics as Quantum Measure Theory,Mod. Phys. Lett. A 9, 3119 (1994).

Testing Quantum Mechanics using a Three Slit Experiment

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Born's rule

Originally published under the title, "Zur Quantenmechanik der Stossvorgänge," *Zeitschrift für Physik*, *37*, 863–67 (1926); reprinted in *Dokumente der Naturwissenschaft*, *1*, 48–52 (1962) and in M. Born (1963); translation into English by J.A.W. and W.H.Z., 1981.

I.2 ON THE QUANTUM MECHANICS OF COLLISIONS

[Preliminary communication]'

MAX BORN

Through the investigation of collisions it is argued that quantum mechanics in the Schrödinger form allows one to describe not only stationary states but also quantum jumps.

...

If one translates this result into terms of particles, only one interpretation is possible. $\Phi_{n,m}(\alpha, \beta, \gamma)$ gives the probability* for the electron, arriving from the z-direction, to be thrown out into the direction designated by the angles α, β, γ, with the phase change δ. Here its energy τ has increased by one quantum $h\nu^{0}_{nm}$ at the

* Addition in proof: More careful consideration shows that the probability is proportional to the square of the quantity $\Phi_{n,m}$.

"Again an idea of Einstein's gave me the lead. He had tried to make the duality of particles – light quanta or photons - and waves comprehensible by interpreting the square of the optical wave amplitudes as probability density for the occurrence of photons. This concept could at once be carried over to the Ψ-function: $|\Psi|^2$ ought to represent the probability density for electrons (or other particles). It was easy to assert this, but how could it be proved?"

M. Born, Nobel Lecture (1954).

Contents

- Born interpretation of probability
- Probabilities from wavefunctions
- Sorkin's sum rules
- Three slits
- An easy experiment?
- Systematic errors
- Single photon source
- Alternatives
- Implications

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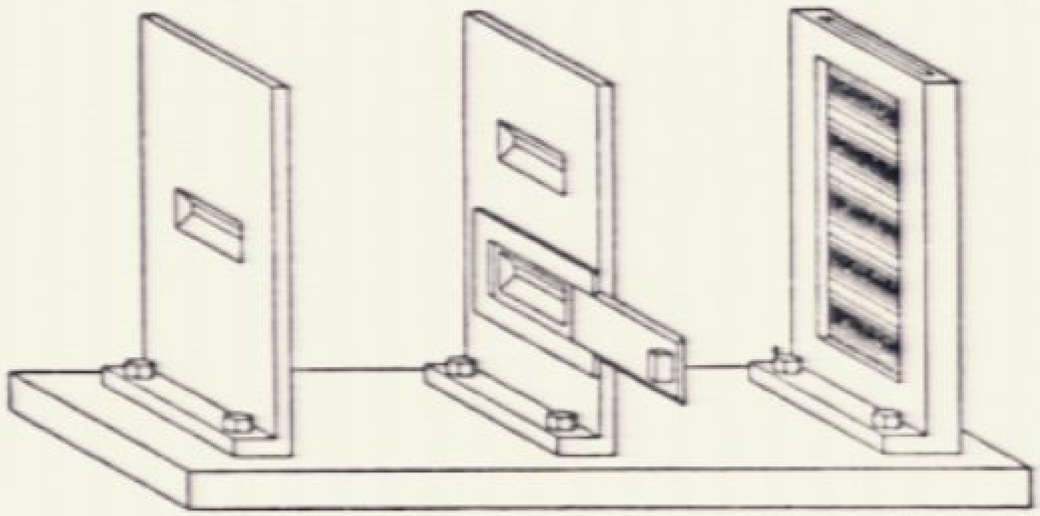
Interference



From N. Bohr 1949/1983: Discussions with Einstein on Epistemological Problems in Atomic Physics, p. 27

Two possible paths $|\psi\rangle = |\psi_A\rangle + |\psi_B\rangle$

Probability
$$P(A,B) = \langle\psi|\psi\rangle = |\psi_A|^2 + |\psi_B|^2 + \psi_A^*\psi_B + \psi_B^*\psi_A$$
$$= P(A) + P(B) + I(A,B)$$

Interference $I(A,B) = P(A,B) - P(A) - P(B)$

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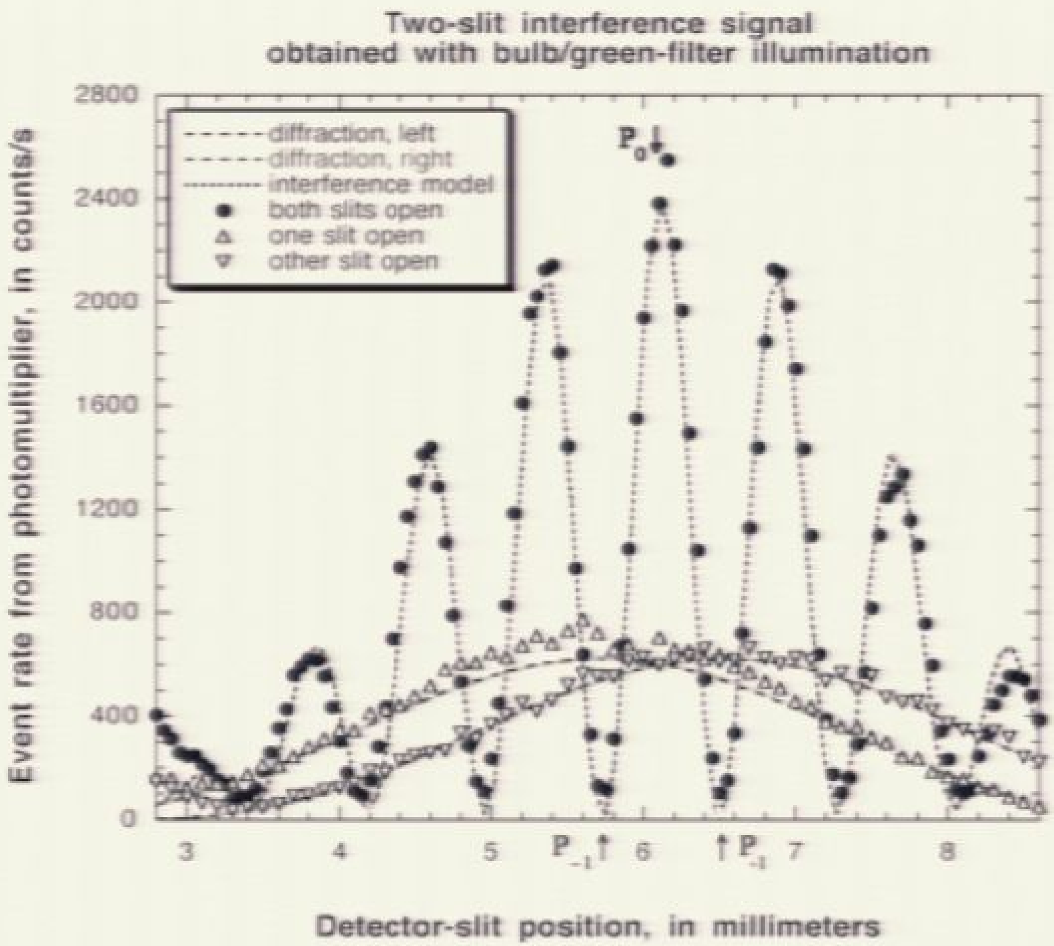

Photon counting data for single and double slit configurations using single photon incidences

Courtesy: http://www.teachspin.com/instruments/two_slit/experiments.shtml

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Interference and Sum Rules

Rafael D. Sorkin,
Quantum Mechanics as Quantum Measure Theory,
Modern Physics Letters A **9**, 3119-3127 (1994).

- Interference describes the deviation from the classical additivity of the probabilities of mutually exclusive events.
- If additivity holds, we call that a **sum rule.**
- A sum rule says that an interference term $I = 0$
- Define a hierarchy of interference terms:

Sum Rules

$$I(A) = P(A)$$
$$I(A,B) = P(A \sqcup B) - P(A) - P(B)$$
$$I(A,B,C) = P(A \sqcup B \sqcup C) - P(A \sqcup B) - P(A \sqcup C) - P(B \sqcup C) + P(A) + P(B) + P(C)$$
$$\vdots$$

- The zeroeth sum rule needs to be violated ($I(A) \neq 0$) for a non-trivial measure.
- If the first sum rule holds ($I(A,B) = 0$) one gets regular probability theory, e.g. for classical stochastic processes.
- Violation of the first sum ($I(A,B) \neq 0$) rule consistent with quantum mechanics.
- A sum rule always entails that the higher ones in the hierarchy hold.
- As far as we know, the second sum rule holds in known physics:

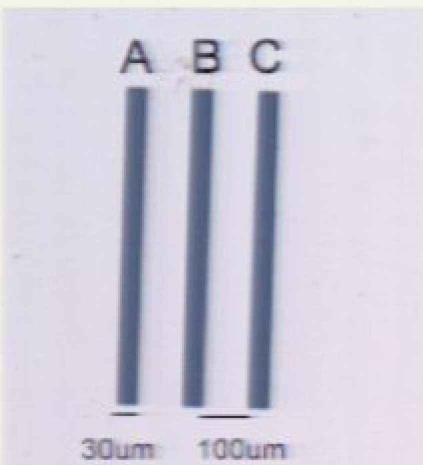
$$\mathbf{I(A,B,C) = 0}$$

i.e. triadditivity of mutually exclusive possibilities is always true!

Can we test this?

Three Slits

Particles encounter three slits, that are assumed to be mutually exclusive possibilities / paths (no loops)

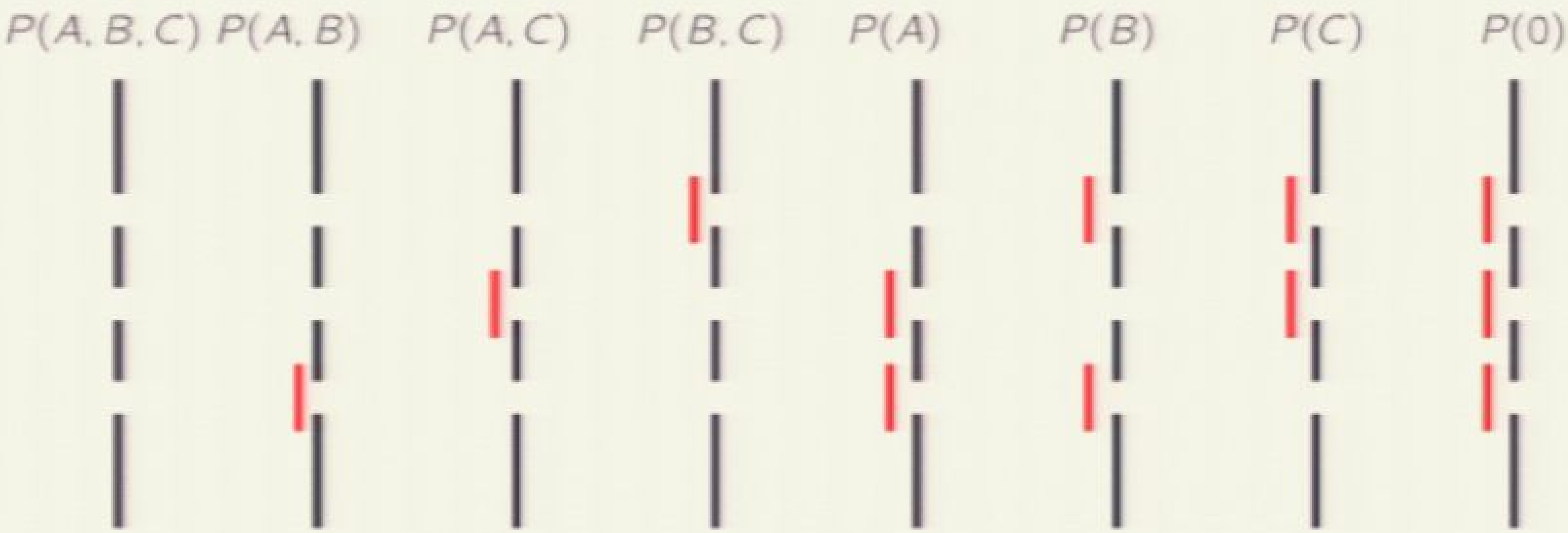


$$
\begin{aligned}
P(A,B,C) &= |\psi_A + \psi_B + \psi_C|^2 = \\
&= |\psi_A|^2 + |\psi_B|^2 + |\psi_C|^2 + \\
&\quad + \psi_A^*\psi_B + \psi_B^*\psi_A + \psi_A^*\psi_C + \psi_C^*\psi_A + \psi_B^*\psi_C + \psi_C^*\psi_B = \\
&= P(A) + P(B) + P(C) + I(A,B) + I(A,C) + I(B,C) \\
&= P(A) + P(B) + P(C) + \\
&\quad + P(A,B) - P(A) - P(B) + \\
&\quad + P(A,C) - P(A) - P(C) + \\
&\quad + P(B,C) - P(B) - P(C) = \\
&= P(A,B) + P(A,C) + P(B,C) - P(A) - P(B) - P(C)
\end{aligned}
$$

$$I(A,B,C) := P(A,B,C) - P(A,B) - P(A,C) - P(B,C) + P(A) + P(B) + P(C) \equiv 0$$

Testing the 2nd Sum Rule

- So we have to measure these seven probabilities to detect a particle at a certain point behind the slits plus the background probability (leakage, dark count)



- Calculate

$$\epsilon := P(A,B,C) - P(A,B) - P(A,C) - P(B,C) + P(A) + P(B) + P(C) - P(0)$$

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Testing the 2nd Sum Rule

- In practice, we can't easily measure a probability, so we use a normalization

$$\delta := |I(A,B)| + |I(A,C)| + |I(B,C)| = |P(A,B) - P(A) - P(B) + P(0)| + \ldots$$

- δ measures the "amount of interference"

$$\rho := \frac{\epsilon}{\delta}$$

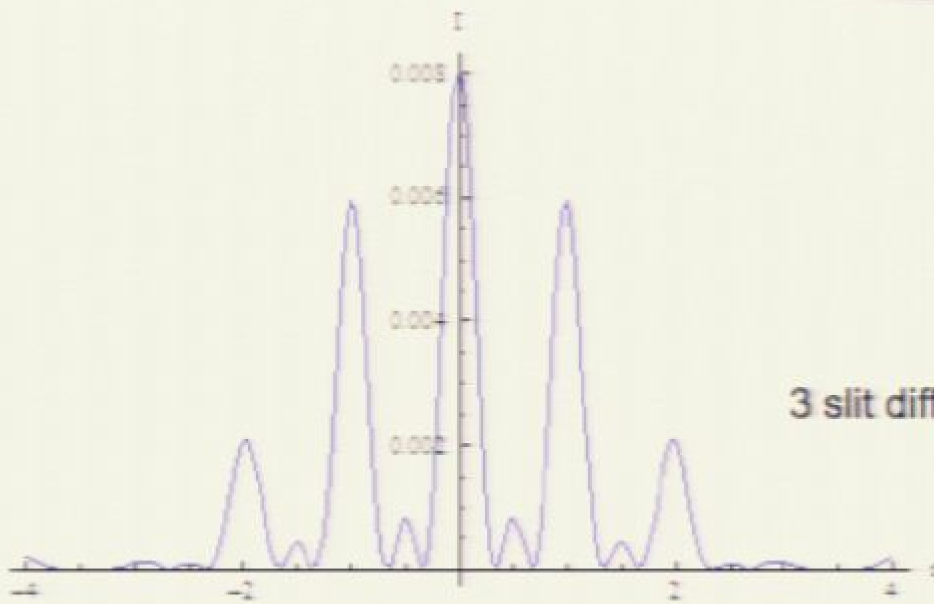
- ρ measures any violation of the second sum rule vs. the expected violation of the first sum rule
- Since the rule supposedly holds point-wise it should also hold for finite detection area.

Photons

- Original suggestion for electrons
- Photons should work just fine
- Single Photons?
  - Just a laser
  - Photons defined by photon counting
  - Single photon source

  - Fraunhoffer diffraction integral is given by:

$$I = \int_{-\infty}^{\infty} f(x) e^{\frac{2i\pi x r}{R\lambda}} dx$$

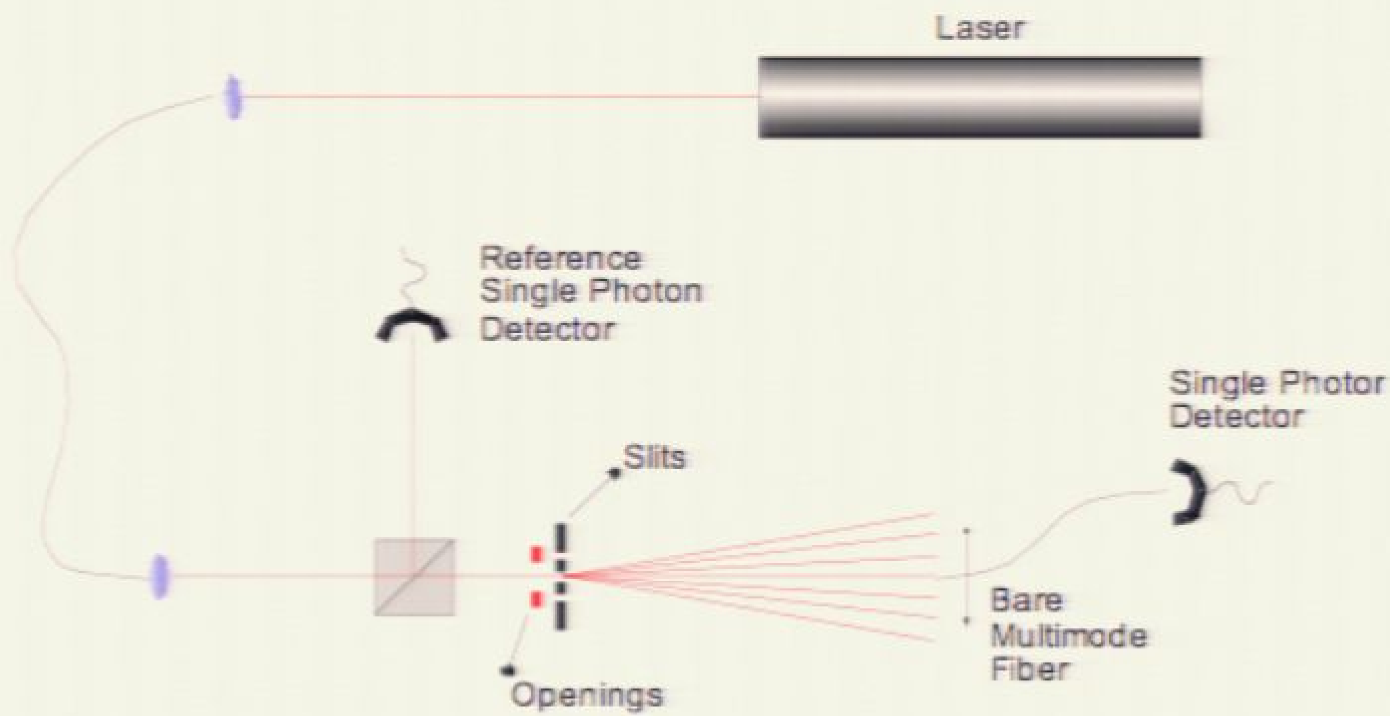


3 slit diffraction pattern

Slits - and how to block them

- Ideally have air slits, but difficult to get smooth ones.
- Three iterations:
  - Homemade photoemulsion mask
    - ~5% spurious transmission
    - Blocking pads
  - Professional Chromium mask
    - ~3% spurious transmission
    - "Unblocking openings"
  - Professional Aluminium mask
    - Less than 0.1% transmission
    - Both sides AR coated
- Use openings created on the same mask for perfect, lithographic alignment

Three Slit Setup



- 50 micron fibre as a point detector
- Reference arm for power monitoring
- Slits stay stationary
- Openings can be switched to different combinations
- Horizontal microscope for opening to slit alignment

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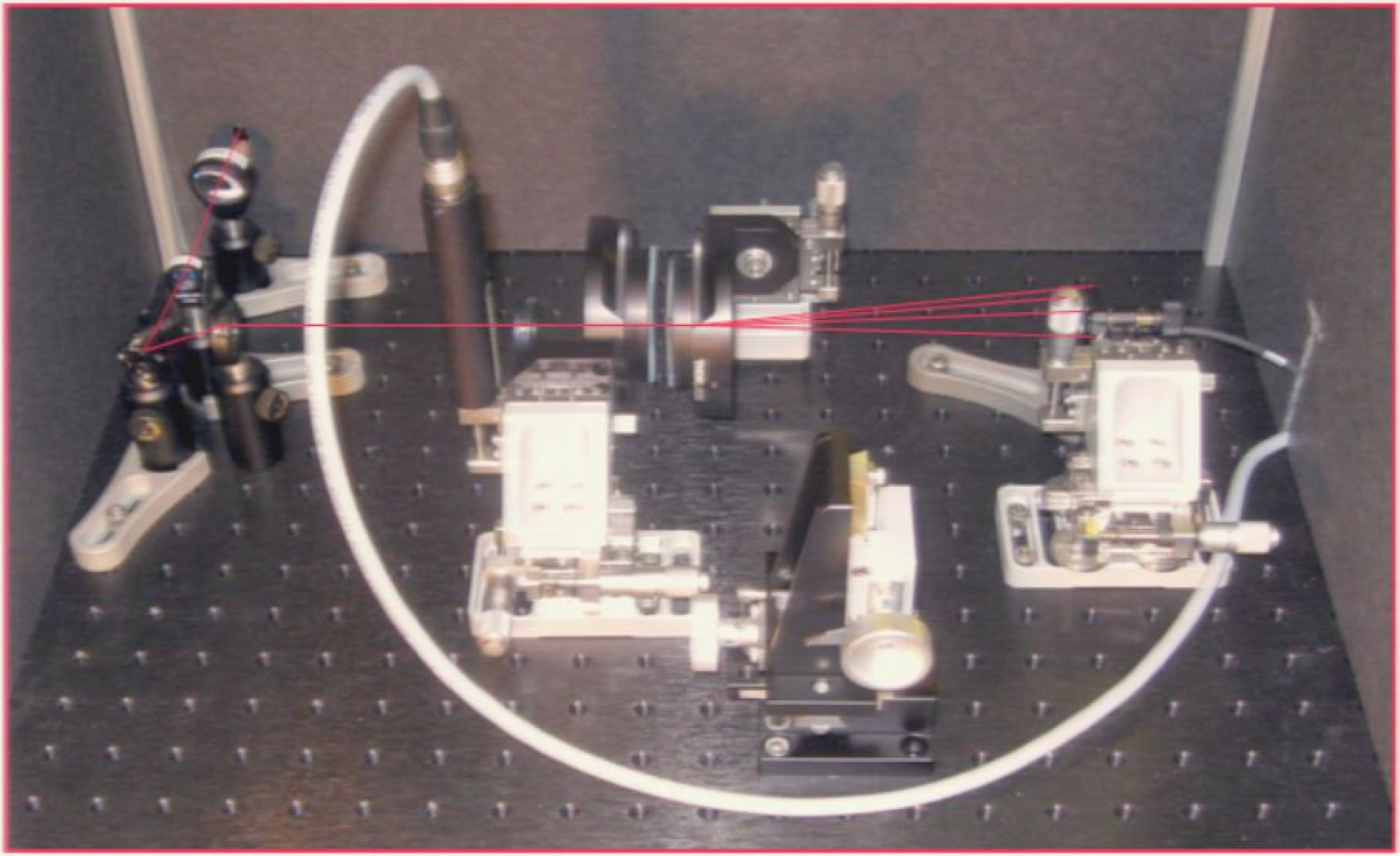
Experiment



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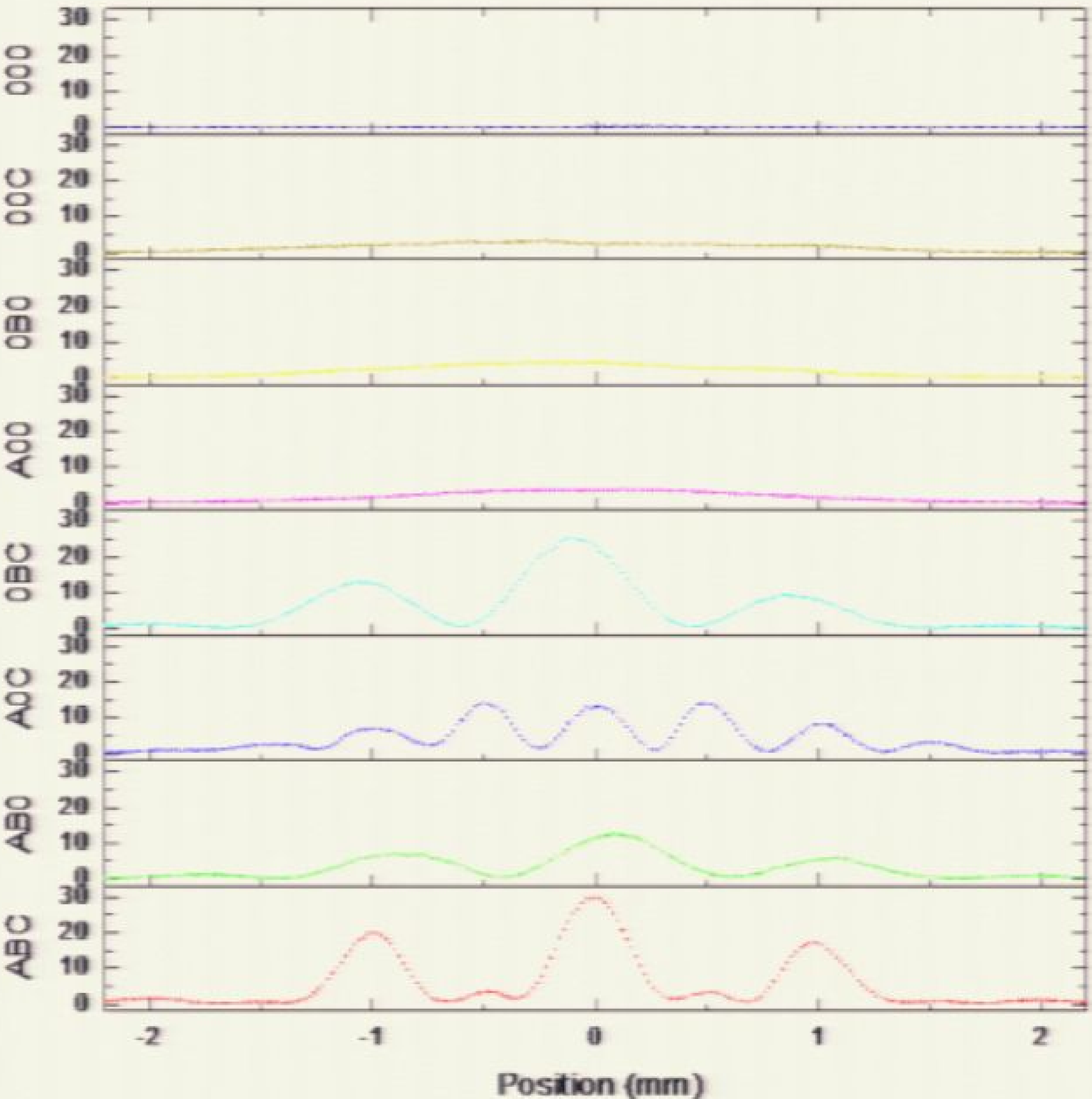
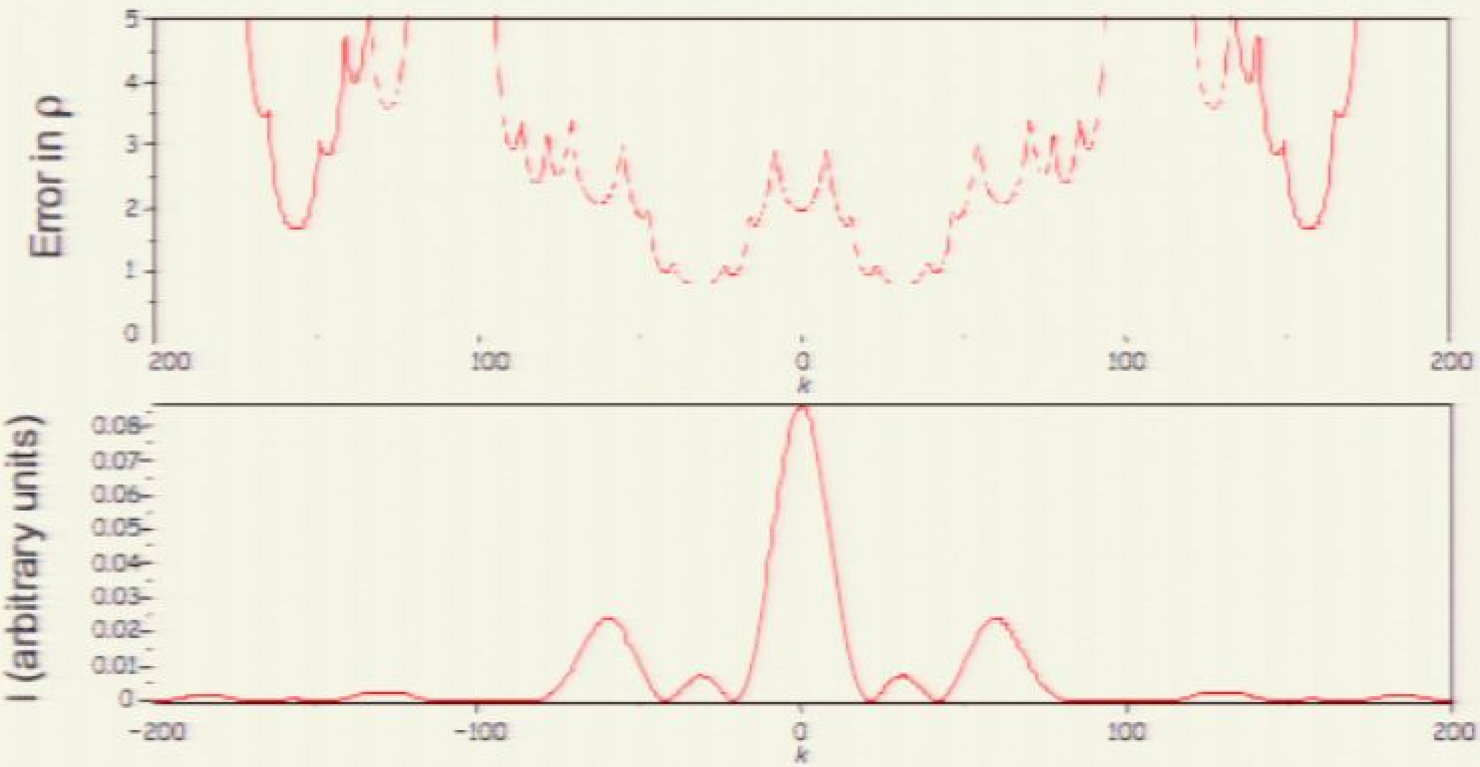
Experimental Diffraction Patterns

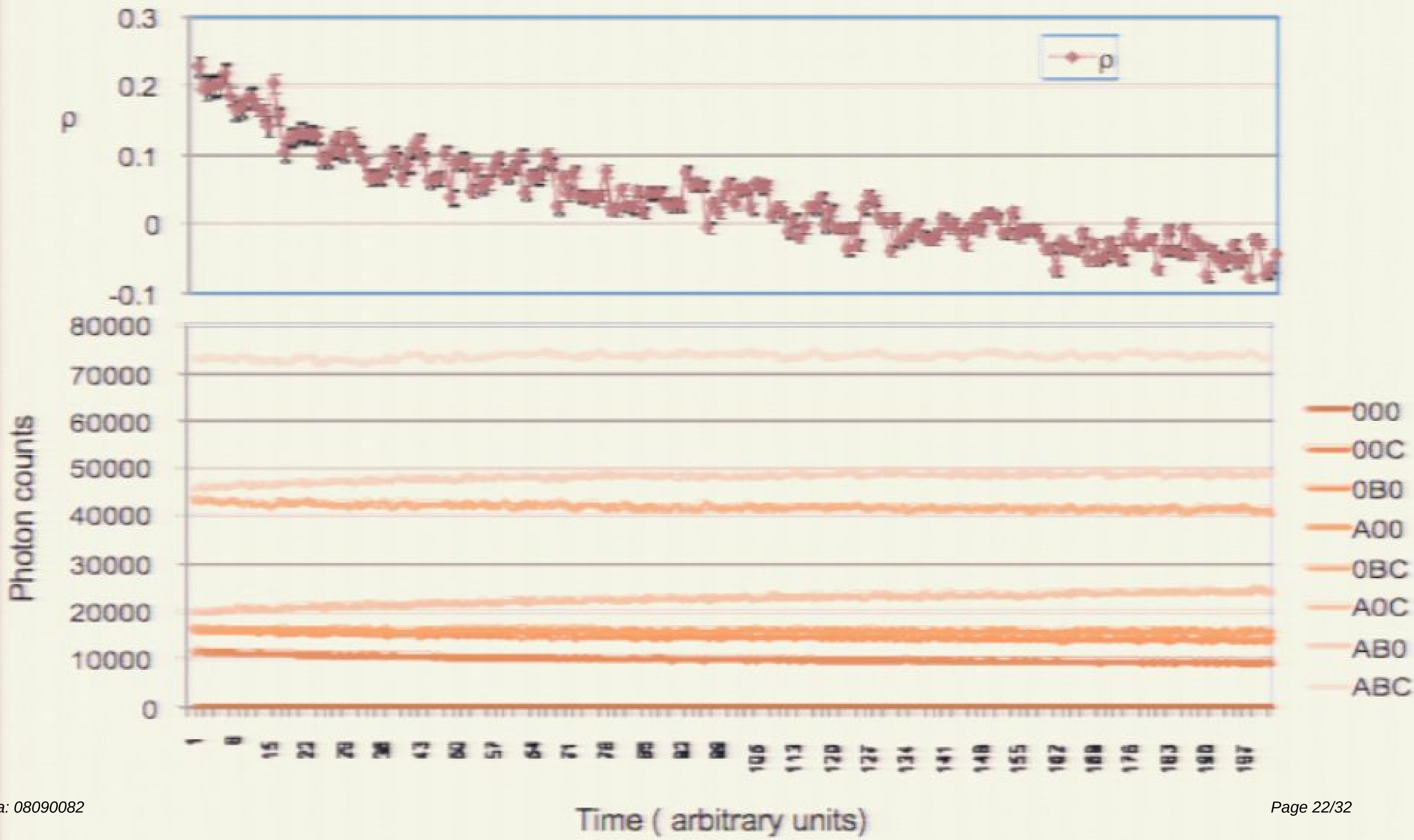


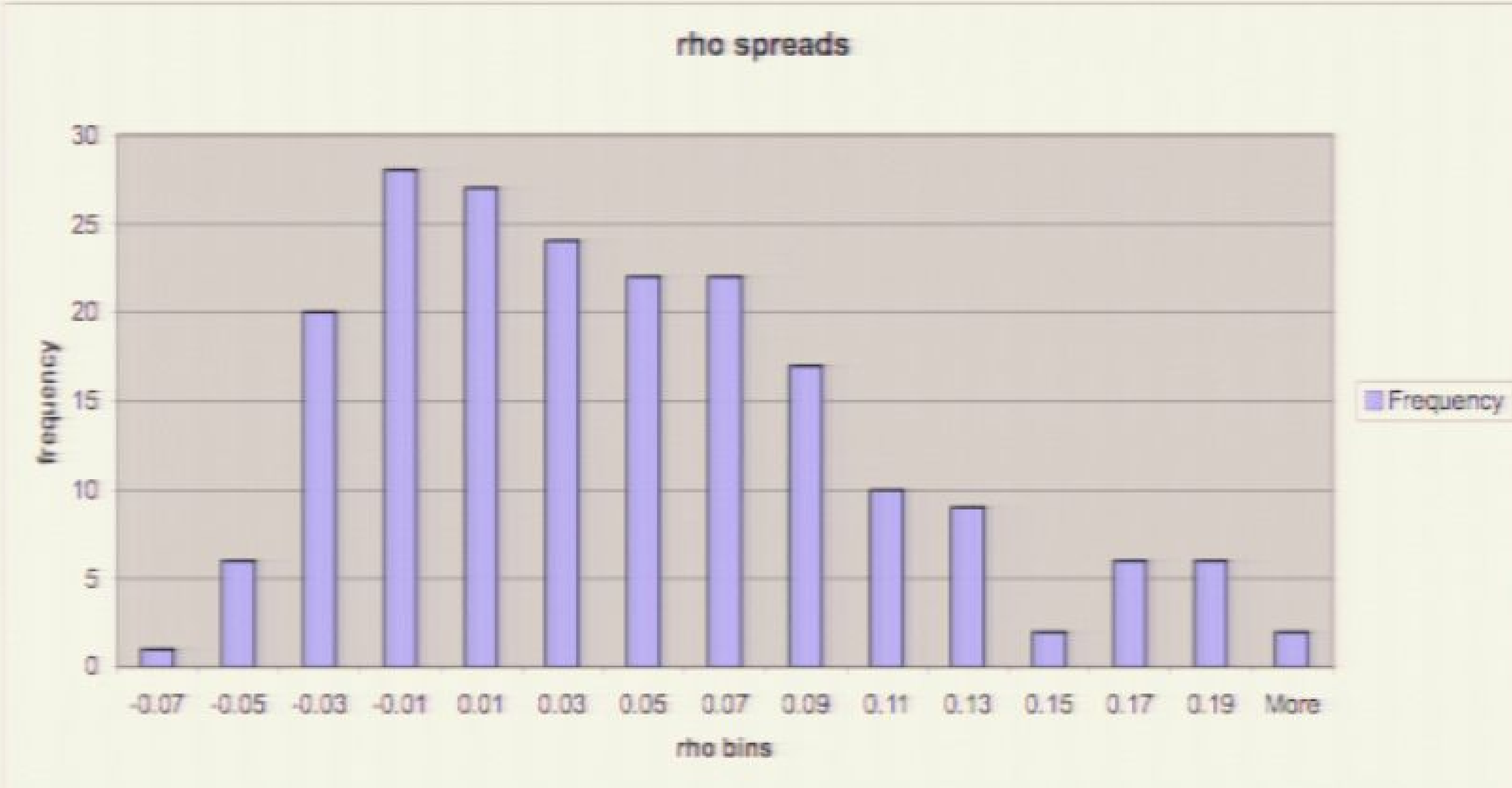
Statistical Errors

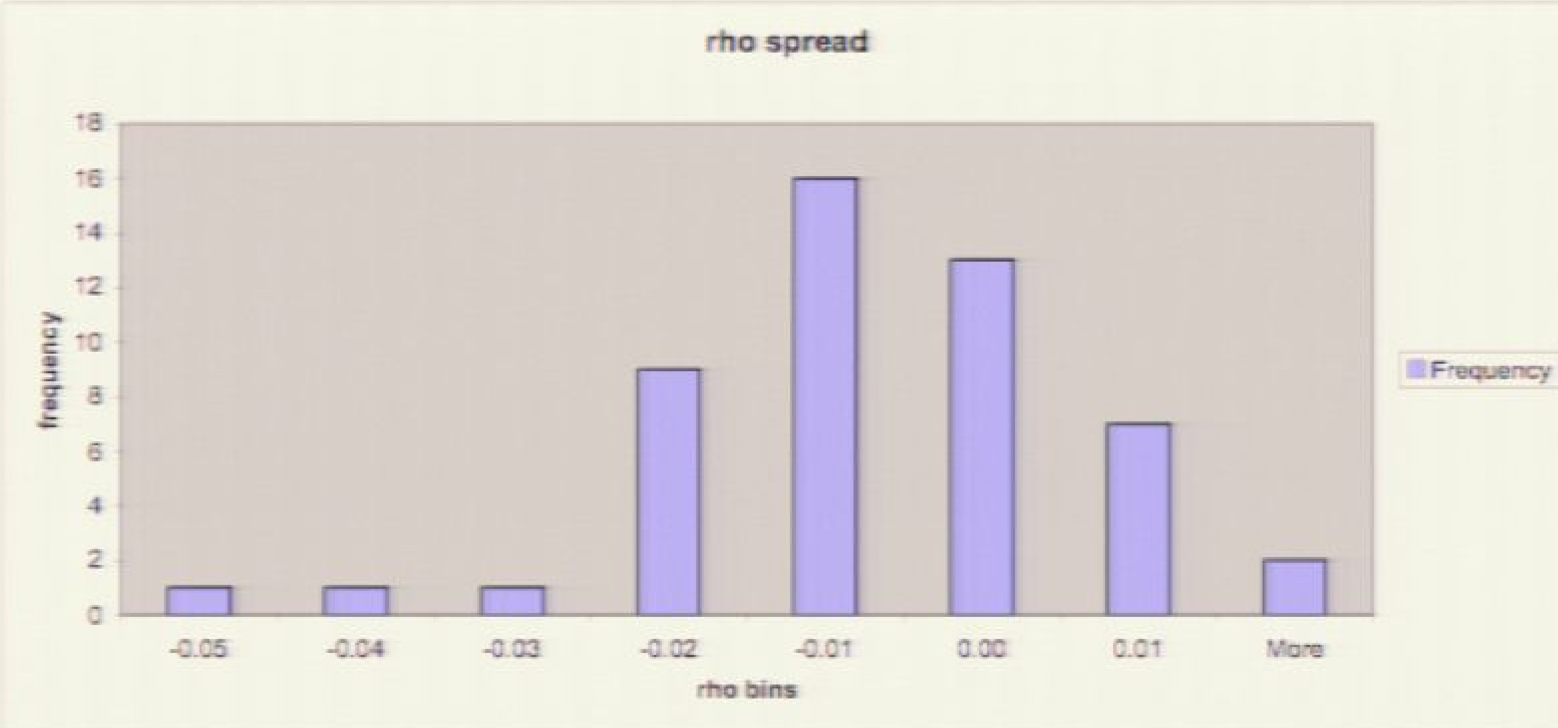
- Where in the diffraction pattern should we measure ρ?
- Plot the error in ρ (normalized for a certain relative error in the intensity / photocount) in the far field
- Generally, just avoid zeros of δ

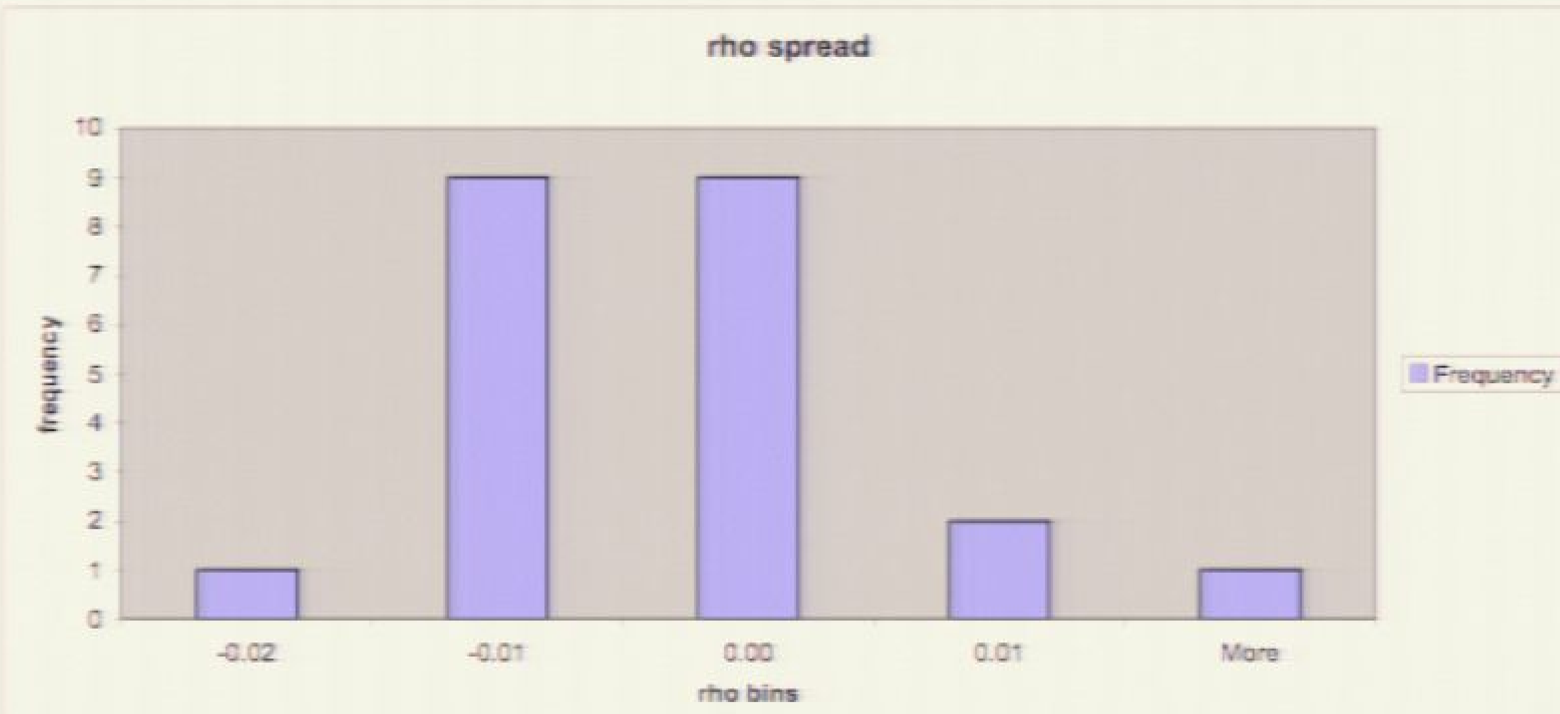


Preliminary results




rho spreads
30
25
20
15
10
5
0
frequency
-0.07
-0.05
-0.03
-0.01
0.01
0.03
0.05
0.07
0.09
0.11
0.13
0.15
0.17
0.19
More
rho bins
Frequency


rho spread
18
16
14
12
10
8
6
4
2
0
frequency
-0.05
-0.04
-0.03
-0.02
-0.01
0.00
0.01
More
rho bins
Frequency


rho spread
10
9
8
7
6
5
4
3
2
1
0
frequency
-0.02
-0.01
0.00
0.01
More
rho bins
Frequency

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What's wrong? (other than QM ☺)

- Any systematic error that produces nonzero ρ must affect the different combinations differently.
- Systematic Errors
  - ~~Irregularity of slits, non-plane wave illumination~~
  - Spurious mask transmission + Misalignment
  - Power drift/fluctuations
    - Laser
    - Fiber coupling
    - Fabry-Perot effects between mask and slit plate
  - Beam shape drift/fluctuation
  - Detector stability
  - Nonlinearity of the detection
  - Inhomogeneous mask transmission

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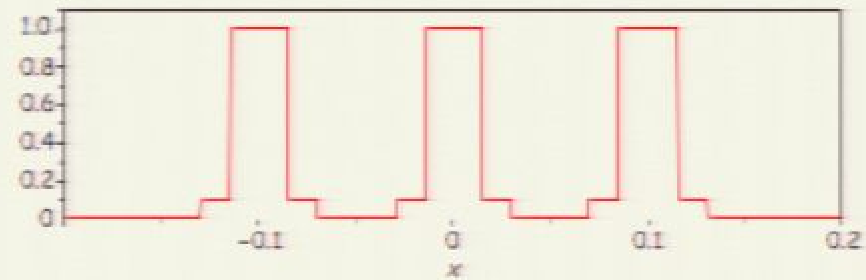
Misalignment + poor blocking

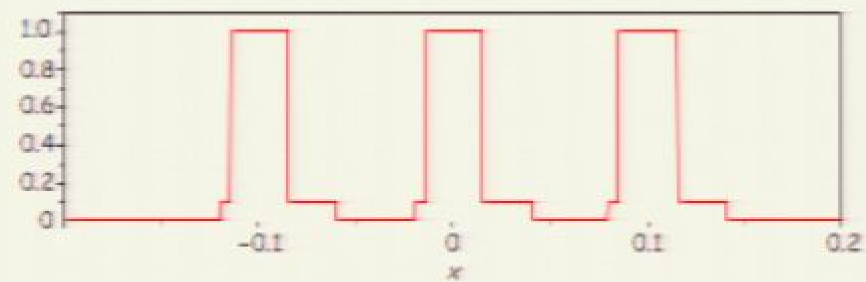
- Incomplete blocking (spurious transmission)

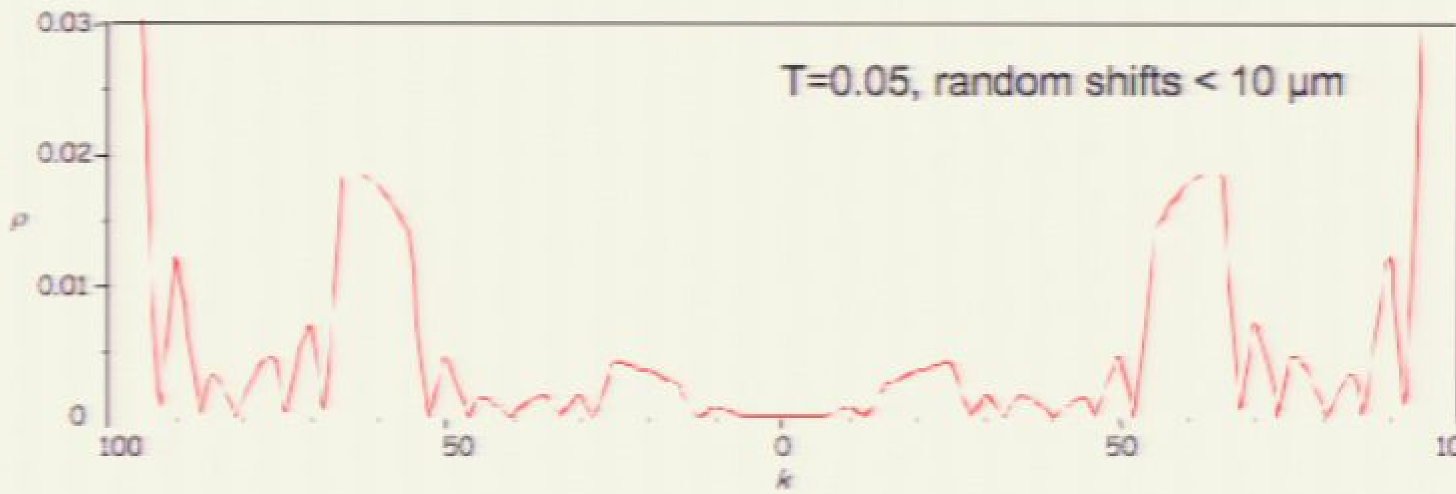
and

- misalignment of the blocking mask relative to the slits

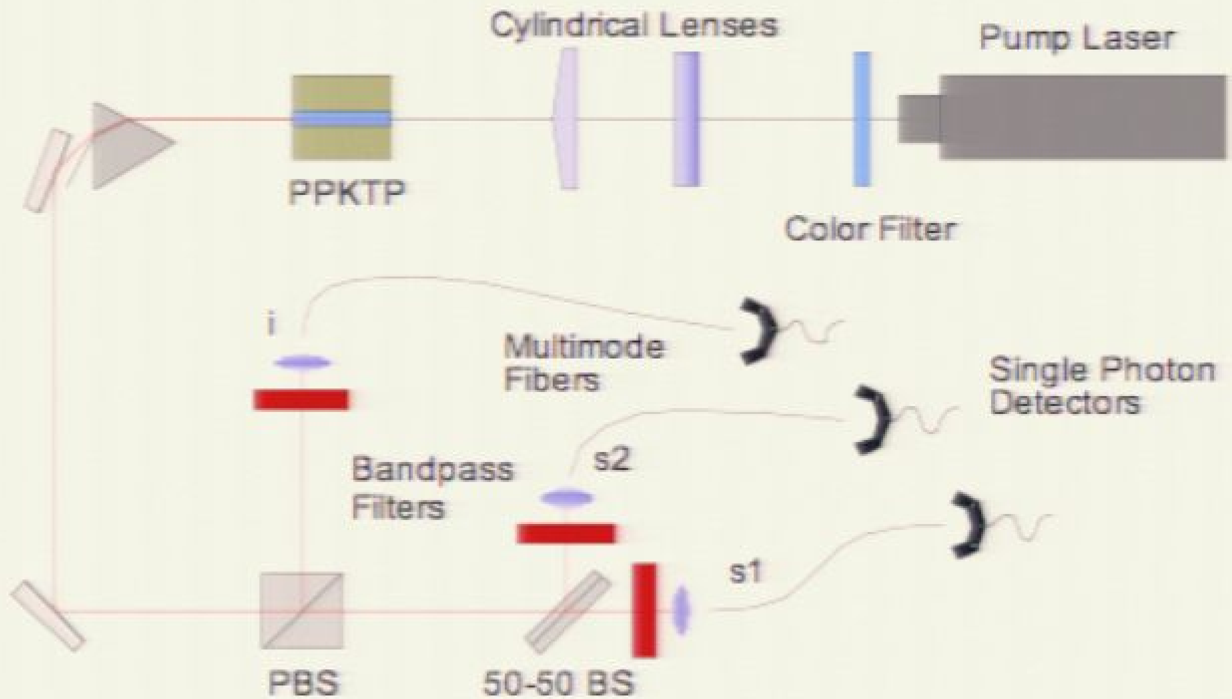
lead to a systematic non-zero ρ







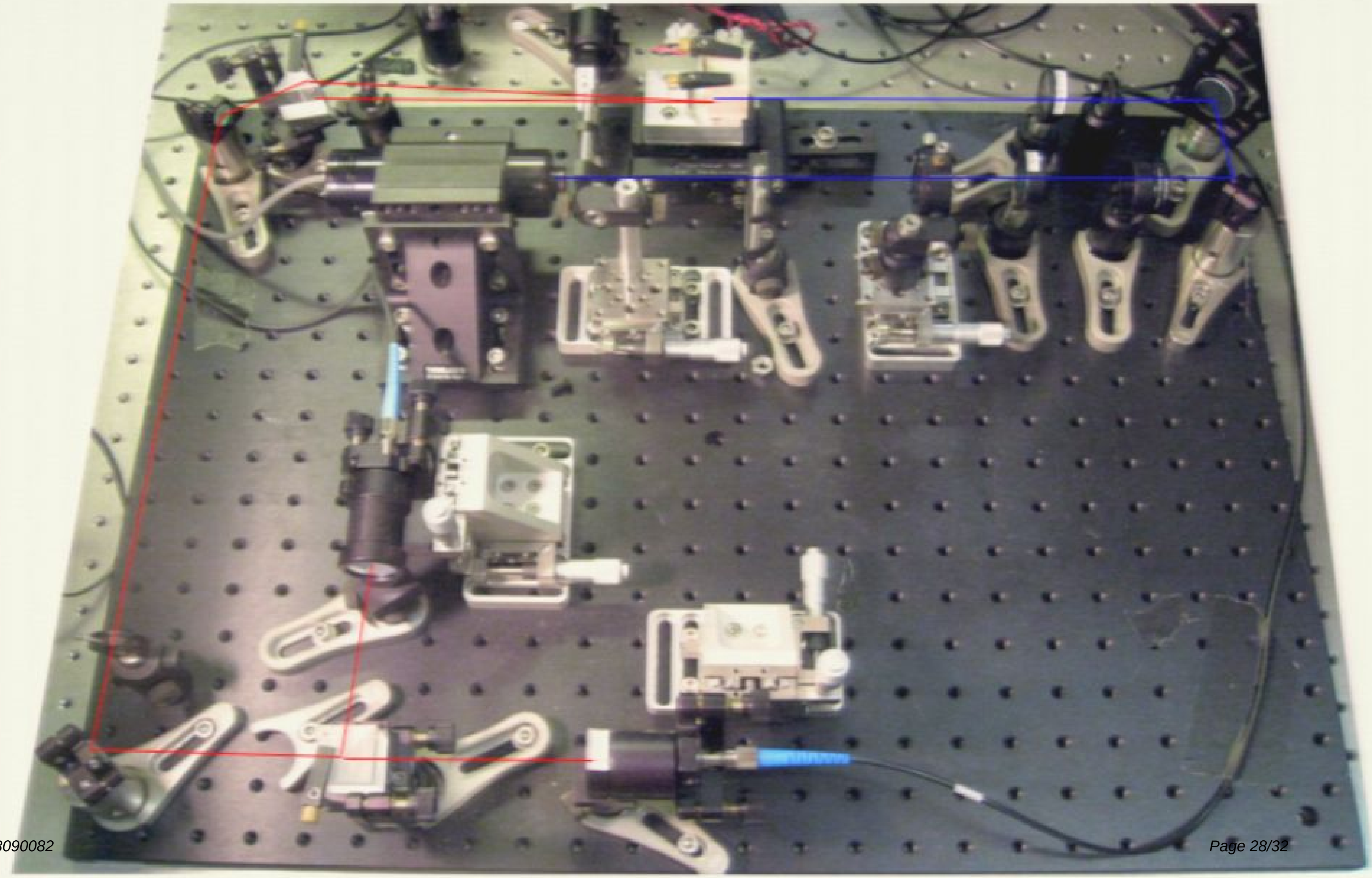
A heralded single photon source



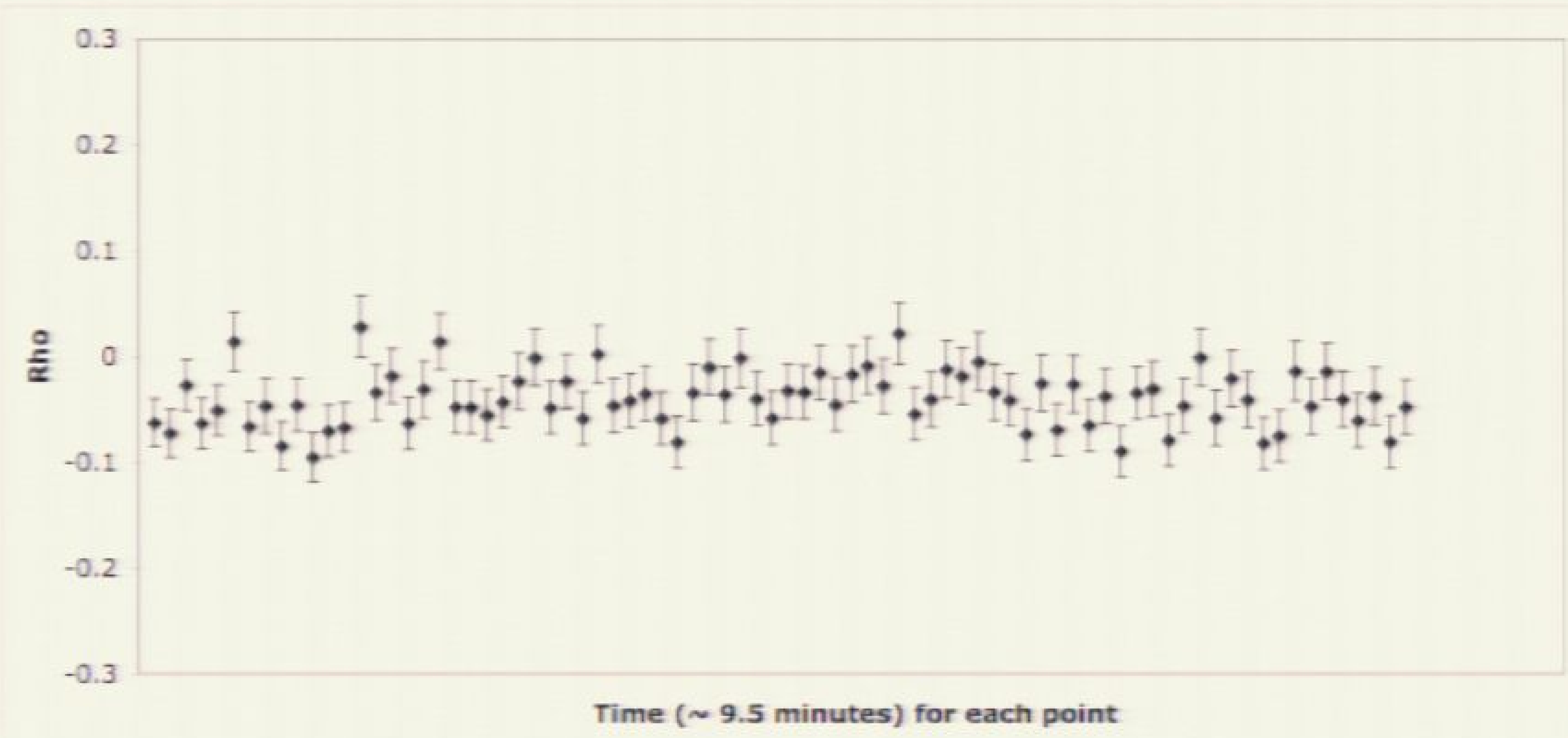
- PPKTP produces HV photon pairs
- Detection of a photon in i channel heralds a photon in the s channel
- Statistics in s channel tested by Hanbury Brown – Twiss interferometry

E. Boquillon et al. arXiv:0807.1725

Setup



Single photon data



Alternative: three path interferometer

- + Easy blocking (chopper?)
- + High throughput
- - phase instability

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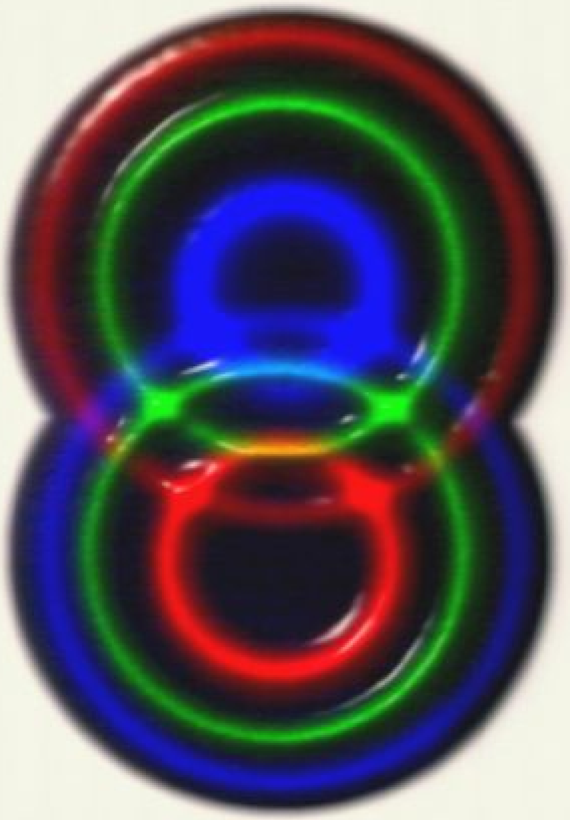
Implications



- How well do we know Born's rule?
- Nonlinearities in quantum mechanics
- Precision experiments are never as easy as you think...

Acknowledgments

- Professor Rafael Sorkin for proposing the expt.
- Professors Raymond Laflamme and Gregor Weihs for conceptualizing the expt.
- Christophe Couteau, Immo Soellner and Zachari Medendorp for their inputs.
- The Institute for Quantum Computing for funding.

Thank you for your attention