Observing and tuning the effect of Feynman paths in a classical regime

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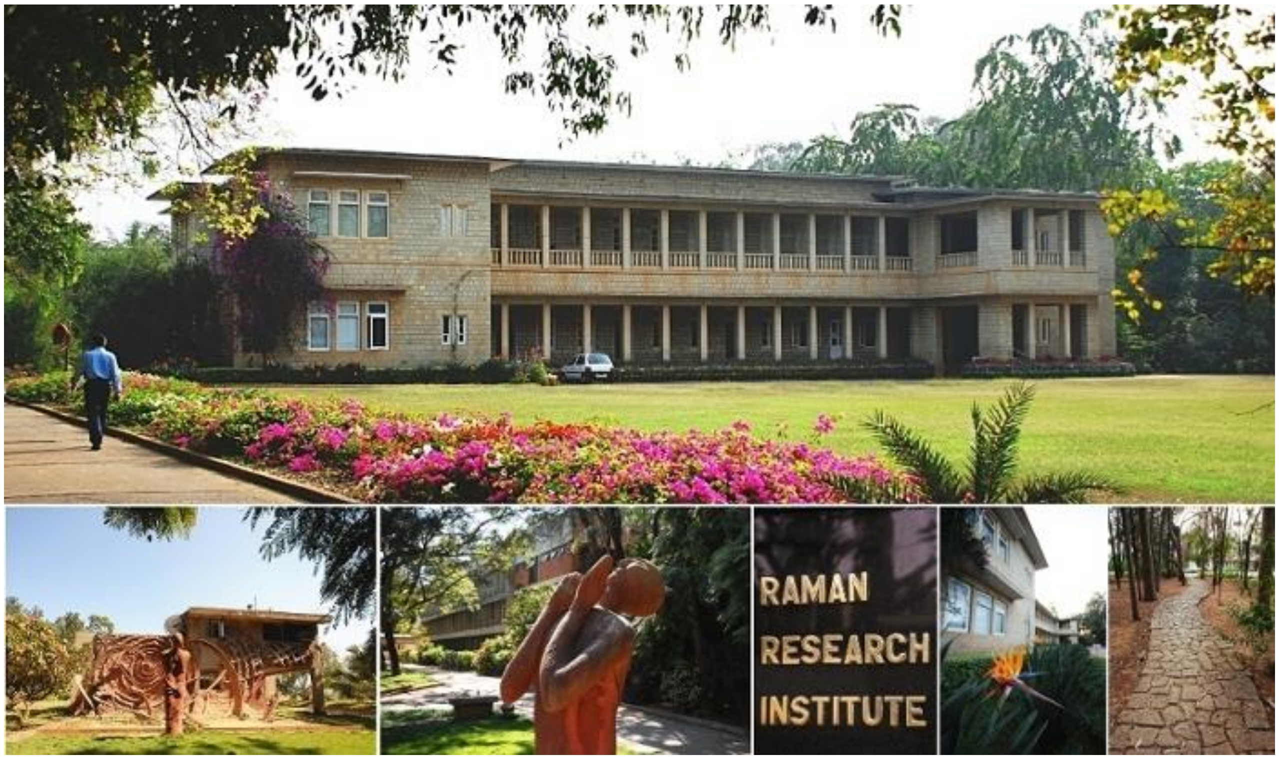

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- **Adjacent lab to be converted to a Class 100 clean room in the next few years, suited to device fabrication for solid state devices – Towards Hybrid Quantum Computing.**
- **Highly modulated environment with precise control on temperature and humidity.**
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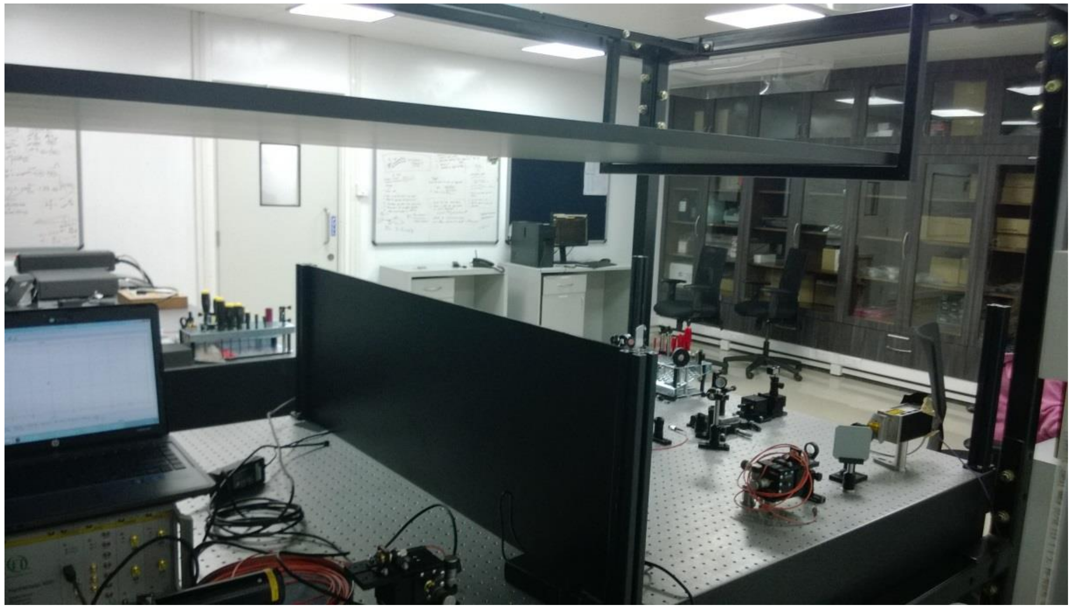

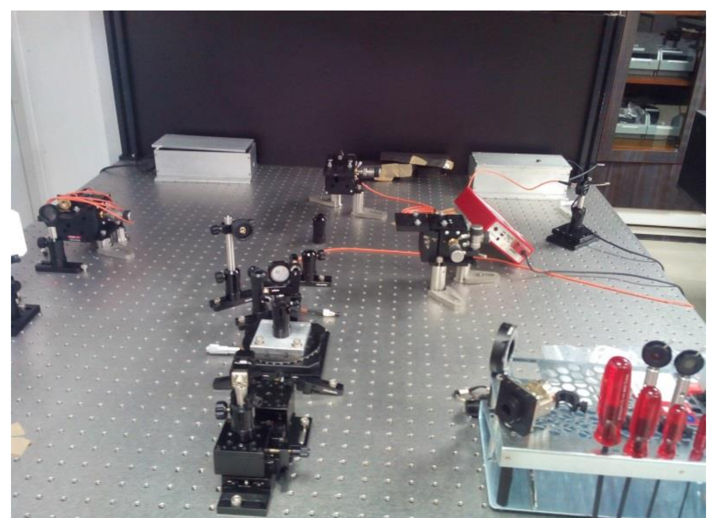

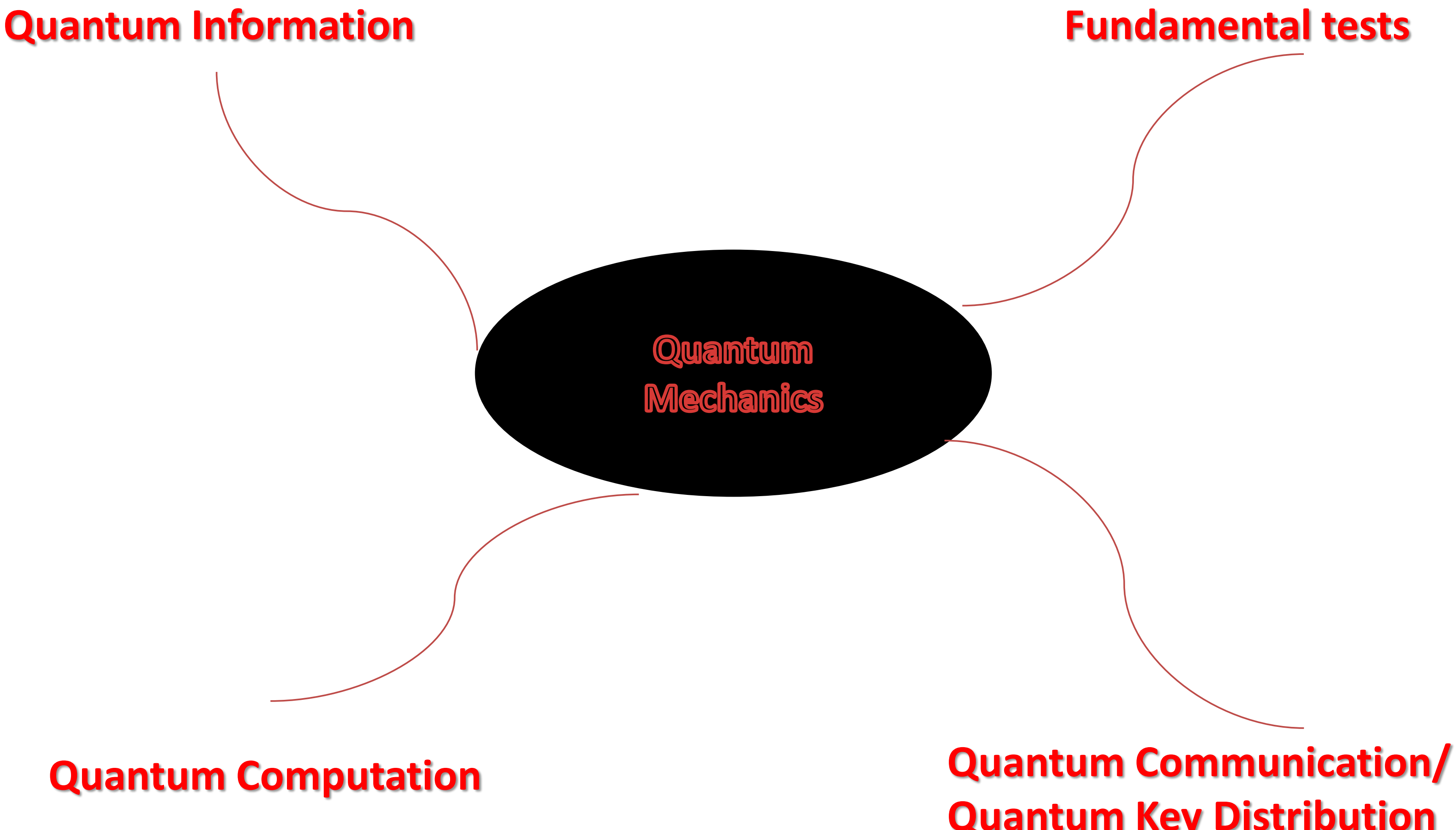
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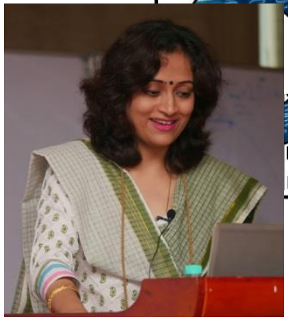

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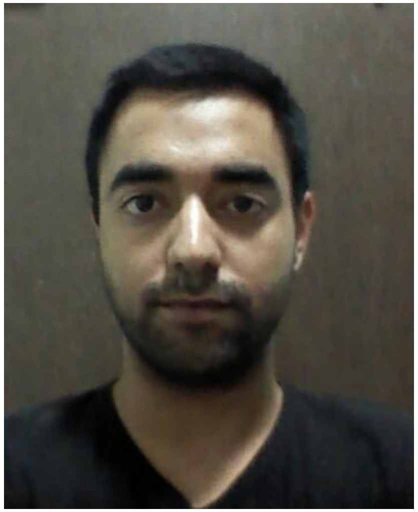

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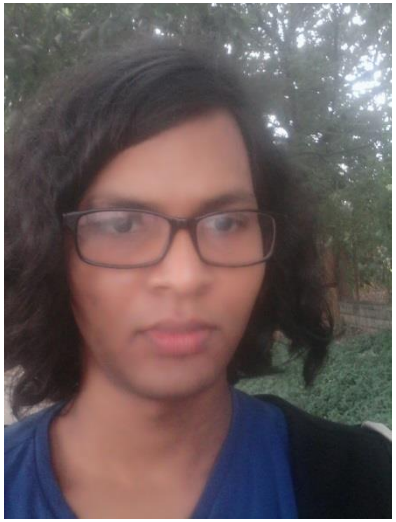

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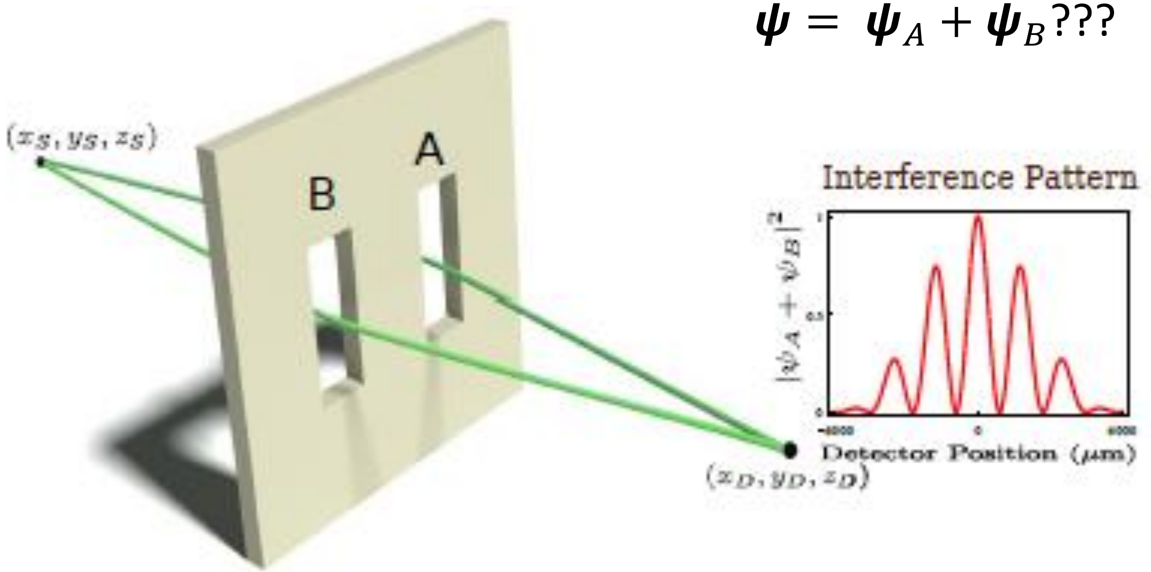
And some more short term students….

Superposition principle in the two slit experiment

$$\boldsymbol{\psi} = \boldsymbol{\psi}_A + \boldsymbol{\psi}_B ???$$



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Previous work

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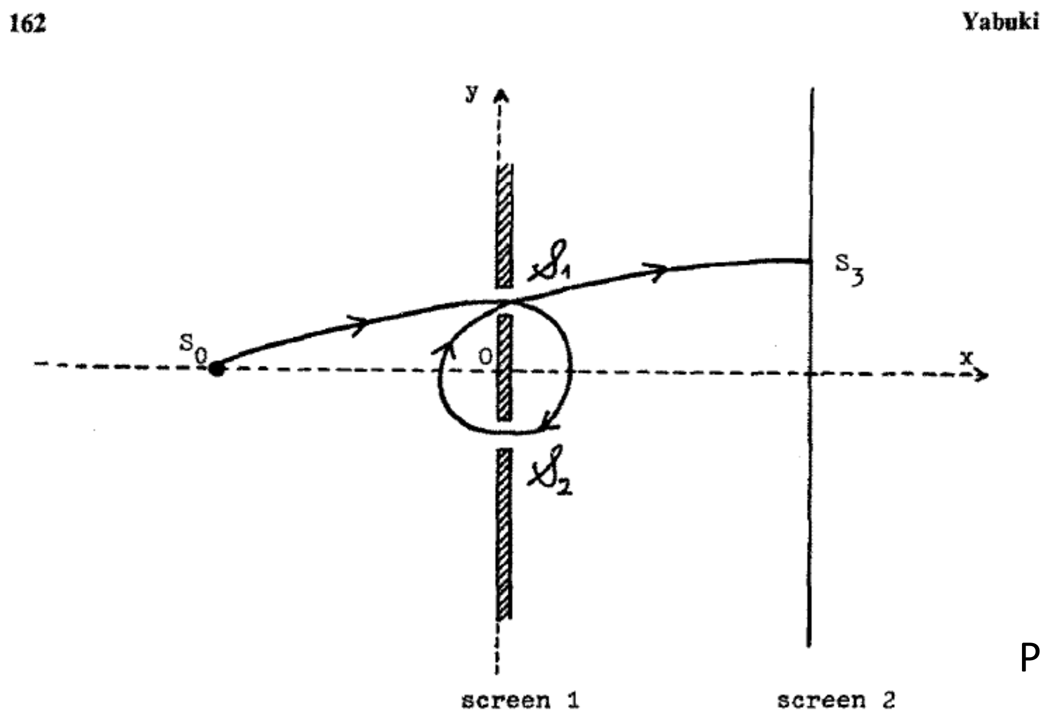

Picture from Yabuki

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Nonclassical Paths in Quantum Interference Experiments

Rahul Sawant, Joseph Samuel, Aninda Sinha, Supurna Sinha, and Urbasi Sinha
Phys. Rev. Lett. **113**, 120406 – Published 19 September 2014

Physics See Focus story: Curvy Photon Trajectories Could Be Detectable

39

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ABSTRACT

In a double slit interference experiment, the wave function at the screen with both slits open is not exactly equal to the sum of the wave functions with the slits individually open one at a time. The three scenarios represent three different boundary conditions and as such, the superposition principle should not be applicable. However, most well-known text books in quantum mechanics implicitly

Issue

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Physics - Curvy Photon Traject...

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Focus: Curvy Photon Trajectories Could Be Detectable

Published September 19, 2014 | Physics **7**, 96 (2014) | DOI: 10.1103/Physics.7.96

Quantum mechanics permits particles to follow bizarre, looping and curving trajectories, usually with very low probability. But a calculation shows that in some cases, these paths can have significant and possibly measurable effects.

Standard quantum mechanics problems such as the classic double-slit experiment usually assume that particles can only follow straight-line trajectories and ignore more exotic, looping paths that are much less likely. Now researchers have calculated the exotic path contribution for particles in multi-slit experiments, effects that were previously known but not precisely calculated. The team shows that the effects of these “nonclassical” paths could be observable in high-precision experiments.

Nonclassical Paths in Quantum Interference Experiments

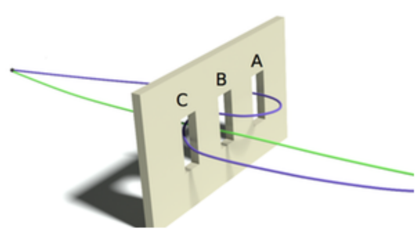
Rahul Sawant, Joseph Samuel, Aninda Sinha, Supurna Sinha, and Urbasi Sinha

Phys. Rev. Lett. **113**, 120406 (2014)

Published September 19, 2014

In the quantum double-slit experiment, a beam of particles (usually photons or electrons) is shot through a mask with two closely spaced slits, and a device on the far side detects particles and records their positions. The measurements reveal a so-called interference pattern with alternating stripes of high and low incidence, exactly what would be expected if classical waves were emitted from the slits, rather than particles. The particle beam’s wavelike behavior can be characterized with a wave function that gives the probability (once you square it) of detecting a particle at any location. It is often assumed that the wave function for both slits open is the sum (or superposition) of two single-slit wave functions—one with just slit A open and one with just slit B open. “This misconception has been around for a long time,” says Urbasi Sinha of the Raman Research Institute in Bangalore, India. In fact, the exact solution is more complicated, because what happens at slit A is influenced by the state of slit B (open or closed).

+Enlarge image



Sinha and her colleagues have explored the implications of this misconception and how it may affect actual

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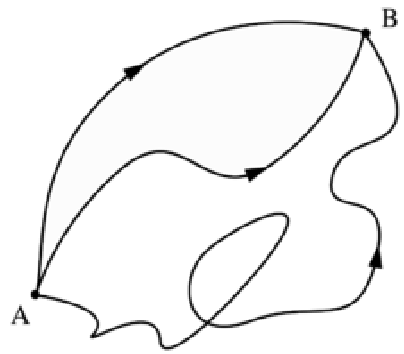
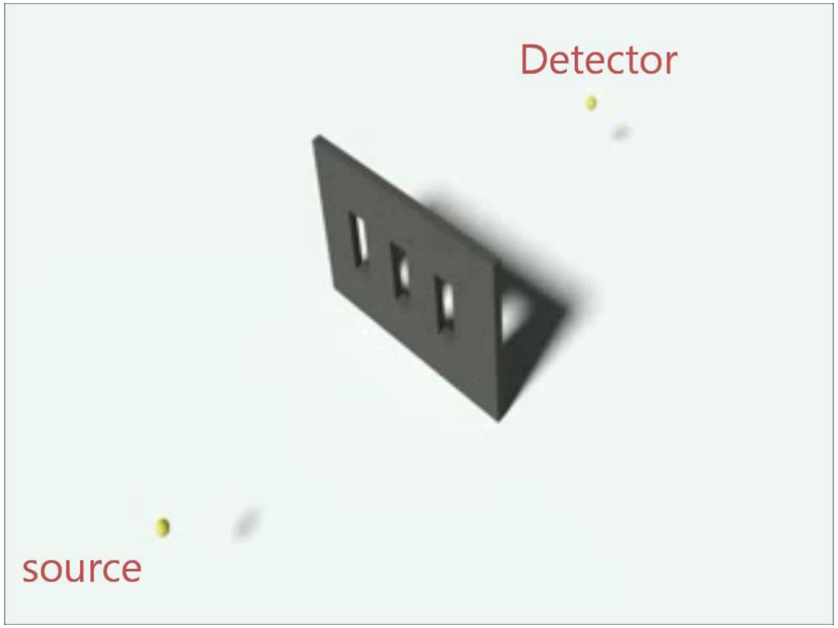
Feynman’s path integral formalism



$$K(A,B) = \int_{A}^{B} exp^{i/\hbar} S[B,A] Dx(t)$$

An integration over all possible paths that can be taken by the particle in going from A to B.

Apply Path integral formalism to the slit problem, instead of two slits now consider the triple slit problem…



All possible paths….not only straight paths from source to detector through any slit (classical path) but also looped (non-classical) paths.

Modification of the wave function which now becomes:

$$\psi_{AB} = \psi_A + \psi_B + \psi_L$$

ψ_L is the contribution due to the looped i.e. non-classical paths.

We have quantified the effect of such non-classical paths in interference experiments for the first time. Proposed simple slit-based experiments which could be used to "see" such non-classical paths in table top experiments….

"*Non classical paths in quantum interference experiments,* R.Sawant, J.Samuel, A.Sinha, S.Sinha and US, *Physical Review Letters,* ***113,*** 120406, 2014

A triple slit experiment provides a simple way to express the failure of the naïve application of the superposition principle in terms of directly measurable quantities. The triple slit (path) set up has been used as a test bed for testing fundamental aspects of quantum mechanics over the last few years….

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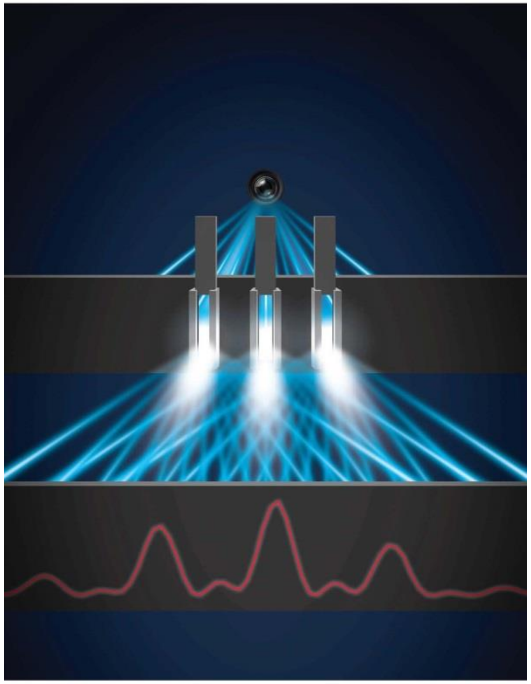
κ

The Quantum World: A place where there is no penalty for interference – Raymond Laflamme, IQC.

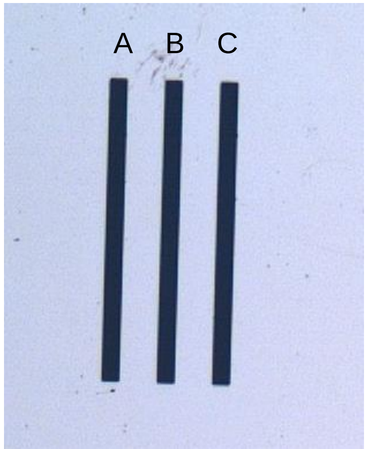


Interference and Sum Rules

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:

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

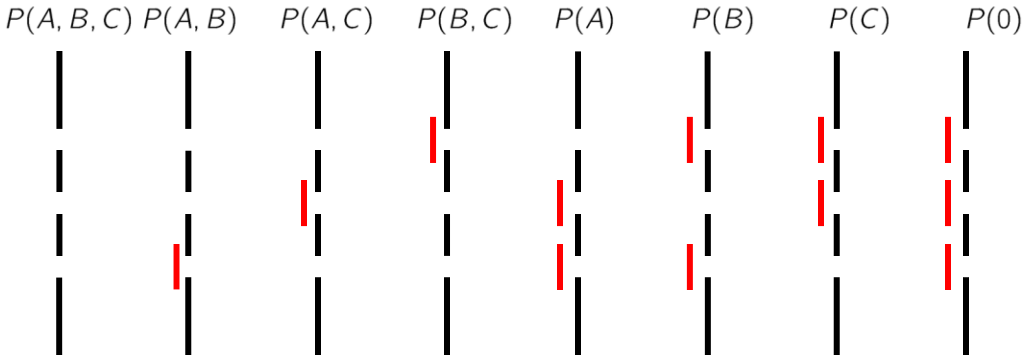


$$\begin{aligned} P(A,B,C) &= |\psi_A + \psi_B + \psi_C|^2 = \\ &= |\psi_A|^2 + |\psi_B|^2 + |\psi_C|^2 + \\ &\quad + \psi_A^*\psi_B + \psi_B^*\psi_A + \psi_A^*\psi_C + \psi_C^*\psi_A + \psi_B^*\psi_C + \psi_C^*\psi_B = \\ &= P(A) + P(B) + P(C) + I(A,B) + I(A,C) + I(B,C) \\ &= P(A) + P(B) + P(C) + \\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

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

Assuming naive application of the superposition principle as well as Born rule for probabilities.

Testing the 2nd Sum Rule



U.Sinha, C.Couteau, T.Jennewein, R.Laflamme and G.Weihs in *Science,* Vol. **329**, No. 5990, pp 418-421, 23rd July 2010.

$$\kappa = \frac{\epsilon}{\delta}$$

Many experimental bounds….

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

- All experiments reported in literature which measure this quantity, implicitly assume that only classical paths contribute to the interference.
- Numerical simulations of classical Maxwell's equations using FDTD analysis have shown that due to difference in boundary conditions, κ can be non-zero*.
- What is the effect of "non-classical" paths on κ???
- A non-zero contribution to κ by taking into account all possible paths in the path integral formalism

=> Naive application of superposition principle in interference experiments needs to be corrected.

=> Non zero κ does not necessarily imply falsification of Born rule.

=>

First non-zero estimate of κ.

* H.D.Raedt et al, *Physical Review A* **85**, 012101 (2012).

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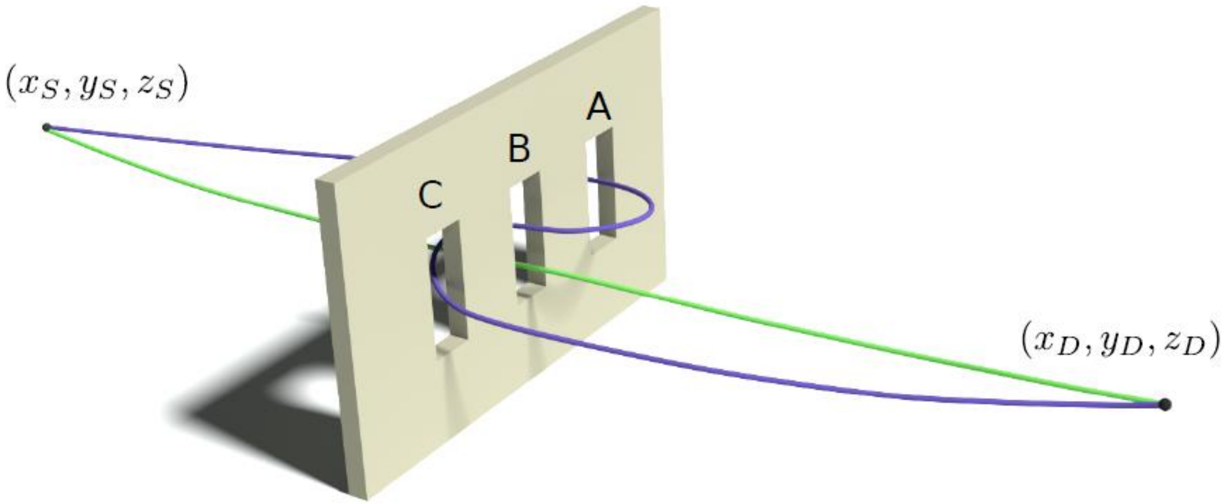

Path integrals in the lab: The green line demonstrates a representative classical path. The purple line demonstrates a representative non classical path.

Observation of a non-zero κ which is expected from the proposed modification to the wave-function hypothesis would in fact serve as an experimental validation of the full scope of the Feynman path integral formalism.

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The calculation…

Assumptions:

- We use the free particle propagator in our calculations. For a particle in free space and away from the slits, this is a reasonable approximation. We account for the slits by simply removing from the integral all paths that pass through the opaque metal.

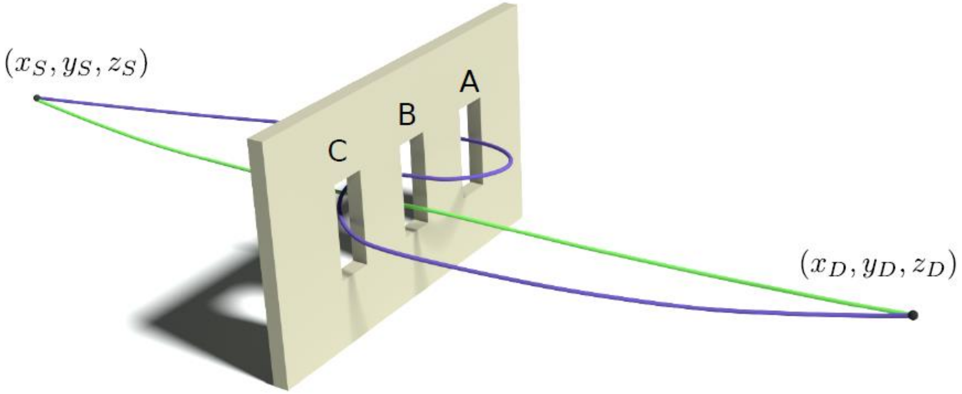
- We use a steady state description. We assume that the detectors integrate over a duration of time which is much longer than any other time scale in the problem like for instance the travel time across the apparatus which justifies the use of the steady state approximation. We go on to use the time independent Feynman path integral.

- We also suppose that the wavelength of the incident source is much smaller than any other length scale in the problem, the sizes and separations of the slits and the distance to the source and the detector.

- We will present results which are applicable to the Fraunhofer regime.

The normalized energy space propagator *K* for a free particle with wave number k from a position **r'** to **r** :

$$K(\vec{r},\vec{r}') = \frac{k}{2\pi i}\frac{1}{|\vec{r}-\vec{r}'|}e^{ik|\vec{r}-\vec{r}'|}\,. \qquad (1)^*$$



In this triple slit configuration, the entire set of paths from source to detector can be divided into two classes:

1. Paths which cross the slit plane exactly once pertaining to a probability amplitude K_C *(green)*
2. Paths which cross the slit plane more than once pertaining to a probability amplitude K_{nc} *(purple)*

$$\therefore K = K_c + K_{nc}\,. \qquad (2)$$

* We should point out that there are corrections to the propagator due to closed loops in momentum space from quantum field theory considerations. We have explicitly estimated that the effects of such corrections will be negligibly small.

We wish to estimate K_{nc} relative to K_c to test the domain of validity of the wave function hypothesis.

A representative K_c in our problem is the probability to go from the source (-L,0,0) to the detector (D,y_D,0) through slit *A* which we call $K_c^A(S,D,k)$. This makes use of the decomposition theorem, i.e. a path in FPI can be broken into many sub-paths and the propagator is the product of the individual propagators. Thus:

$$K_c^A \;=\; -(\frac{k}{2\pi})^2 \int_{d-\frac{w}{2}}^{d+\frac{w}{2}} \int_{-h}^{h} dy\ dz\ \frac{e^{ik(l_1+l_2)}}{l_1 l_2} \qquad (3)$$

In the Fraunhofer regime this becomes:

$$K_c^A \;=\; -\gamma(\frac{k}{2\pi})^2 \int_{d-\frac{w}{2}}^{d+\frac{w}{2}} \int_{-h}^{h} dy\ dz\ e^{ik[\frac{(y)^2+z^2}{2L}+\frac{(y_D-y)^2+z^2}{2D}]} \qquad (4)$$

d = inter-slit distance
w= slit width
h= slit height

$$l_1 \approx L + \frac{y^2+z^2}{2L}$$

$$l_2 \approx D + \frac{(y_D-y)^2+z^2}{2D}$$

$$\gamma = \frac{1}{LD} e^{ik(L+D)}.$$

These are Fresnel integrals and have been solved using Mathematica.

A representative K_{nc} in our problem is the probability to go from the source (-L,0,0) to the detector (D,y_D,0) following a path where the particle goes from the source to the first slit, then loops around the second and third slits before proceeding to the detector. We call this $K_{nc}^A(S,D,k)$.

$$K_{nc}^A \;=\; i(\frac{k}{2\pi})^3 \int dy_1\ dy_2\ dz_1\ dz_2\ \frac{e^{ik(l_1+l_2+l_3)}}{l_1 l_2 l_3} \qquad (5)$$

$$l_1^2 = (y_1 - y_S)^2 + L^2 + z_1^2$$

$$l_2^2 = (y_2 - y_1)^2 + (z_2 - z_1)^2$$

$$l_3^2 = (y_D - y_2)^2 + D^2 + z_2^2.$$

y_1 integral runs over slit A,
y_2 integral runs over slits B and C.

Taking approximations appropriate to the Fraunhofer regime, using stationary phase approximation for the oscillatory integrals, eqn.(5) becomes:

$$K_{nc}^{A} = \gamma i^{3/2}(\frac{k}{2\pi})^{5/2} \int dy_1 \, dy_2 \, dz_1 \, (y_2 - y_1)^{-1/2} e^{ik\left[\frac{y_1^2+z_1^2}{2L}+(y_2-y_1)+\frac{(y_D-y_2)^2+z_1^2}{2D}\right]}$$

In terms of K_c and K_{nc} the propagator to go from the source to the detector when all three slits are open is:

$$K^{ABC} = K_c^A + K_c^B + K_c^C + K_{nc}^{ABC} \quad (7)$$

Similarly,

$K_{nc}{}^{ABC}$ nc terms when all slits open,
$K_{nc}{}^{AB}$ nc terms when A and B open….

$$K^{AB} = K_c^A + K_c^B + K_{nc}^{AB} \quad (8)$$

Thus, in terms of propagators:

(9)

And,

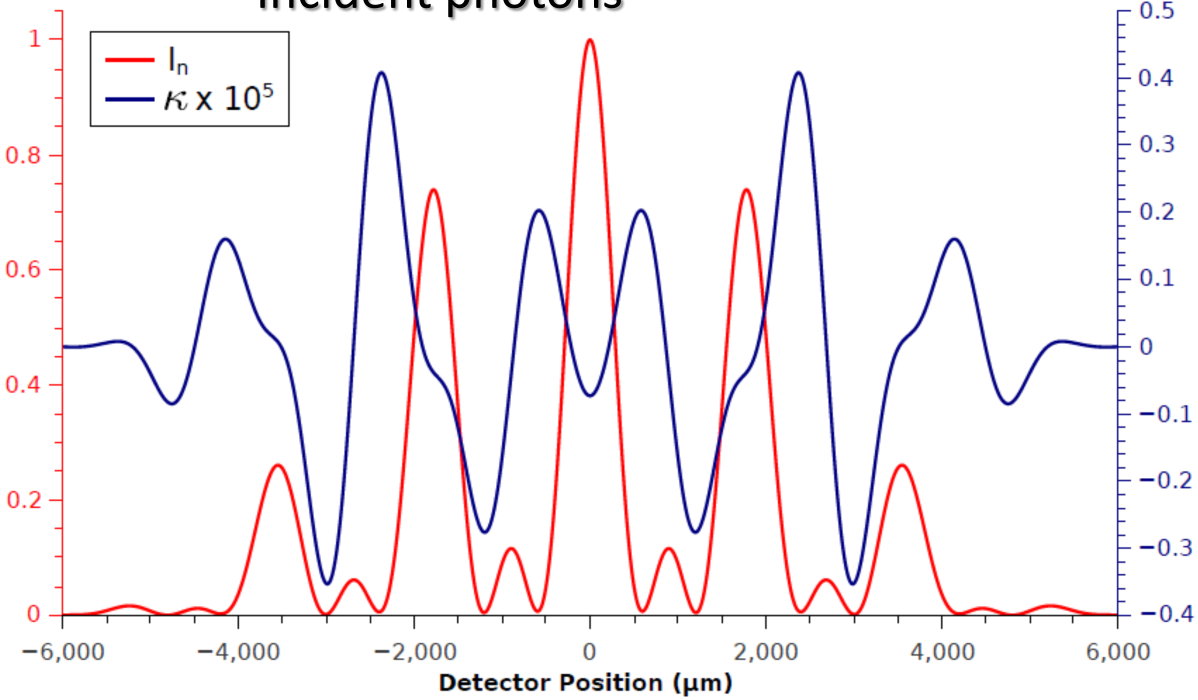
$$\epsilon = |K^{ABC}|^2 - |K^{AB}|^2 - |K^{AC}|^2 - |K^{BC}|^2 + |K^A|^2 + |K^B|^2 + |K^C|^2$$

$$\kappa = \frac{\varepsilon}{\delta}$$

where $\delta = |K^{ABC}(0)|^2$ and $|K^{ABC}(0)|^2$ is the value of $|K^{ABC}|^2$ at the central maximum of the triple slit interference pattern.

κ ≠ 0!!

Incident photons

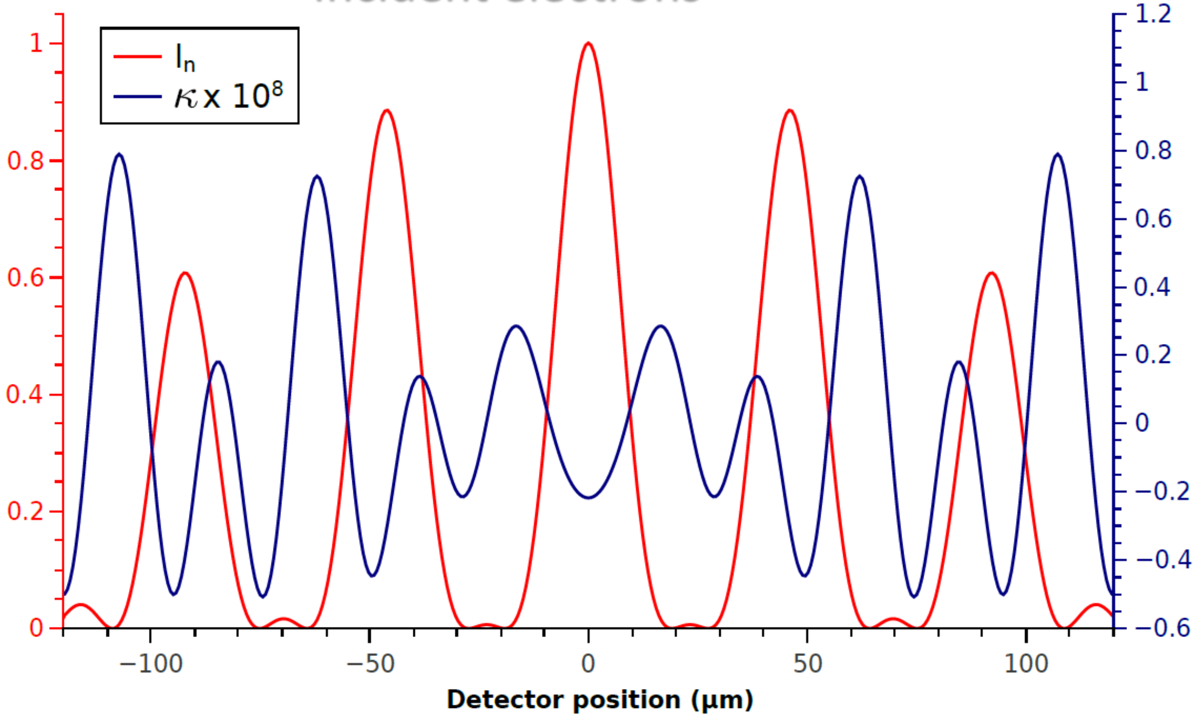


<u>Normalized values of *κ* as a function of detector position (blue line).</u>

$I_n = |K^{ABC}(y)|^2/|K^{ABC}(0)|^2$ is a plot of the triple slit interference pattern as a function of detector position (red line), it gives a clearer understanding of the modulation in the plot for *κ*.
Slit width = 30μm, inter-slit distance = 100μm, distance between source and slits and slits and detector = 18cm and incident wavelength = 810nm (parameters taken from [*])

* U.Sinha et al, *Science,* Vol. **329**, No. 5990, pp 418-421, 23rd July 2010.

Incident electrons



<u>Normalized values of κ as a function of detector position (blue line).</u>

I_n = $|K^{ABC}(y)|^2/|K^{ABC}(0)|^2$ is a plot of the triple slit interference pattern as a function of detector position (red line), it gives a clearer understanding of the modulation in the plot for κ.
Slit width = 62nm, inter-slit distance = 272nm, distance between source and slits = 30.5cm and slits and detector = 24cm and DeBroglie wavelength = 50pm (parameters taken from [**])

** R.Bach et al, *New Journal of Physics* **15**, 033018 (2013)

Further work

Analytical expression for κ in the Fraunhofer regime

A.Sinha, A.H.Vijay and US, *On the Superposition principle in interference experiments*, arXiv: 1412.2198

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On the superposition principle in interference experiments

Aninda Sinha[1], Aravind H. Vijay[1,2] & Urbasi Sinha[2,3]

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The superposition principle is usually incorrectly applied in interference experiments. This has recently been investigated through numerics based on Finite Difference Time Domain (FDTD) methods as well as the Feynman path integral formalism. In the current work, we have derived an analytic formula for the Sorkin parameter which can be used to determine the deviation from the application of the principle. We have found excellent agreement between the analytic distribution and those that have been earlier estimated by numerical integration as well as resource intensive FDTD simulations. The analytic handle would be useful for comparing theory with future experiments. It is applicable both to physics based on classical wave equations as well as the non-relativistic Schrödinger equation.

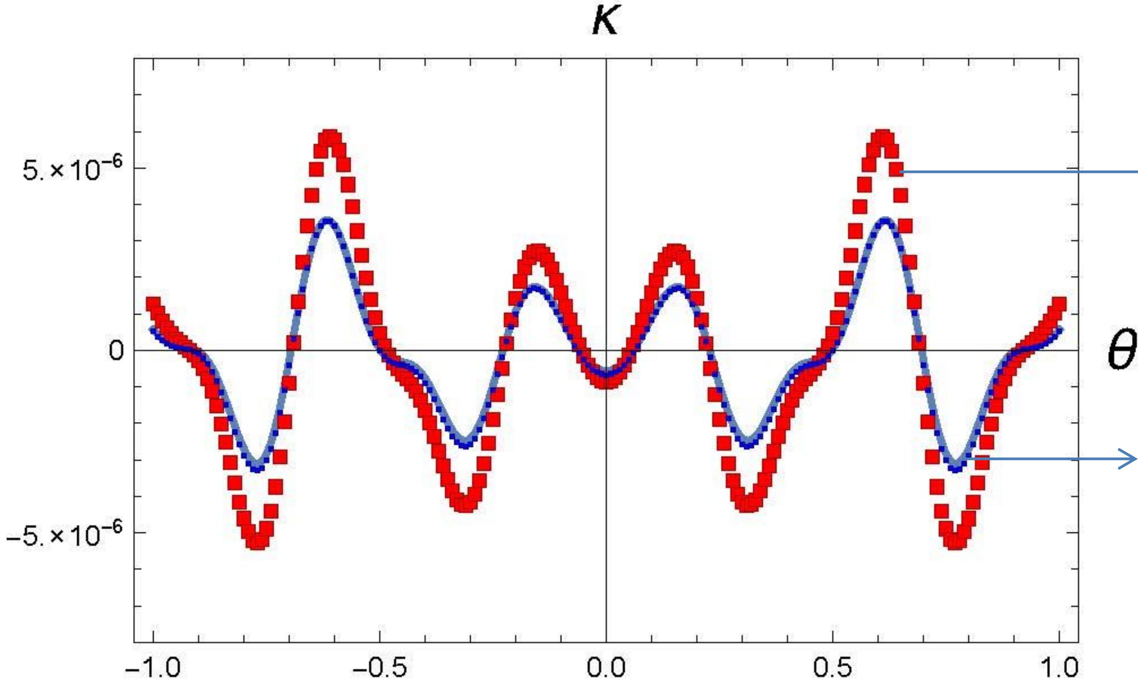
- Thin slit approximation
- Fraunhofer regime
- Paths with one kink have leading contribution
- More than one kink, we have seen by adding more than one kink that their contribution goes down drastically
- θ << k w and θ <<k d

$$k(\theta) = \frac{1}{9\sqrt{2\pi d}} \frac{Sin\,(w\theta)}{w^2\theta} f(d, w, \theta).$$

- Using kw>>1 and d>>w, we get a strict upper bound on κ which we have verified in several examples:

$$|k_{max}| \approx 0.03\, \frac{\lambda^{3/2}}{d^{1/2} w}$$

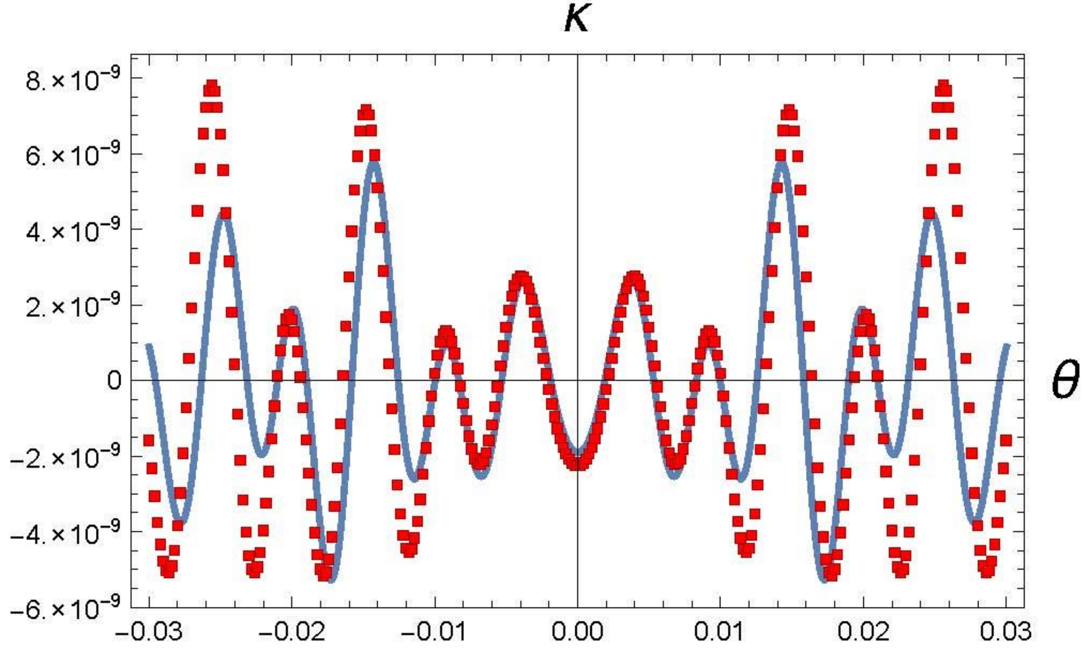
Simple formula, useful to remember…



Fresnel number =0.006

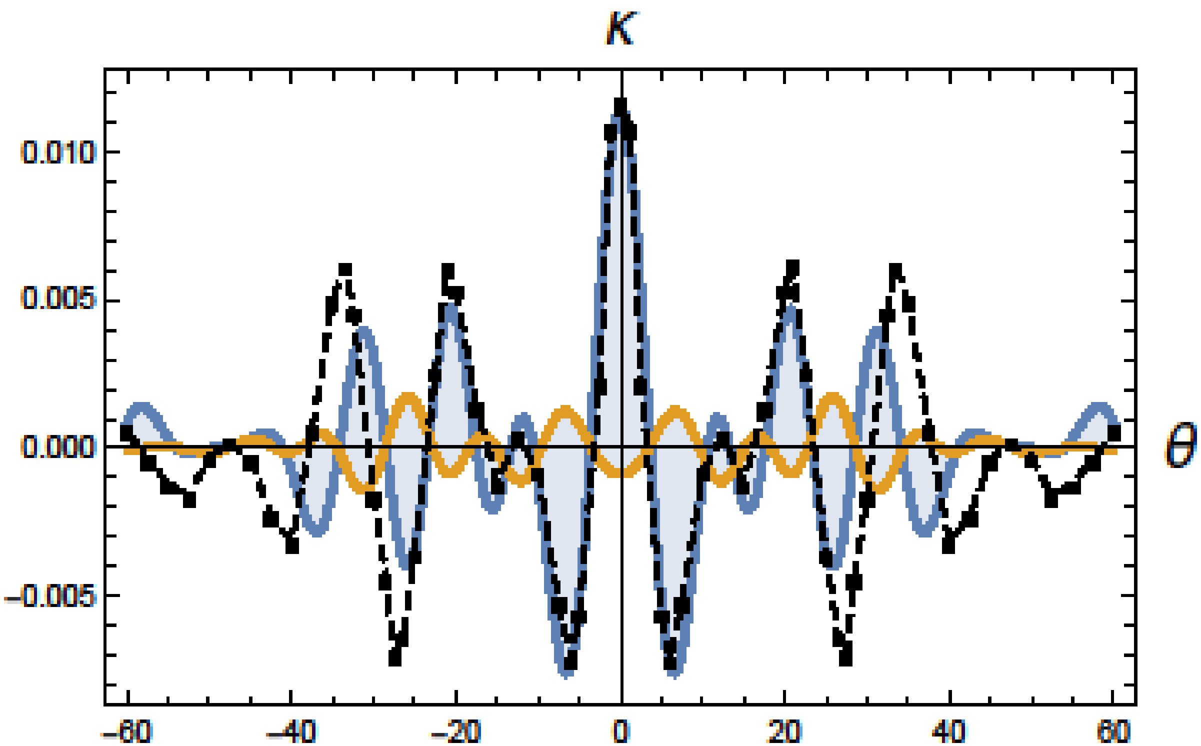
Fresnel number =0.0002

For the earlier photon parameters



For the earlier electron parameters

Piece de resistance……..Remarkable agreement with FDTD simulations…



Comparison with the FDTD simulations in PRA **85** (2012) for the d = 3λ; w = λ ; t = 4 λ case. The black dots indicate the FDTD values which have been read off from figure in above reference. The orange line indicates the analytic expression while the blue line which leads to an agreement with the FDTD result is the analytic expression with d = 3 λ; w = 1.15 λ

FDTD simulation of $k(\theta)$:

- Three and a half days of computation time on supercomputer.
- 6.3 TB of memory

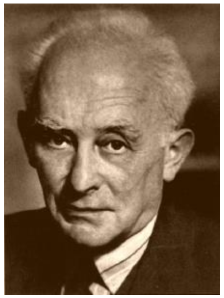
Our analytical formula for $k(\theta)$:

Gives the distribution almost immediately on a standard laptop using *Mathematica* !!

``It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong."

----Richard Feynman

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. $\Phi_{n_\tau m}(\alpha, \beta, \gamma)$ 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 $\Phi_{n_\tau m}$.

"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).

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REPORT

Ruling Out Multi-Order Interference in Quantum Mechanics

Urbasi Sinha[1,*], Christophe Couteau[1,2], Thomas Jennewein[1], Raymond Laflamme[1,3], Gregor Weihs[1,4,*]

+ Author Affiliations

*To whom correspondence should be addressed. E-mail: usinha@iqc.ca, gregor.weihs@uibk.ac.at

Science 23 Jul 2010:
Vol. 329, Issue 5990, pp. 418-421
DOI: 10.1126/science.1190545

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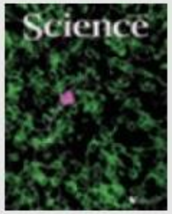

Science
Vol 329, Issue 5990
23 July 2010

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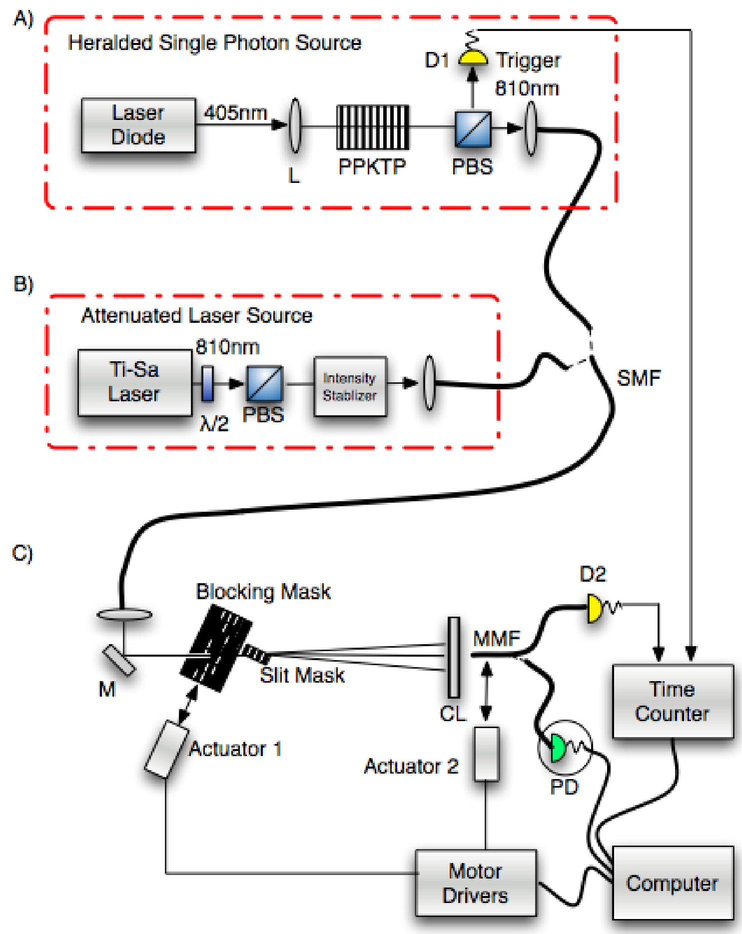
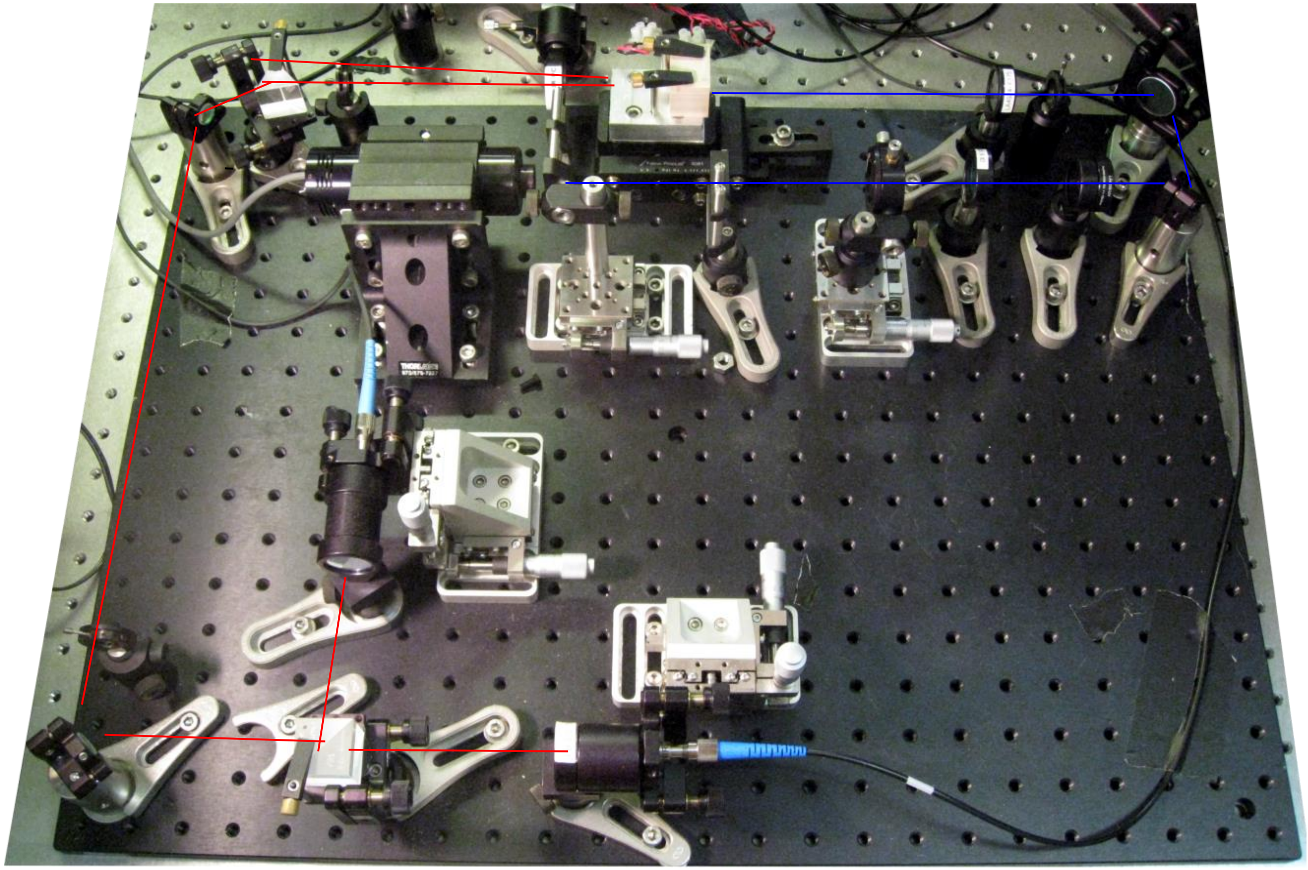
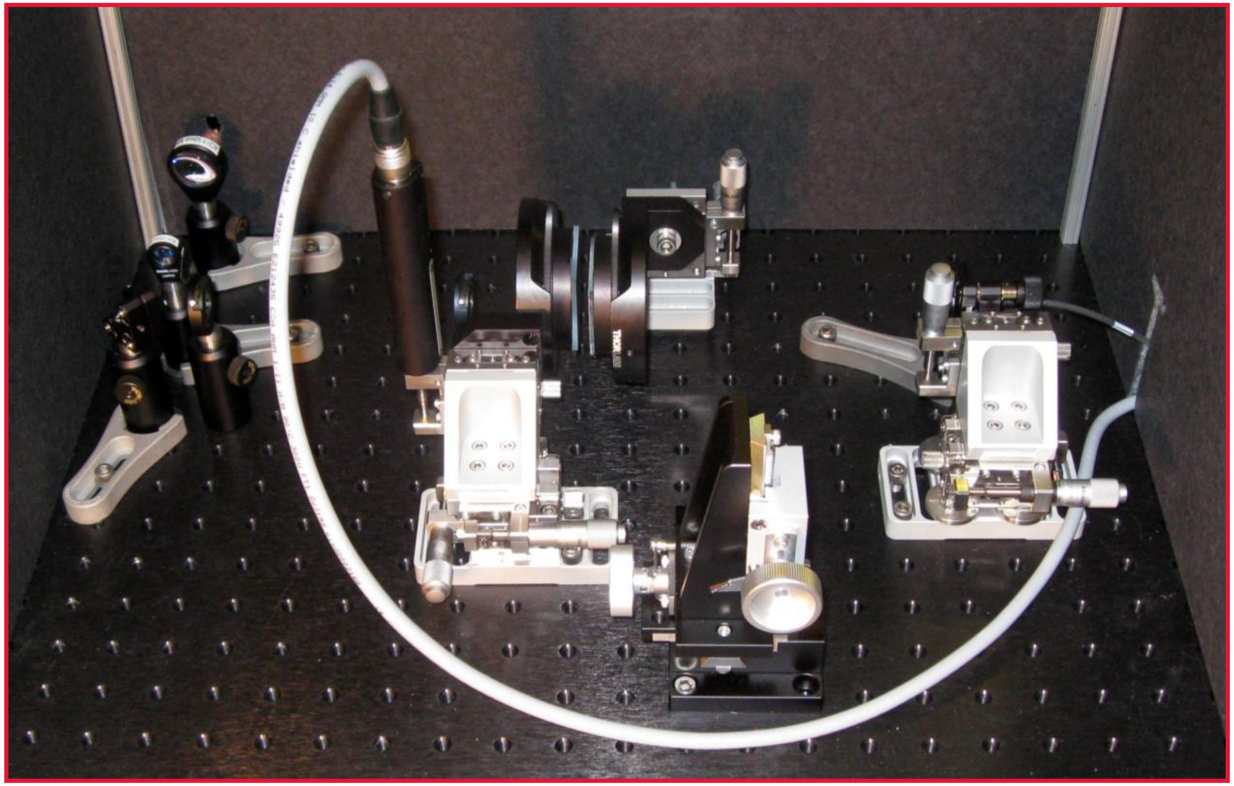
Three Slit Setup



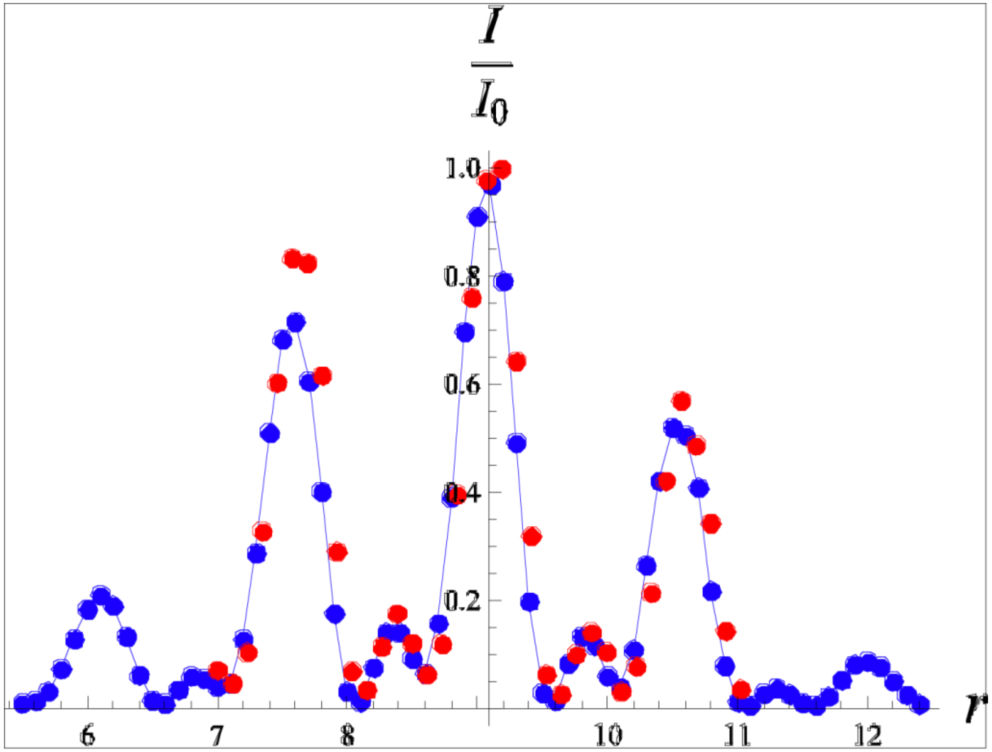
Setup

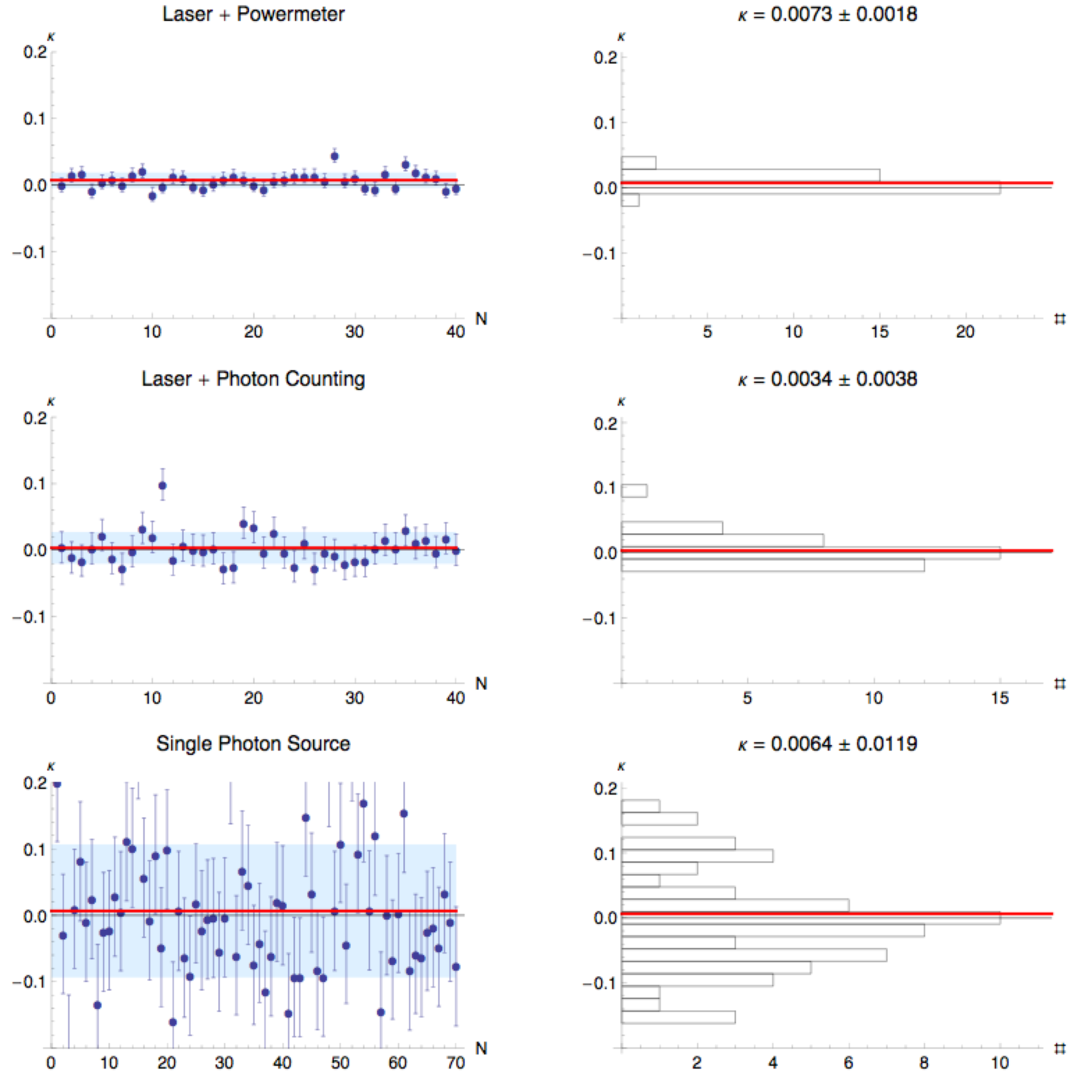


Experiment



Triple slit interference pattern

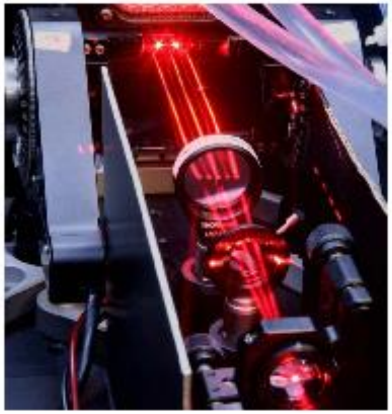


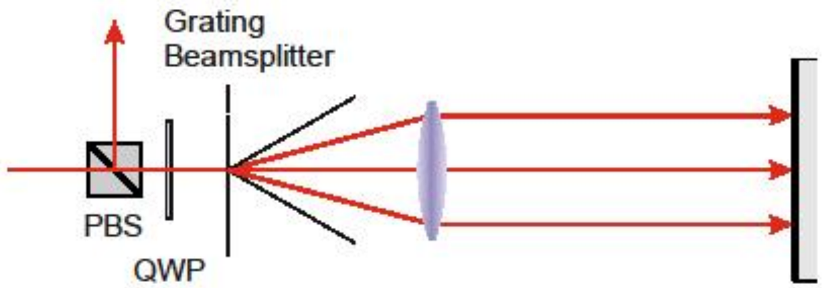


<u>US</u>, C.Couteau, T.Jennewein, R.Laflamme and G.Weihs in *Science*, Vol. **329**, No. 5990, pp 418-421, 23rd July 2010.

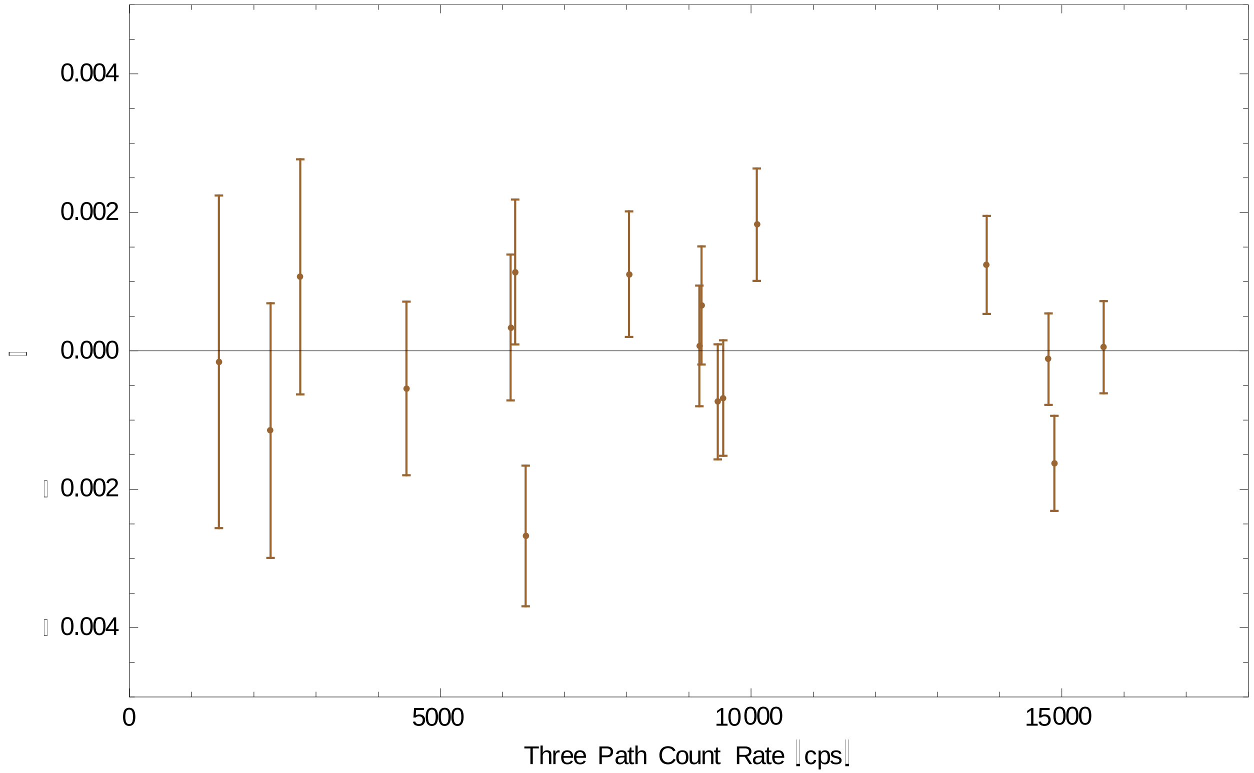
HIGHER ORDER INTERFERENCE

- Improve throughput
- Shutter paths independently
- Access entire phase space



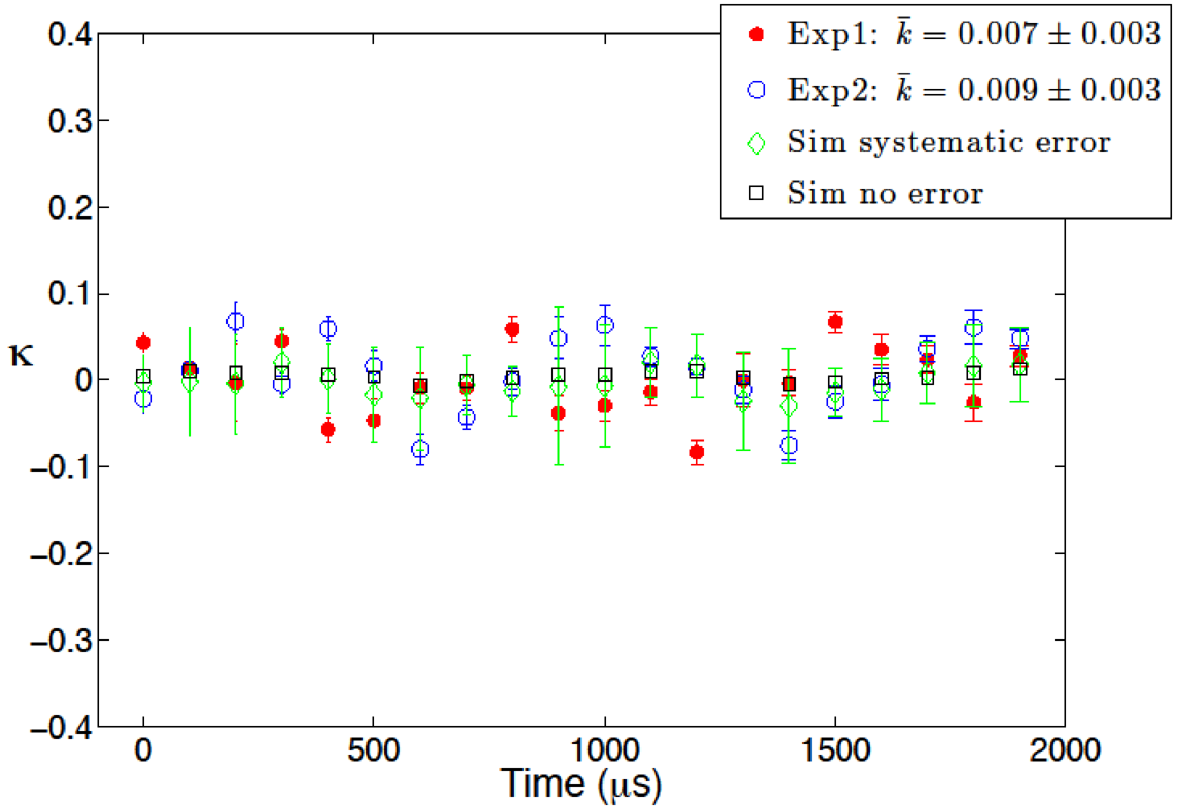


I.Sollner, B.Gschosser, P.Mai, B.Pressl, Zoltan Voros and Gregor Weihs, Foundatons of Physics, Vol. 42, No.6, pp 742751, June 2012.



$$\kappa = 4\times10^{-5} \pm 4\times10^{-4}$$

NMR Implementation



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nature COMMUNICATIONS

ARTICLE

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Exotic looped trajectories of photons in three-slit interference

Omar S. Magaña-Loaiza[1,*], Israel De Leon[2,3,*], Mohammad Mirhosseini[1], Robert Fickler[3], Akbar Safari[3], Uwe Mick[4], Brian McIntyre[1], Peter Banzer[3,4], Brandon Rodenburg[5], Gerd Leuchs[3,4] & Robert W. Boyd[1,3]

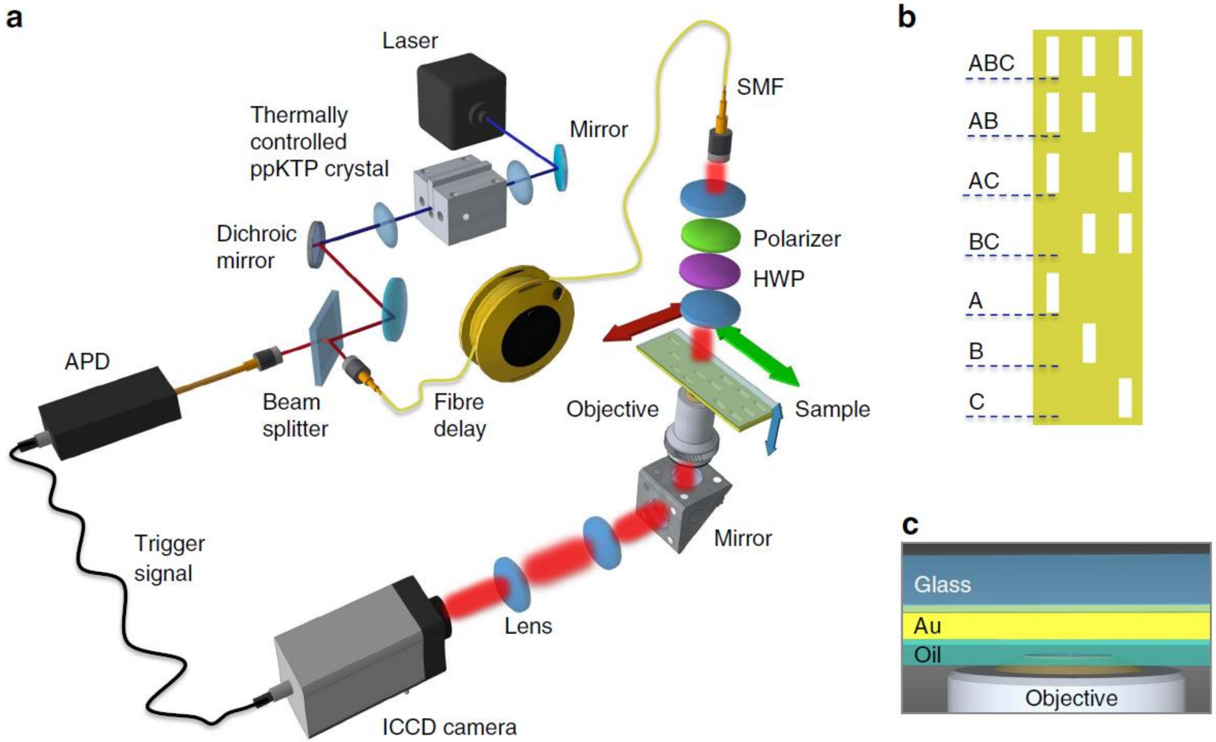
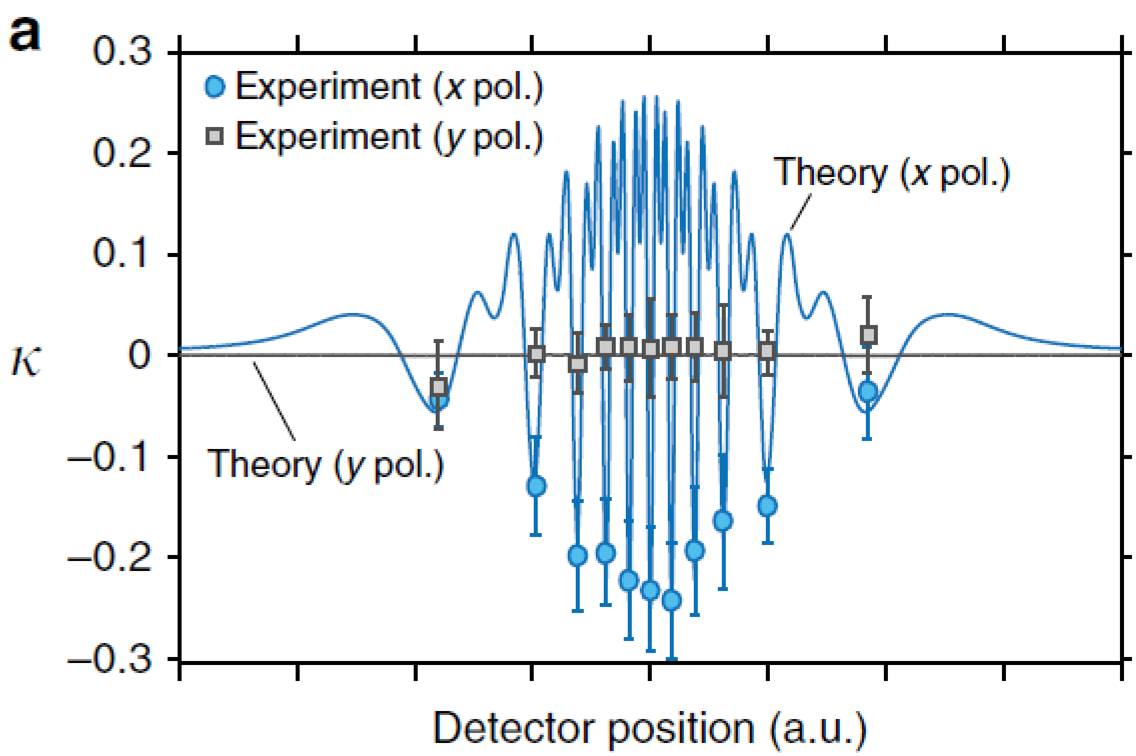


Figure 2 | Experimental set-up utilized to measure exotic trajectories of light. (**a**) Sketch of the experimental set-up used to measure the far-field interference patterns for the various slit configurations. (**b**) The seven different slit arrangements used in our study. This drawing is not to scale; in the actual experiment each slit structure was well separated from its neighbors to avoid undesired cross talk. (**c**) Detail of the structure mounted on the set-up. The refractive index of the immersion oil matches that of the glass substrate creating a symmetric index environment around the gold film.


a
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
κ
Experiment (x pol.)
Experiment (y pol.)
Theory (x pol.)
Theory (y pol.)
Detector position (a.u.)

But we could do better………….

Measuring the deviation from the Superposition Principle in interference experiments, A.Rengaraj, U. Prathwiraj, Surya Narayan Sahoo, R. Somshekhar and US, arXiv: 1610.09143

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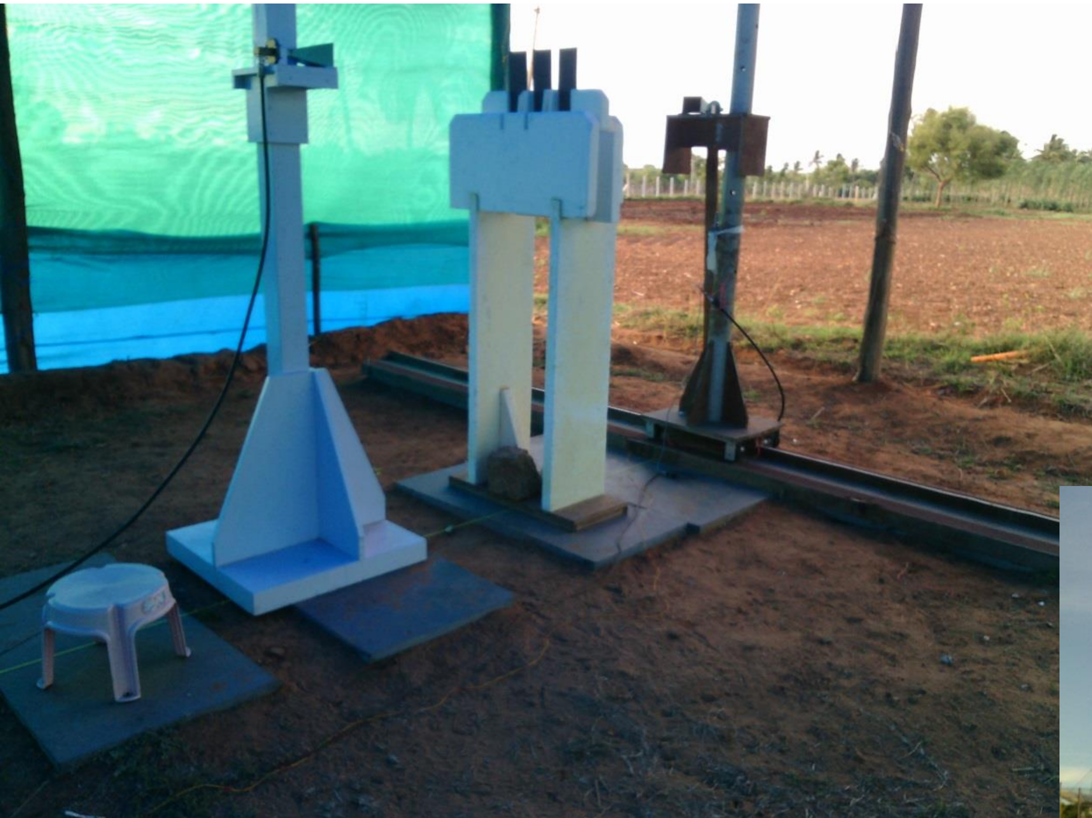


Experimental parameters

- Wavelength : 5 cm (6 GHz)
- Slot width : 10 cm
- Inter slot distance : 13 cm
- Slot thickness : average 8.4 mm
- Distance between Transmitter horn and slot plane:1.25 m
- Distance between Receiver horn and slot plane: 1.25 m

Measuring the deviation from the Superposition Principle in interference experiments, A.Rengaraj, U. Prathwiraj, S.N.Sahoo, R. Somshekhar and US, arXiv: 1610.09143

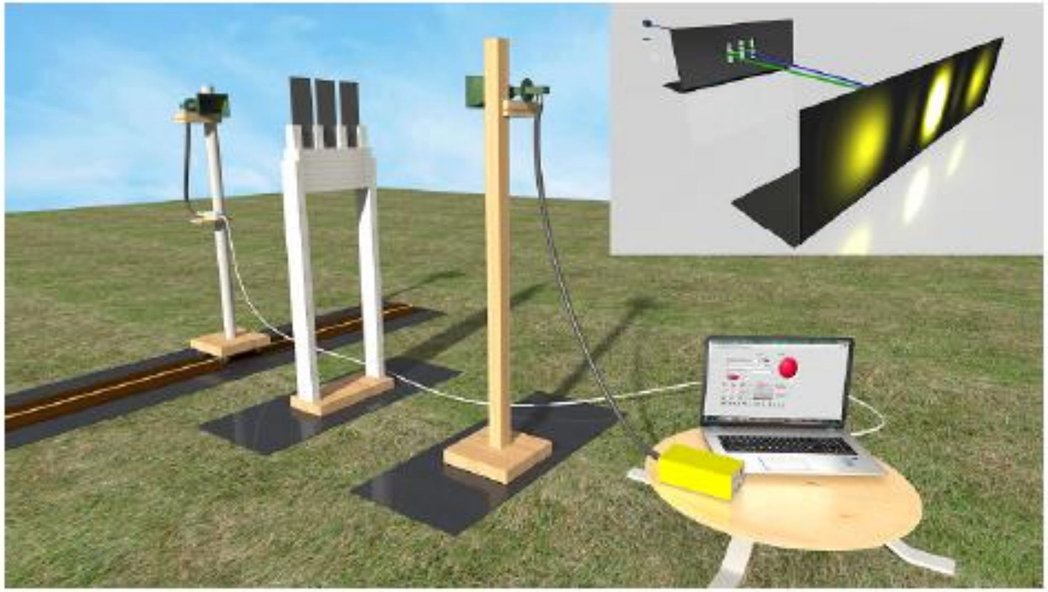
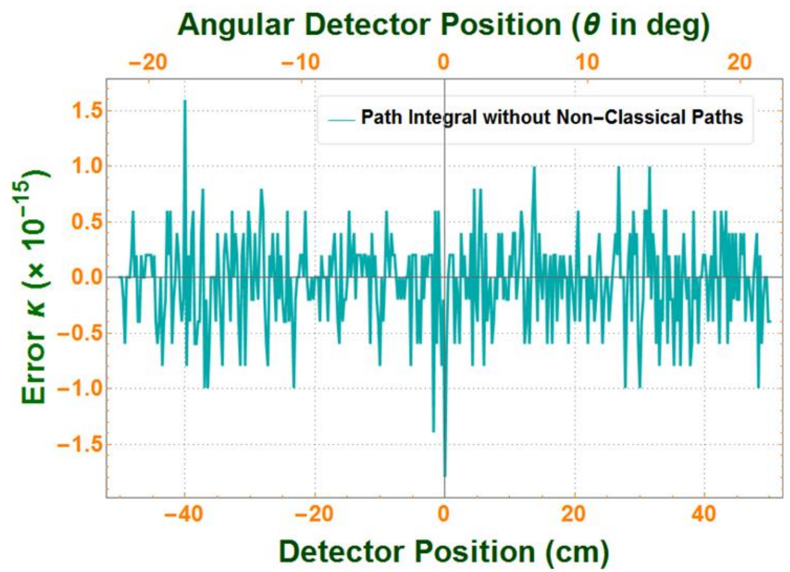
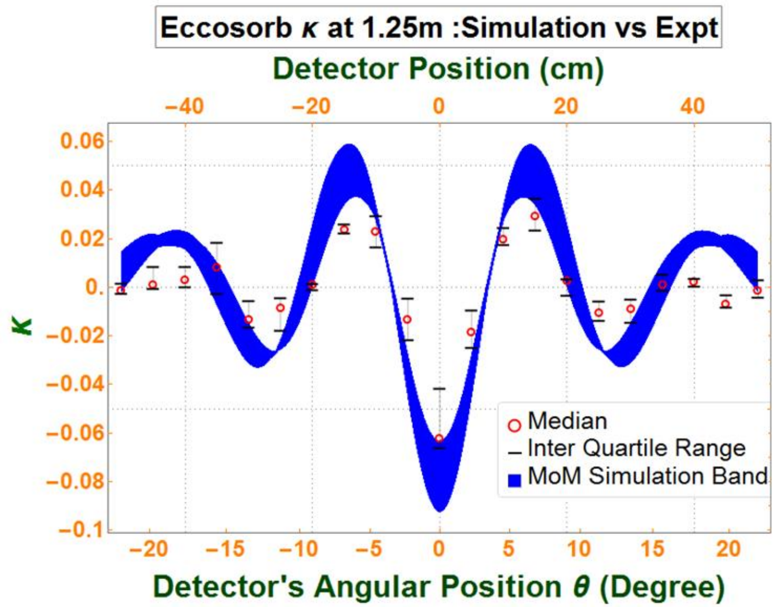


Figure 1: A schematic of the experimental set up. The green antennas on either side are pyramidal horn antennas which act as the source and detector of electromagnetic waves respectively. The detector antenna is placed on a moving rail to enable measuring of diffraction patterns. The three slots are placed between the source and the detector. The inset shows a triple slit schematic where the blue line is a representative classical path and the green line a representative non classical path in path integral formalism.



Angular Detector Position (θ in deg)
Path Integral without Non−Classical Paths
Error κ (× 10^−15)
Detector Position (cm)



Eccosorb κ at 1.25m :Simulation vs Expt
Detector Position (cm)
κ
Median
Inter Quartile Range
MoM Simulation Band
Detector's Angular Position θ (Degree)

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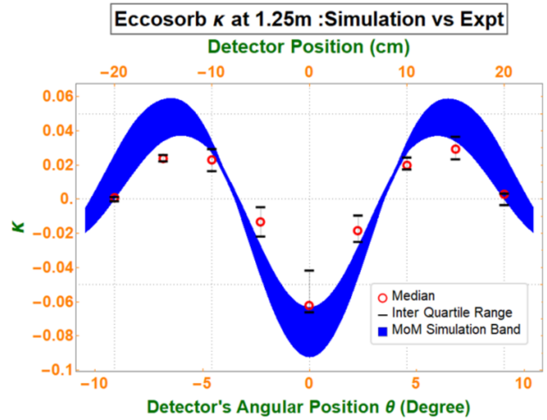
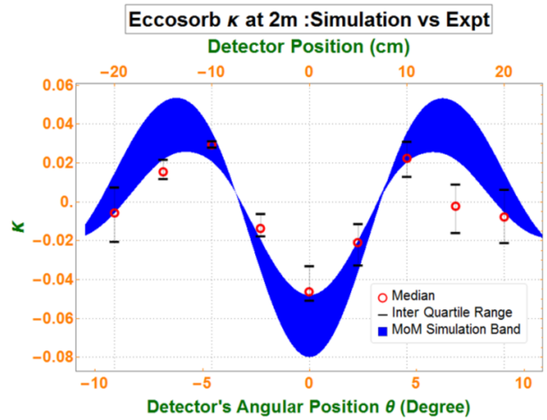
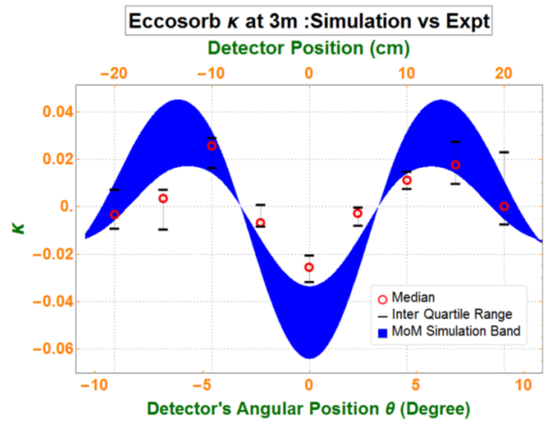
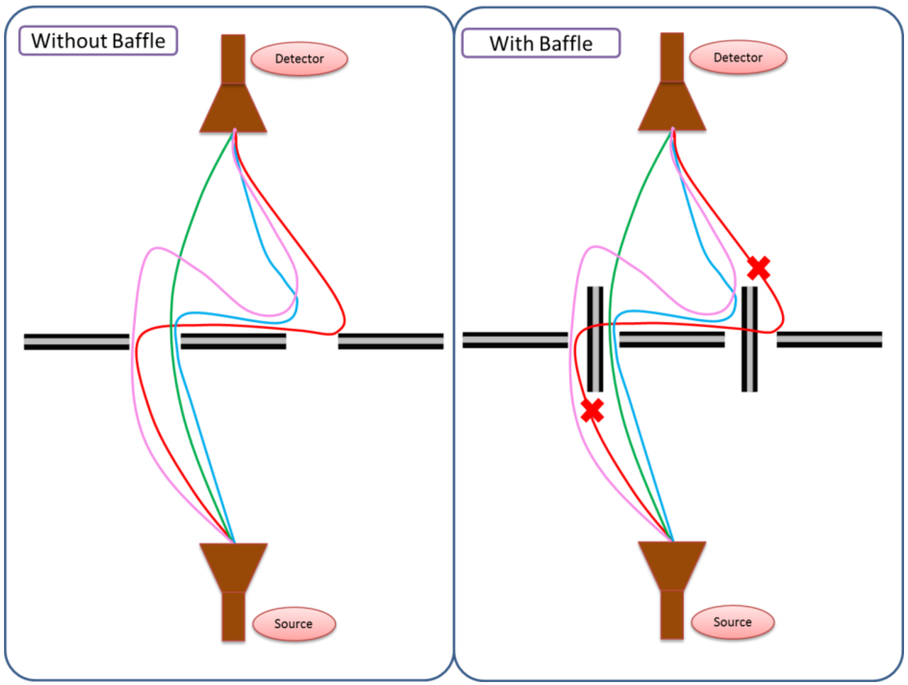
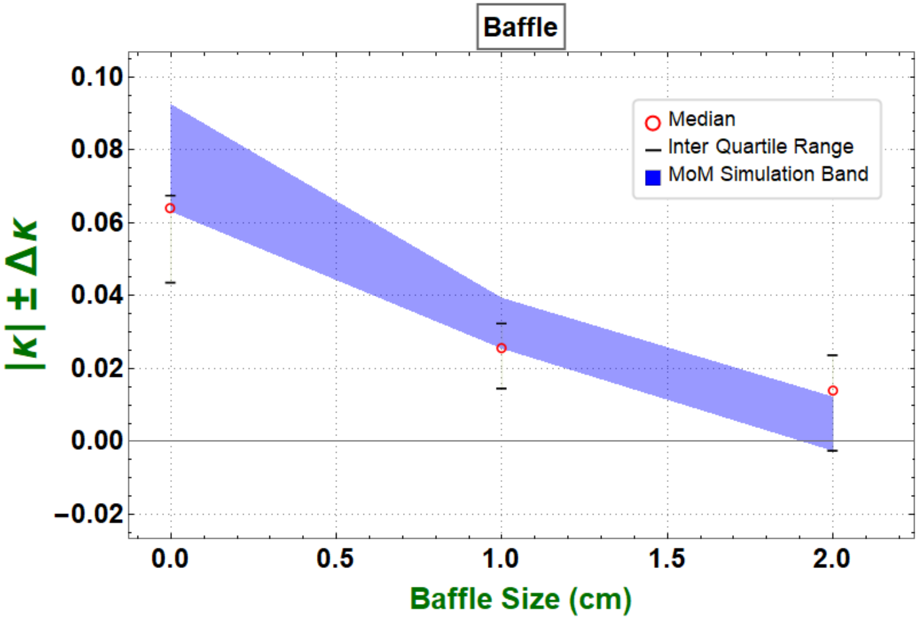






Baffle experiment





Implications on precision cosmology

Figure S11 shows the configuration that we have used to calculate κ from parameters used in simulations of signals from the epoch of reionization of the early universe (*6*).

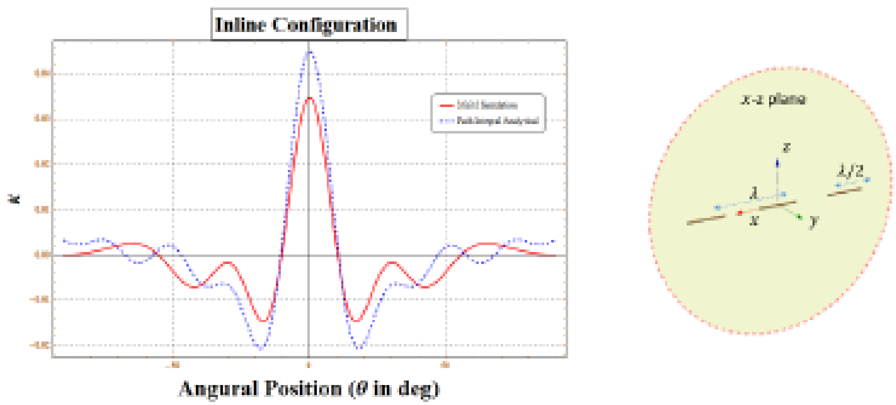
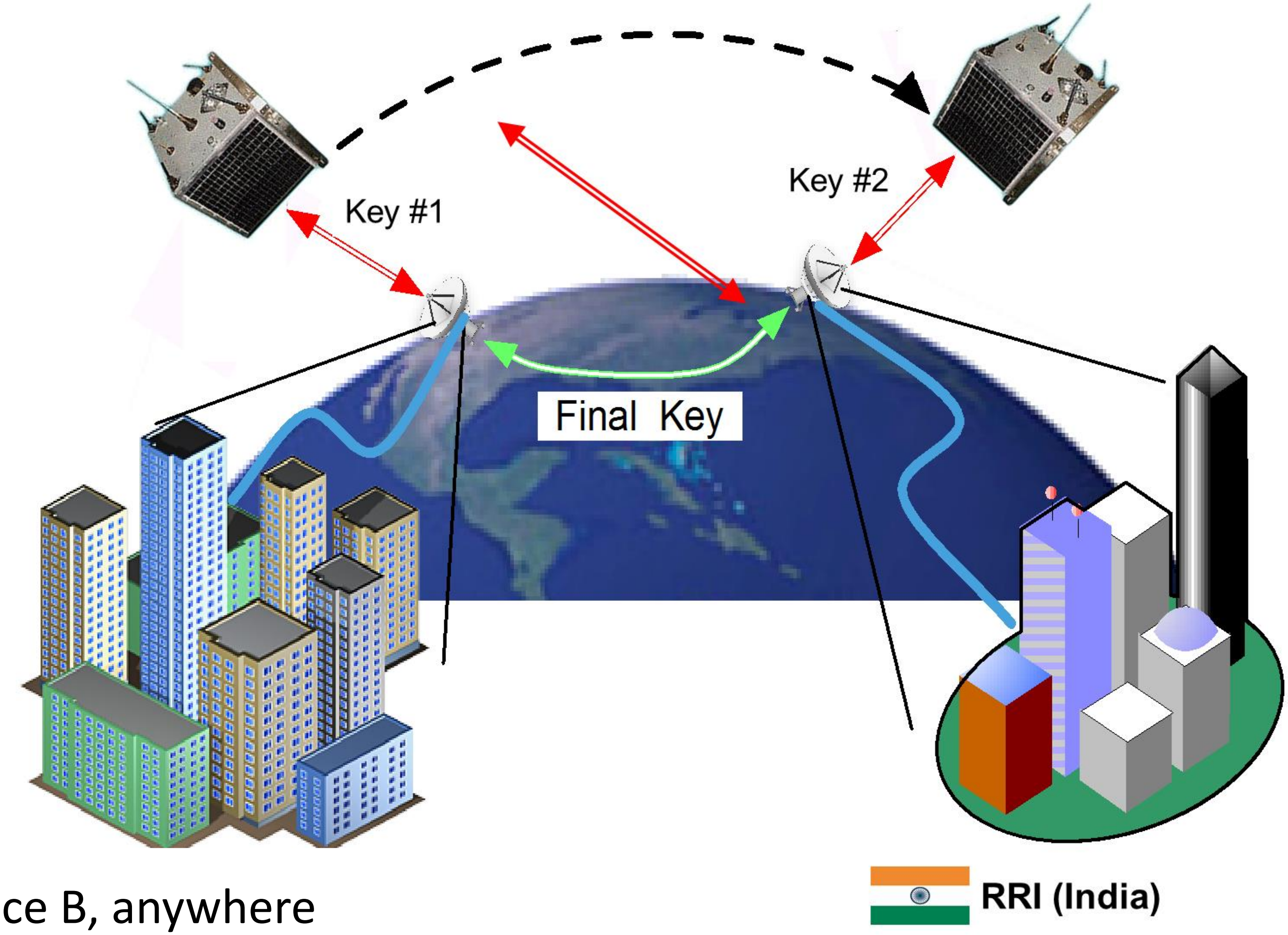


Figure S11: The figure on the left shows κ as a function of detector position. The red line indicates simulation done using Method of Moments. The blue dotted line is the result from the analytical formula based on path integral formalism derived in (2). The figure on the right shows the dipole array configuration that was simulated.

- First “observation” of the non classical paths in slit based interference in a classical domain.
- Tunability parameter makes this unambiguous.
- Feynman Path Integral is an over arching framework and transcends classical-quantum boundaries.
- Our experiment serves as a test bed for future experimental design for Born rule tests.
- Simplicity is beautiful!

Our Big Vision – Quantum Internet
Flagship project from RRI in collaboration with ISRO



Place B, anywhere

China launches 'hack-proof' quantum communications satellite

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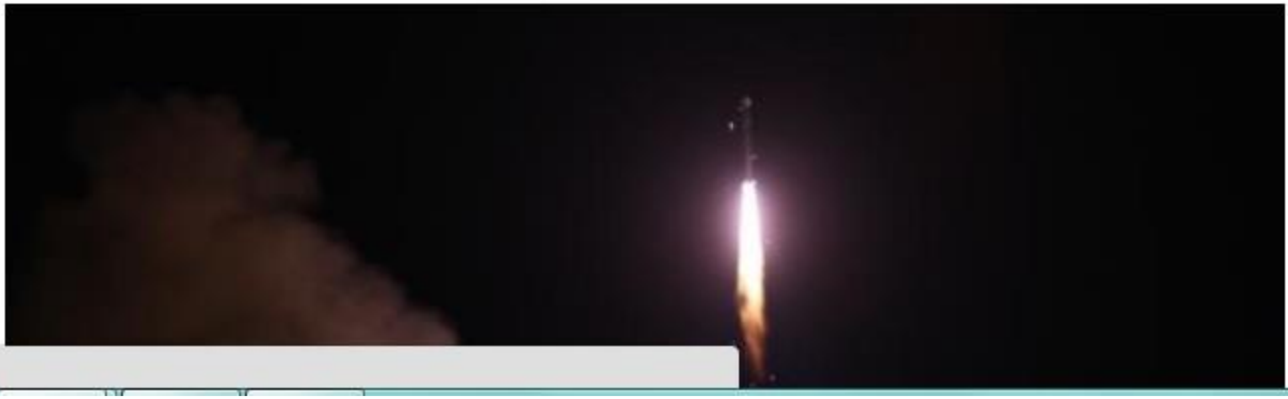

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DEMONSTRATION SETUP FOR BB84 QUANTUM KEY DISTRIBUTION USING CLASSICAL LIGHT

Raman Research Institute
Bangalore

Kaushik Joarder, Neha K Nasar, G Rengaraj, Urbasi Sinha
Quantum Information and Computation (QuIC) lab, Light And Matter Physics (LAMP) group, RRI, Bangalore

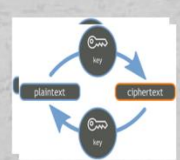
OBJECTIVE:

• To implement a demonstration setup for BB84 Quantum Key Distribution (QKD) By using classical pulsed laser source instead of single photon source.

QUANTUM KEY DISTRIBUTION (QKD) :

• Quantum Key Distribution (QKD) is a standard quantum cryptographic technique using which two distant communicating parties (Alice and Bob) can generate and distribute among themselves a secret key. This key can be used for encryption and decryption of any secret message in any classical secure protocol (Information-theoretic security).

• Perfect security of the key from any QKD is guaranteed by the laws of Quantum Mechanics; where security in any classical public key cryptography is based on the limitation of computational power of the adversary.



BB84 PROTOCOL:

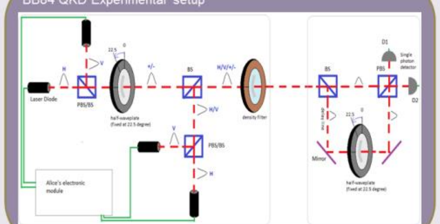
• BB84 protocol is a standard QKD protocol originally developed by Charles Bennett and Gilles Brassard in 1984.
• The security of BB84 is based on the Heisenberg uncertainty principle. If a state is prepared in certain basis, one cannot measure that state in any other basis non-orthogonal to the original basis, without disturbing it.

STEPS:

1) Alice prepares her photon in any one of the four polarization (H, V, +, -) randomly and sends to Bob.
2) Bob randomly selects his basis (either H/V or +/-) and measures the photon in that basis.
3) If both of their basis match together, they will have the same key.
4) They will discard those cases where their basis do not match.
5) If any eavesdropper tries to measure the polarization, he/she has 25% chance to introduce an error which will be detected by Alice and Bob.

Polarization	Symbol	Bit value
Horizontal	H	0
Vertical	V	1
+45	+	0
-45	-	1

BB84 QKD Experimental setup



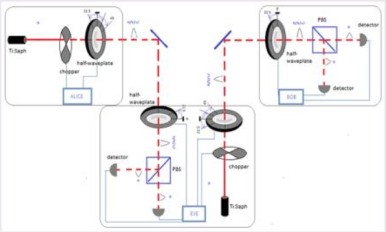
D: Diagonal basis (+/-) R : Rectilinear basis (H/V)

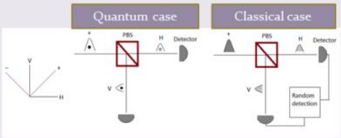
ALICE'S BASIS	D	R	R	D	R	D	D	R	D
ALICE'S BITS	0	1	0	1	1	0	1	0	0
ALICE SENDS	+	V	H	-	V	+	-	H	+
EVE'S BASIS	D		R		D		R	D	R
EVE'S BITS	0		0		0		1	1	0
BOB'S BASIS	D	R	D	R	R	D	D	D	R
BOB'S BITS	0	1	0	0	0	0	1	1	0
SAME BASIS?	YES	YES	NO	NO	YES	YES	YES	NO	NO
ALICE'S KEY	0	1			1	0	1		
BOB'S KEY	0	1			0	0	1		

BB84 QKD USING CLASSICAL LIGHT :

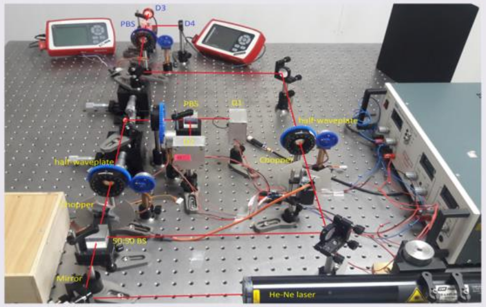
• Classical pulsed light contains a large number of photons in each pulse, so any eavesdropper can divide the pulse into two and measure their polarization without introducing any error. So, this procedure is completely insecure.
• In our demo setup, we can, in principle put some constraints or assumptions such that we can simulate BB84 QKD.

Assumptions:
1) If the detected power is more than certain threshold, we will assign it the binary value '1', otherwise it is '0'.
2) Both detectors in Bob's setup cannot have simultaneously value '1'. In that case, when both detectors show detection, a random variable (0 or 1) generated in Bob's computer will select which detection to choose between the two.
3) Though the random value is generated in Bob's computer he will not have any knowledge of that. In that case the random variable acts as a 'hidden variable' to him.
4) Any eavesdropper is also bounded by the assumptions 2 and 3.





EXPERIMENTAL SETUP AND RESULTS:



ALICE:
01010101110001011100010111000101000011101101000000
BOB:
01010101110001011100010110000101000011101101000000

FUTURE DEVELOPMENT :

• We will integrate all electronics module for Alice, Bob and Eve and control them via LabView-Arduino interface.

• We will develop a BB84 QKD setup by using single photon source and SPAD.

REFERENCES:

1) Ch. H. Bennett and G. Brassard, in *Proceedings of the IEEE International Conference of Computers, Systems and Signal Processing, Bangalore, India* (IEEE, New York, 1984), pp. 175-179.
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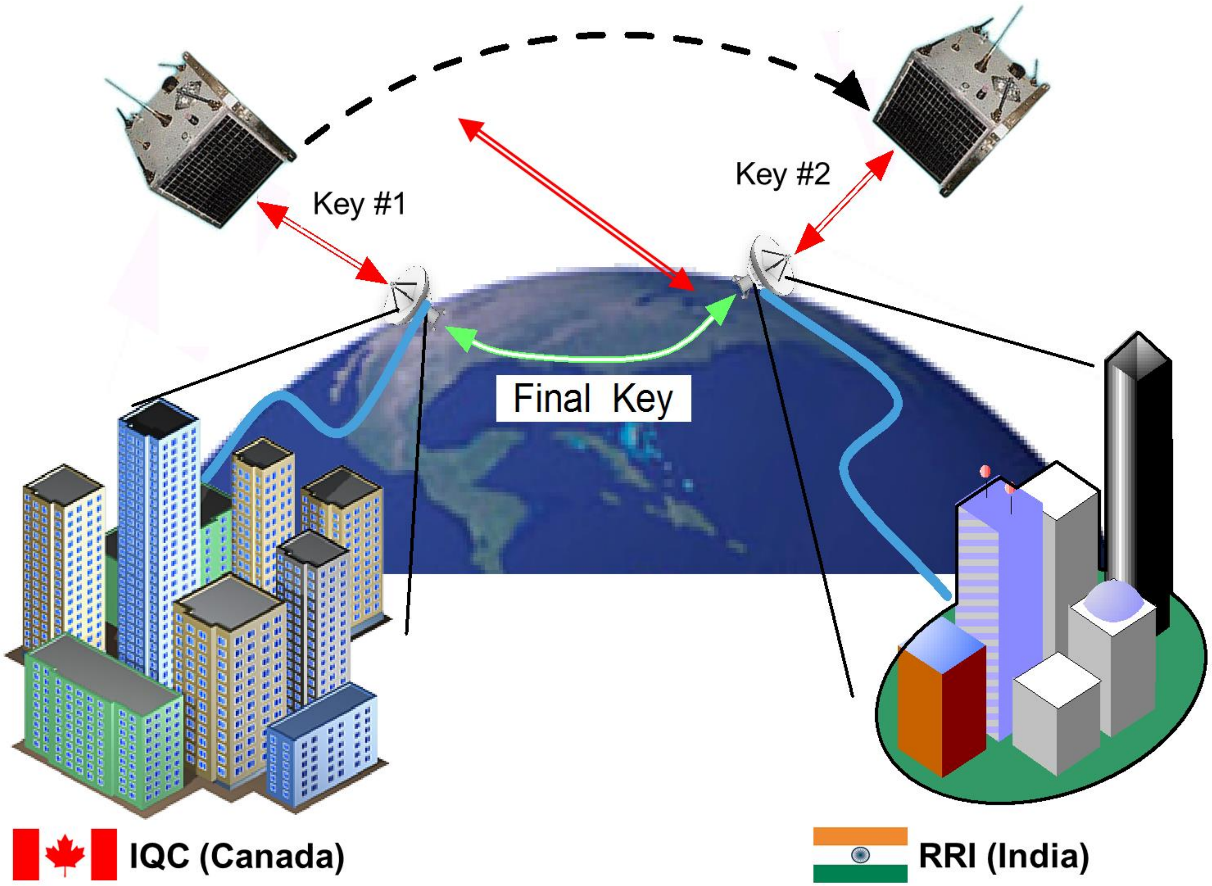
3) *Practical free-space Quantum Key Distribution over 10 km in Daylight and at Night*, R. J. Hughes, J. E. Nordholt, D. Derkacs, C. G. Peterson, New Journal of Physics 4 (2002) 43.1- 43.14

ACKNOWLEDGEMENT:

We would like to acknowledge Rakshita R. M. and Meena M. S. for their contributions to the preparation of photo detectors.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Key #2
Final Key
IQC (Canada)
RRI (India)

Shameless advertizement slide….

- Recently awarded a grant from the Indian Space Research Organization for a mega project on satellite based quantum key distribution.
- Will shortly be advertizing Scientist positions (higher salary, higher value, long term contract based) for the same.
- Will encourage you to inform your students/colleagues/experimental colleagues to encourage them to apply for the same and contribute to a very exciting first of its kind in India project!!

Raman Research Institute

11.8.2010

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Lyncham, Oxfordshire OX7 6QL
Tel/Fax : 01993 830 492

Dear Dr. Sinha,

I thought I would like to tell you of the great surprise and pleasure your paper in the July issue of Science has given me. I am the son of Max Born, and am greatly gratified that theoretical work he did in 1926 (when I was five) should now receive experimental confirmation,

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3/4 of a century later. I am a biomedical scientist, far from properly understanding your work – and my father's either, of course. But he and I were very close in every way and so you can imagine my gladness when a physicist friend of mine drew my attention to your, clearly excellent work. Please let me know of any follow-up papers on this.

With best wishes, Yours sincerely, Gustav Born.

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THANK YOU ☺