Title: Quantum Measurement in the Real World

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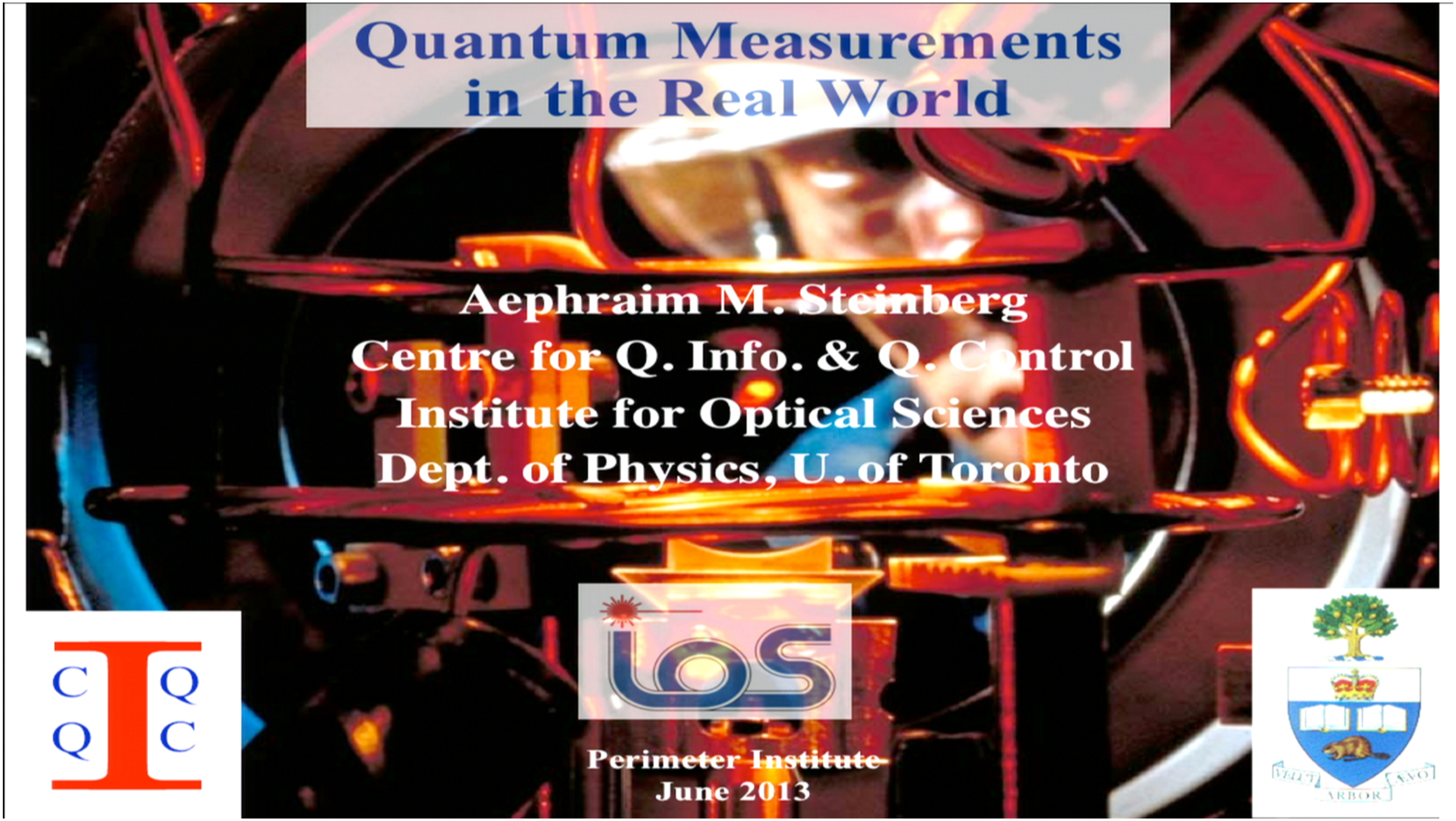
Abstract: While quantum measurement remains the central philosophical conundrum of quantum mechanics, it has recently grown into a respectable (read: experimental!) discipline as well. New perspectives on measurement have grown out of new technological possibilities, but also out of
attempts to design systems for quantum information processing, which promise to be exponentially more powerful than any possible classical computer. I will try to give a flavour about some of these perspectives, focussing largely on a particular paradigm known as "weak measurement."
Weak measurement is a natural extension of a pragmatic view of what it means to measure something about a quantum system, yet leads to some rather surprising results. I will describe a few examples of our recent experiments using weak measurement to probe fundamental issues in uantum mechanics such as what the minimum disturbance due to a quantum measurement is. I will also argue that there are regimes in which weak measurement offers a practical advantage for sensitive measurements.


Quantum Measurements
in the Real World
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Centre for Q. Info. & Q. Control
Institute for Optical Sciences
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Perimeter Institute
June 2013

http://www.fields.utoronto.ca/programs/scientific/13-14/CQIQCV/

$$2013 \geq 1964 + 50$$

CQIQC

CQIQC-V

Conference on Quantum Information & Quantum Control

a joint CQIQC-Fields Institute conference

August 12-16, 2013 at the Fields Institute, Toronto
Paper submission deadline – April 15th 2013

Organizing Committee:
Amr S. Helmy (Director, CQIQC), Univ. Toronto; **David G. Cory**, University of Waterloo; **Paul Brumer**, U. Toronto; **Aephraim Steinberg**, U. Toronto; **Li Qian**, U. Toronto

CQIQC-V will be the fifth in the series of biennial conferences jointly organized by the Toronto Centre for Quantum Information & Quantum Control and the Fields Institute, which aim to bring together researchers from a broad set of areas ranging from quantum cryptography and computation to quantum control to quantum foundations to device fabrication, in a setting which encourages discussion and can help stimulate new collaborations and interactions. The 2013 meeting will also be a celebration of the upcoming quinquagenary of Bell's Inequalities, slightly violating the inequality atop this flyer. There will be roughly 24 invited talks and 24 contributed talks, as well as a poster session.

The meeting will also be the occasion of the awarding of the 3rd biennial John Stewart Bell Prize for Research on Fundamental Issues in Quantum Mechanics and Their Applications (see http://cqiqc.physics.utoronto.ca/bell_prize/home.html).

The morals of the story

1 Quantum Measurement is much richer than the textbooks acknowledge
2 Different sorts of Q.Msmt's prove useful for different real-world tasks

- "Interaction-free" measurement & Hardy's Paradox

- Weak measurement: can we talk about history in QM?

- Back to Hardy's paradox...
- Measuring the momentum kick due to a which-way measurement
- Trajectories in two-slit interferometers
- How much does a measurement need to disturb a state, anyway?
- When is weak measurement useful for, you know, *measurement*?
  - possible application to looking for "giant" optical nonlinearities

DRAMATIS PERSONÆ

Toronto quantum optics & cold atoms group:

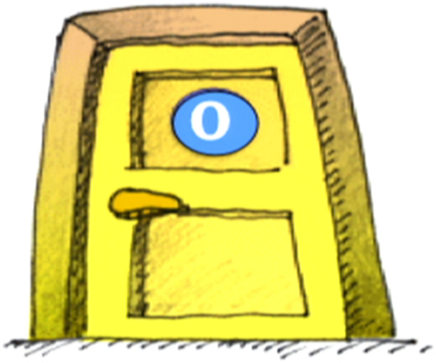
Postdoc: Alex Hayat

Photons: Xingxing Xing, ***Lee Rozema***, Greg Dmochowski, ***Dylan Mahler***, **Amir Feizpour**, Xin Song

Atoms: Rockson Chang, Chao Zhuang, Matin Hallaji, Shreyas Potnis, Ramon Ramos, Saeed Oghbaey

Some alums: Kevin Resch, Jeff Lundeen, Krister Shalm, Rob Adamson, Stefan Myrskog, Jalani Kanem, Ana Jofre, Chris Ellenor, Samansa Maneshi, Chris Paul, ***Reza Mir***, ***Sacha Kocsis,*** Masoud Mohseni, Zachari Medendorp, ***Ardavan Darabi***, ***Yasaman Soudagar***, Boris Braverman, Sylvain Ravets, Nick Chisholm, Max Touzel, Julian Schmidt, Xiaoxian Liu, Lee Liu, James Bateman, Zachary Vernon, Timur Rvachov, Luciano Cruz, Morgan Mitchell,...

Some helpful theorists:
Daniel James, Pete Turner, ***Robin Blume-Kohout***, Chris Fuchs, ***Howard Wiseman***, János Bergou, John Sipe, Paul Brumer, Michael Spanner...



"Quantum Seeing in the Dark"

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(AKA: "Interaction-free" measurement, aka "Vaidman's bomb")

A. Elitzur and L. Vaidman, Found. Phys. **23**, 987 (1993)
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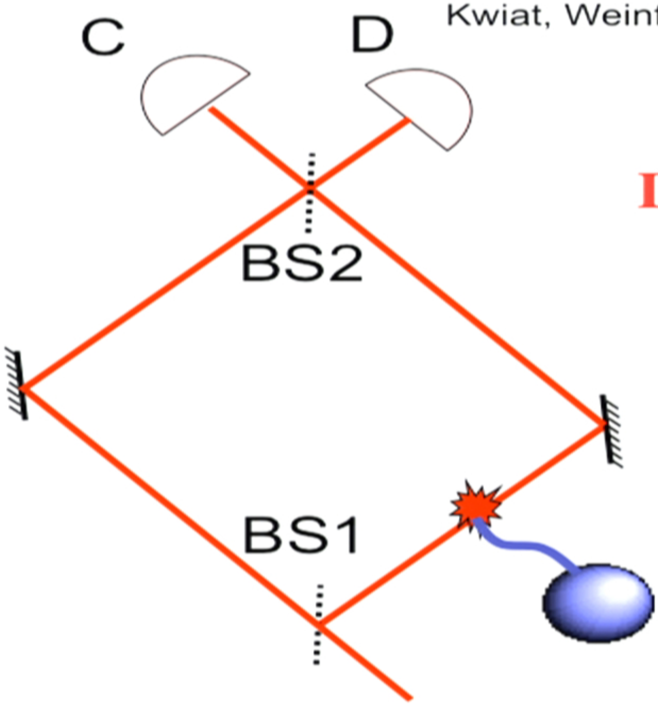

Detector absent/ineffectual:

Only detector C fires

Detector working:

"boom!"	1/2
C	1/4
D	1/4

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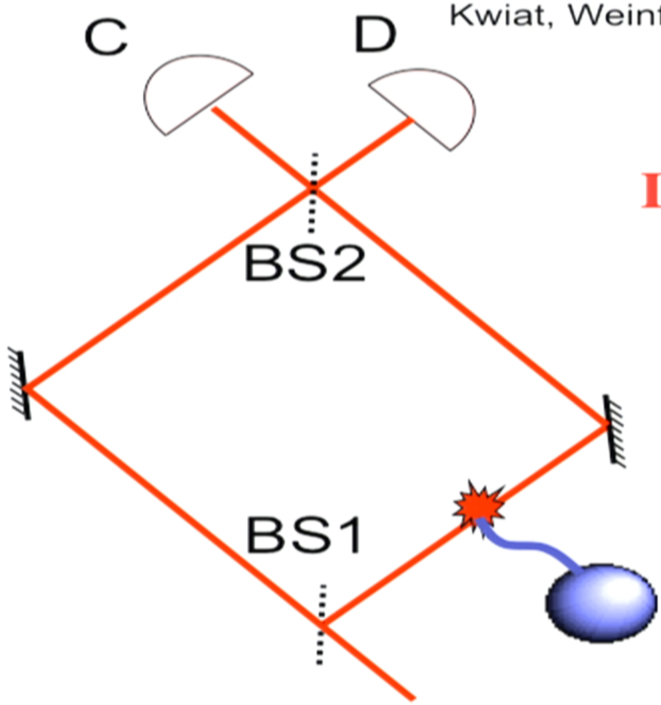

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Fanciful musing about this

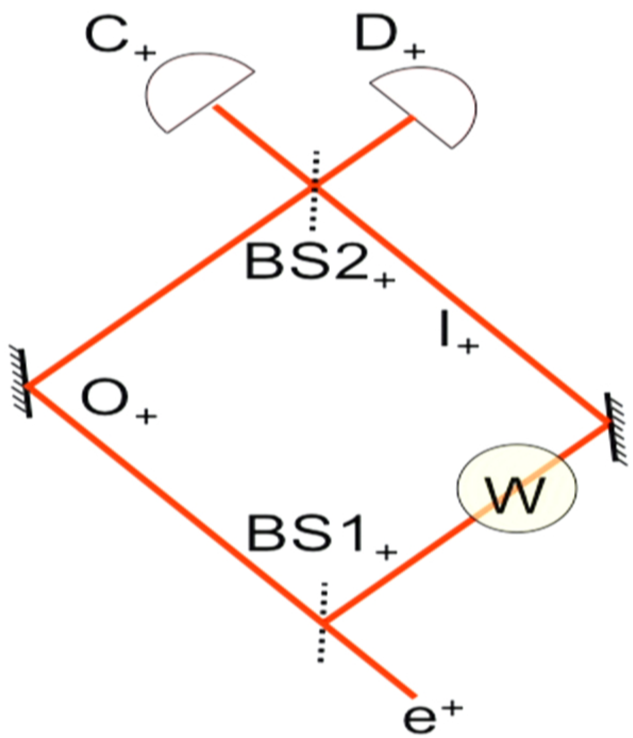
Many feel that QM implies a tree falling in an empty forest makes no sounds.

Not only is this an inappropriate conclusion, but:

- **QM says you can tell that a tree *would have made a sound had it fallen*, even if it doesn't fall!**
- **QM is not a theory of what happens, but of all the possible things which could happen.**

Hardy's Paradox

(for Elitzur-Vaidman "interaction-free measurements")



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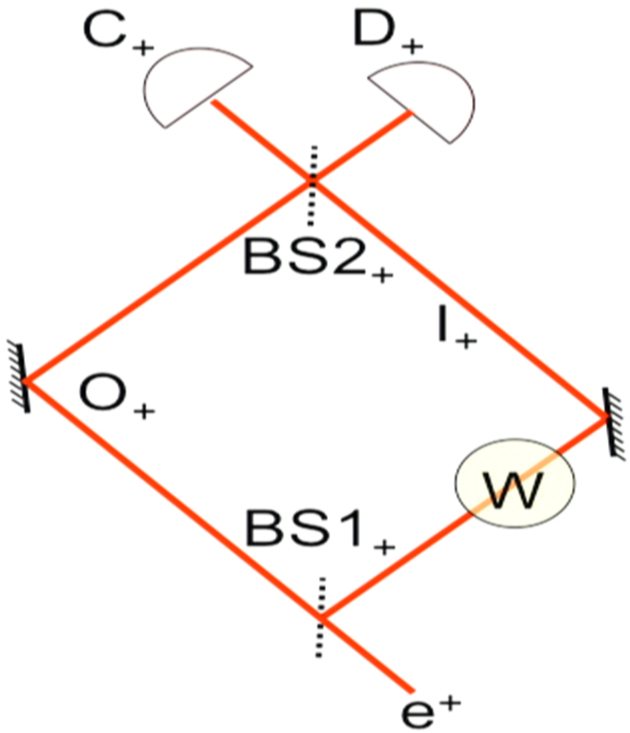

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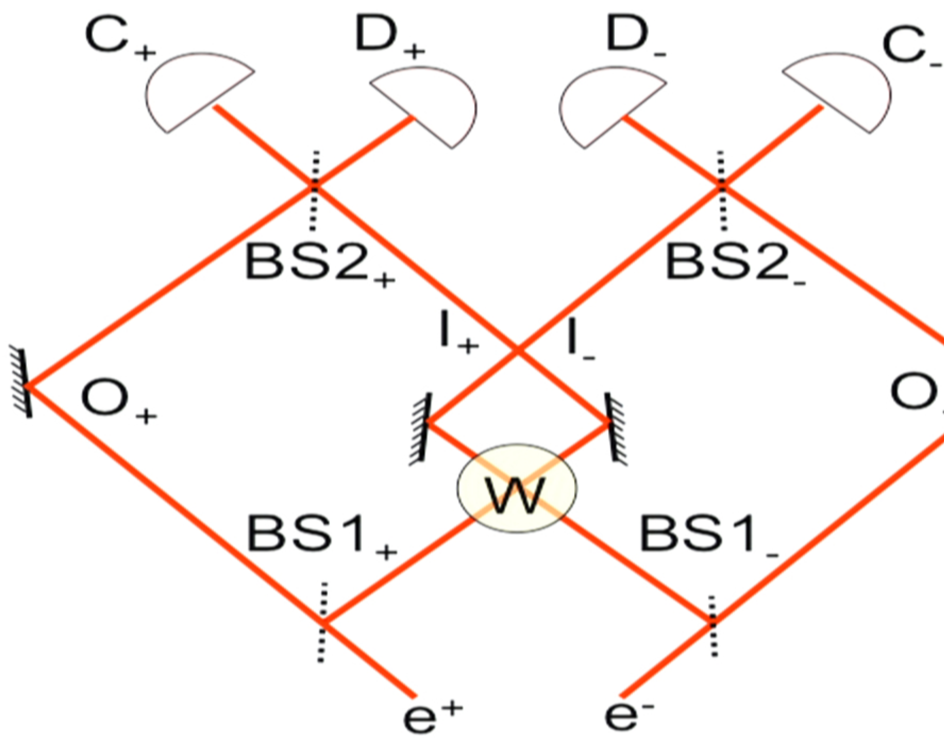

D+ → e− was in
D− → e+ was in

D+D− → ?

But ... if they were both in, they should have annihilated!

Can we talk about what goes on behind closed doors?

**(“Postselection” is the big new buzzword in QIP...
but how should one describe post-selected states?)**

Predicting the past...

Conditional measurements (Aharonov, Albert, and Vaidman)

AAV, PRL 60, 1351 ('88)

Prepare a particle in |i> ...try to "measure" some observable A...
postselect **the particle to be in |f>**

Does <A> depend more on i or f, or equally on both?
Clever answer: both, as Schrödinger time-reversible.
Conventional answer: i, because of collapse.

Reconciliation: measure A "weakly."
Poor resolution, but little disturbance.

⇒ **the "weak value"**
(but how to determine?)

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Interpretational digression

Note: Hardy's reading of his paradox (filtered through me) is that it's simply not fair to ascribe real values to *potential* measurements, without knowing which sets of measurements are really going to be done -- quantum mechanics is known to be *contextual*.

Weak measurements, on the other hand, are *non*-contextual, and allow one to ask what properties a system had before post-selection.

But what can we say about where the particles were or weren't, once D+ & D– fire?

Probabilities	e- in	e- out	
e+ in	**0**	1	1
e+ out	1	**−1**	0
	1	0	

Y. Aharonov, A. Botero, S. Popescu, B. Reznik, J. Tollaksen, PLA 301, 130 (2002); quant-ph/0104062

Weak Measurements in Hardy's Paradox

Ideal Weak Values

	N(I⁻)	N(O⁻)	
N(I⁺)	0	1	1
N(O⁺)	1	−1	0
	1	0	

Experimental Weak Values ("Probabilities"?)

	N(I⁻)	N(O⁻)	
N(I⁺)	0.243±0.068	0.663±0.083	0.882±0.015
N(O⁺)	0.721±0.074	−0.758±0.083	0.087±0.021
	0.925±0.024	−0.039±0.023	

J.S. Lundeen and A.M. Steinberg, *Phys. Rev. Lett.* **102**, 020404 (2009);
also Yokota *et al.*, *New. J. Phys.* **11**, 033011 (2009).

Can we understand what is really happening physically?

$$\mathrm{Re}\,\langle\hat{\sigma}_{\bar{z}P}\hat{\sigma}_{\bar{z}E}\rangle = \frac{R_{\nearrow\nearrow} + R_{\nwarrow\nwarrow} - R_{\searrow\nearrow} - R_{\nearrow\searrow}}{R_{\nearrow\nearrow} + R_{\nwarrow\nwarrow} + R_{\searrow\nearrow} + R_{\nearrow\searrow}}$$

$$\langle\hat{N}(M_P)\hat{N}(M_E)\rangle_W = g^{-2}\mathrm{Re}\langle\hat{\sigma}_{\bar{z}P}\hat{\sigma}_{\bar{z}E}\rangle, \qquad - \frac{R_{\circlearrowleft\circlearrowright} + R_{\circlearrowright\circlearrowleft} - R_{\circlearrowright\circlearrowright} - R_{\circlearrowleft\circlearrowleft}}{R_{\circlearrowleft\circlearrowright} + R_{\circlearrowright\circlearrowleft} + R_{\circlearrowright\circlearrowright} + R_{\circlearrowleft\circlearrowleft}},$$

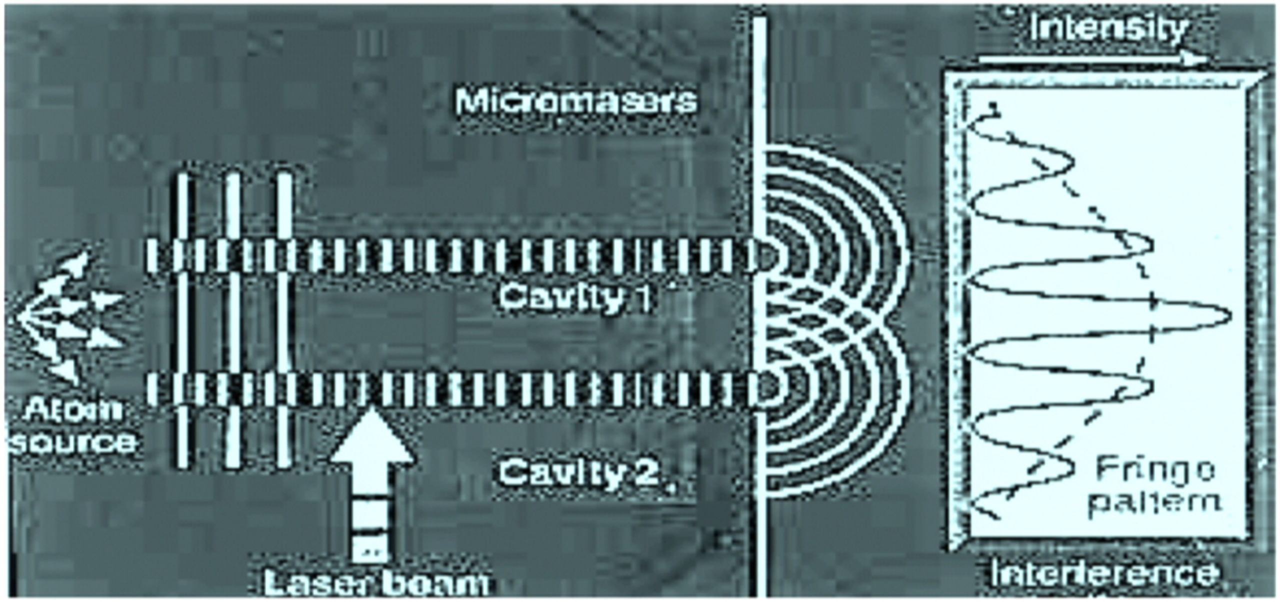
TABLE I. The measured coincidence rates needed to determine the weak values.

E	P	$R_{\nearrow\nearrow}$	$R_{\nearrow\searrow}$	$R_{\nwarrow\nwarrow}$	$R_{\searrow\nearrow}$	$R_{\circlearrowleft\circlearrowright}$	$R_{\circlearrowleft\circlearrowleft}$	$R_{\circlearrowright\circlearrowleft}$	$R_{\circlearrowright\circlearrowright}$	g_E	g_P
O	O	556	834	583	730	750	543	666	571	0.674	0.541
I	I	2261	772	115	746	1030	762	913	729	0.635	0.570
I	O	1152	1079	351	179	484	655	452	654	0.635	0.541
O	I	1051	260	329	769	715	609	388	825	0.674	0.570

What is the meaning of the negative joint occupation? Recall that the joint values are extracted by studying the polarization rotation of both photons in coincidence. Consider a situation in which both photons always simultaneously passed through two particular arms. When a polarization rotator is placed in each of these arms, it would tend to cause their polarizations to rotate in a correlated fashion: when P was found to have 45° polarization, E would also be more likely to be found at 45° than −45°. Experimentally, we find the reverse—when P is found to have 45° polarization, E is preferentially found at −45° (and vice versa), as though it had rotated in the direction opposite to the one induced by the physical wave plate. As in all weak-measurement experiments, a negative

Which-path controversy

[Reza Mir *et al.*, New. J. Phys. 9, 287 (2007)]



Which-path measurements destroy interference.
This is usually explained via measurement backaction & HUP.
Suppose we use a *microscopic* pointer.
Is this really irreversible, as Bohr would have all measurements? NO!
***Then....* Need it disturb momentum?**
Which is «more fundamental» – uncertainty or complementarity?

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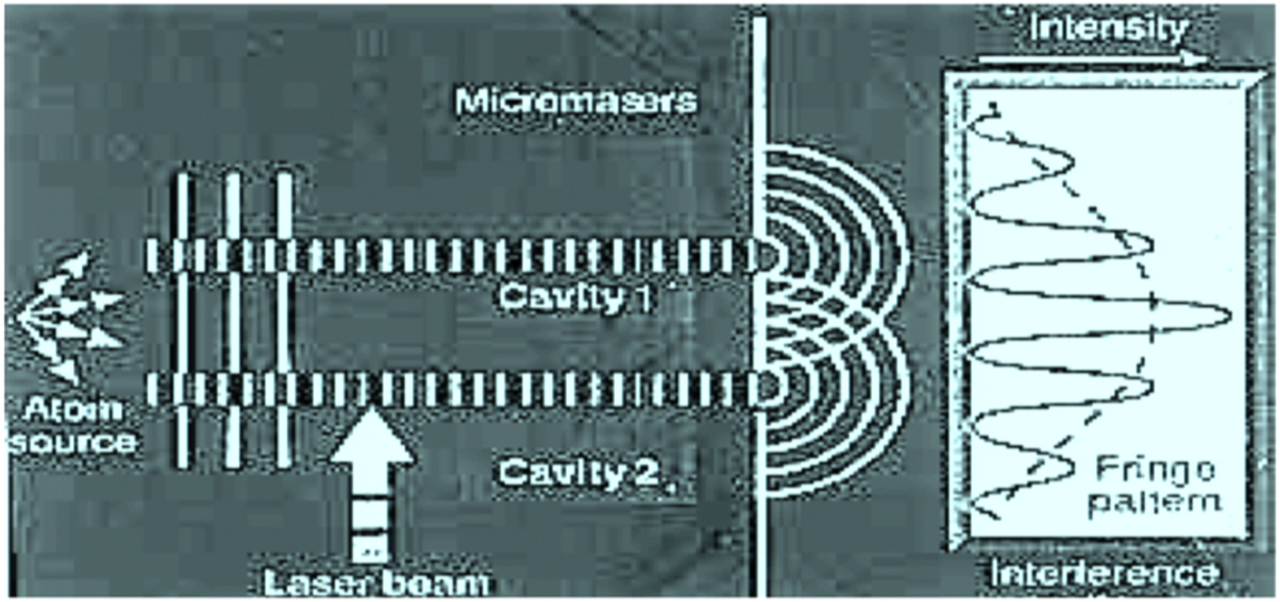

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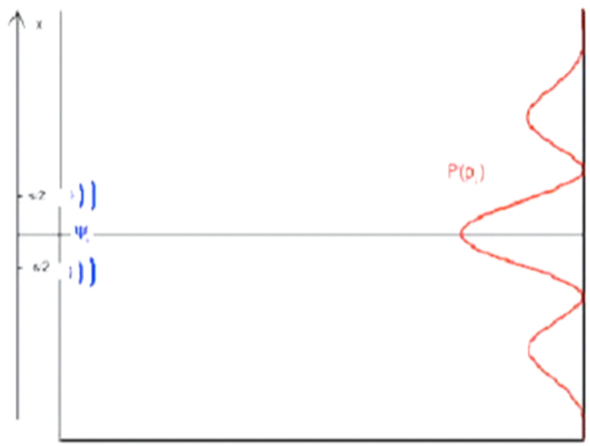
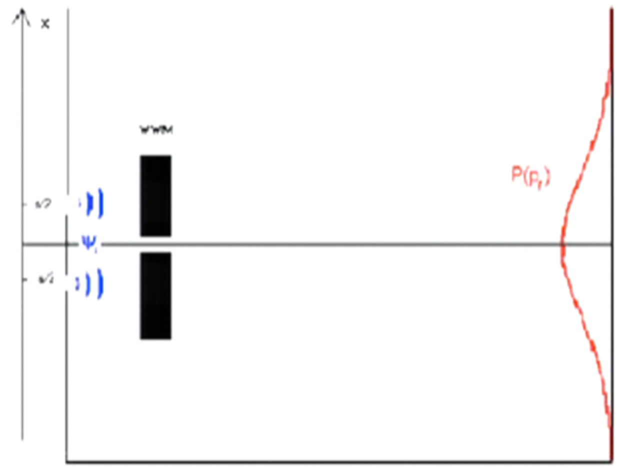
Which-path measurements destroy interference (modify p-distrib!)





- The momentum distribution clearly changes
- Scully *et al.* prove there is no momentum kick
- Walls *et al.* prove there must be some momentum kick.
- Obviously, different measurements and/or definitions.
- Is it possible to directly measure the momentum transfer?

Why the ambiguity?

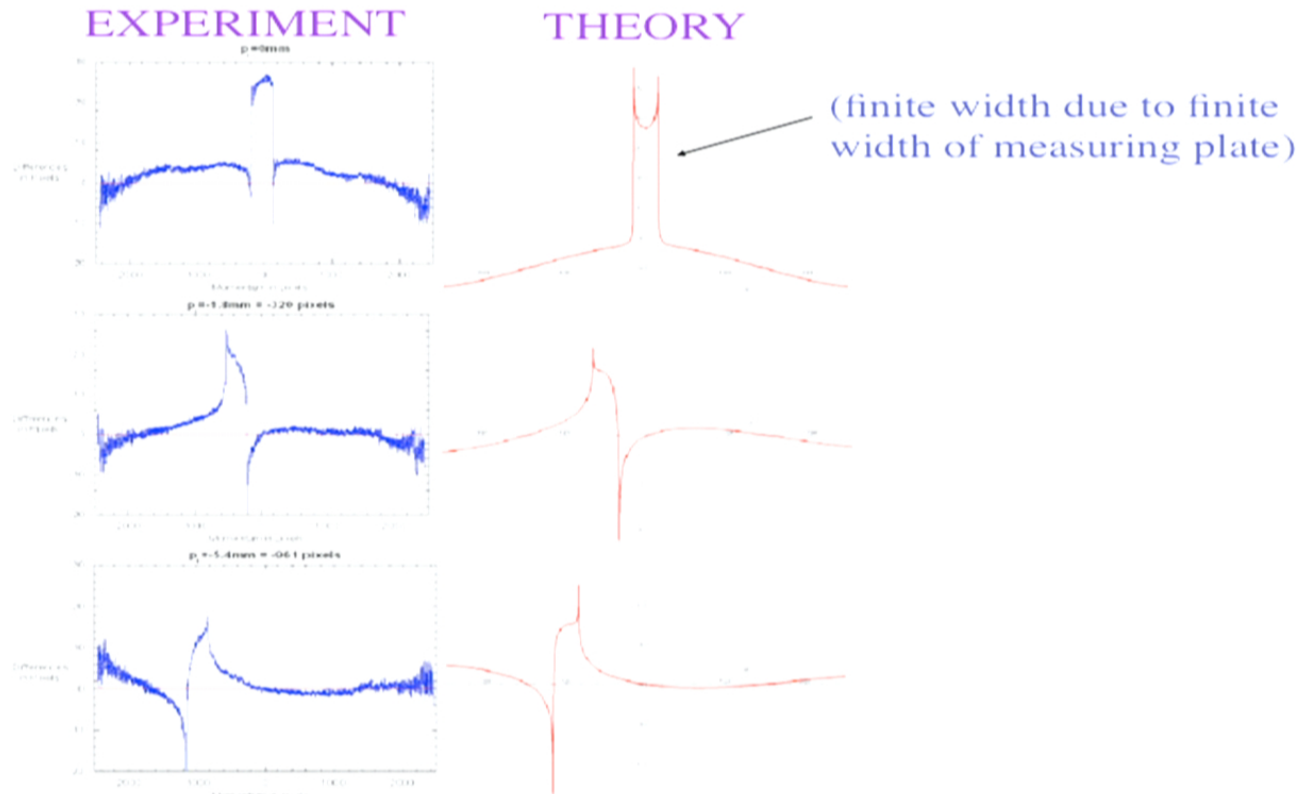
Classically, one would just measure p_i (just after the slits), and p_f (after the *welcher Weg* measurement), and determine the distribution for $\Delta p = p_f - p_i$

Quantum mechanically, measuring p destroys the two-slit wavefunction (creating a momentum eigenstate).

But if we start with a momentum eigenstate, we get the result of Walls *et al*.

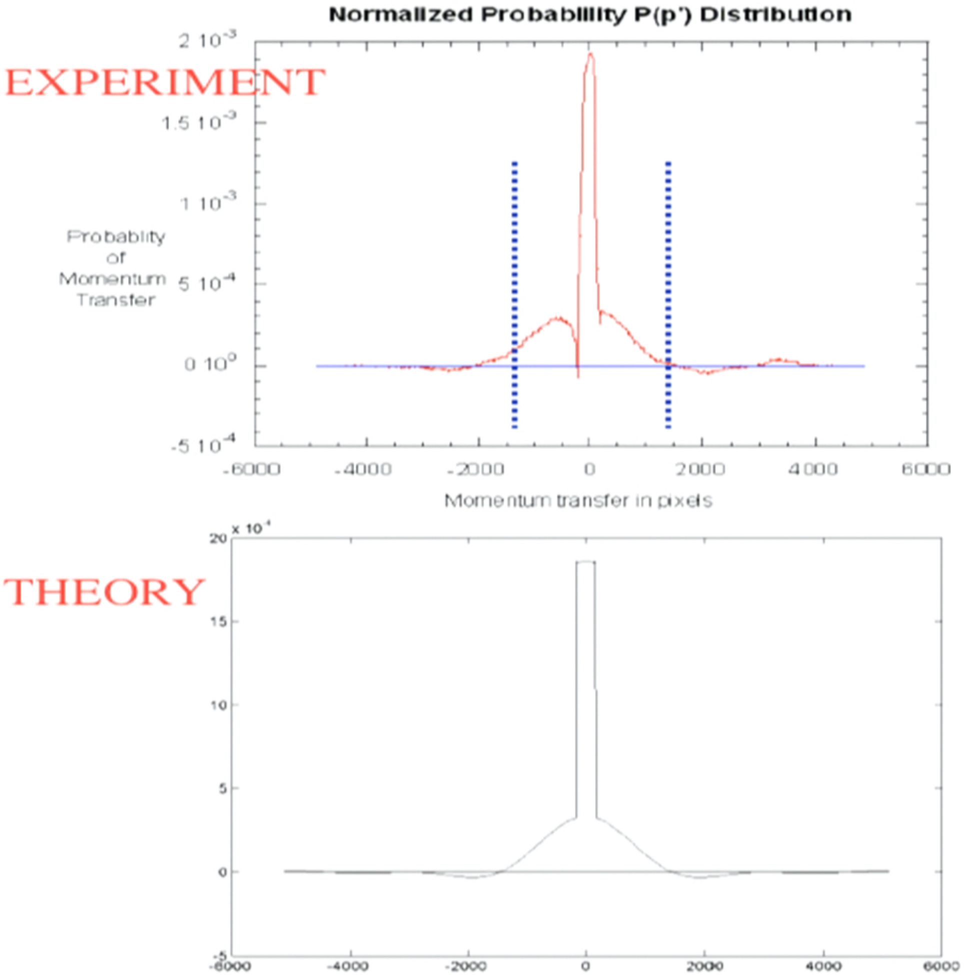
If we consider moments for $P(p_i)$ and $P(p_f)$ individually, we instead get the result of Scully *et al*.

A few distributions $P(p_i \mid p_f)$



Note: not delta-functions; i.e., momentum may have changed.
Of course, these "probabilities" aren't always positive, etc etc...

The distribution of the integrated momentum-*transfer*



Reza Mir *et al.*, New. J. Phys. 9, 287 (2007)

Note: the distribution extends well beyond h/d.

On the other hand, all its moments are (at least in theory) 0.

The former fact agrees with Walls *et al*; the latter with Scully *et al*.

For weak distributions, they may be reconciled *because the distributions may take negative values* in weak measurement.

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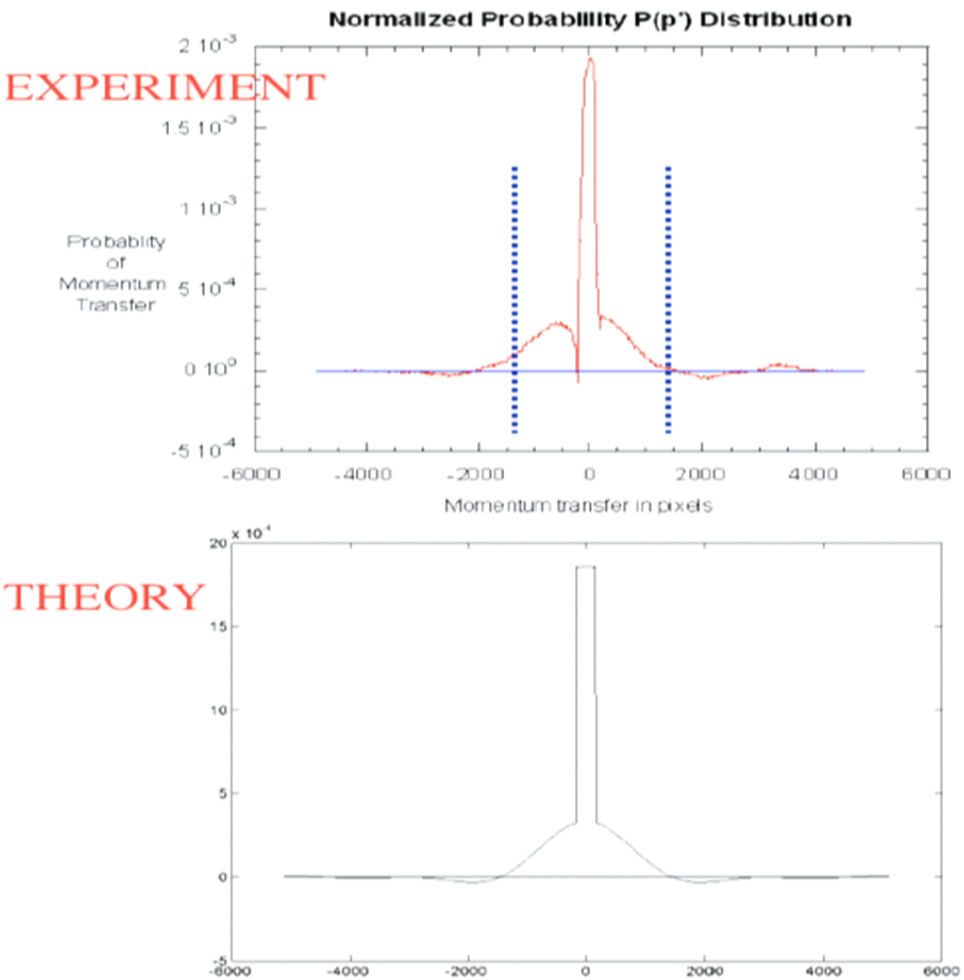

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Bending the rules...

BBC NEWS

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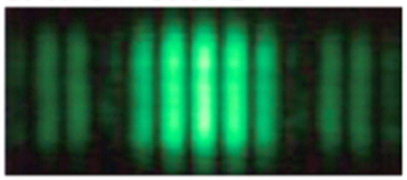
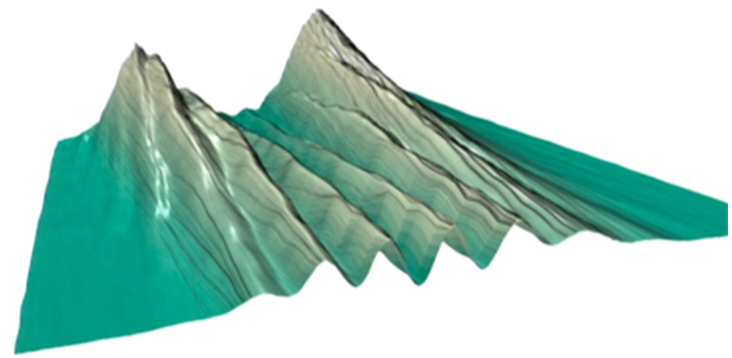
Quantum mechanics rule 'bent' in classic experiment

03 June 11 05:38 ET





By Jason Palmer
Science and technology reporter, BBC News

Researchers have bent one of the most basic rules of quantum mechanics, a counterintuitive branch of physics that deals with atomic-scale interactions.

Its "complementarity" rule asserts that it is impossible to observe light behaving as both a wave and a particle, though it is strictly both.

In an experiment reported in Science, researchers have now done exactly that.

"Any precise measurement of X is guaranteed to disturb P, by an amount $\Delta P \geq h/2\Delta X$"

What I've always taught my students:

- **This is true, but it puts a limit on measurement only.**
- **A much deeper statement puts a limit on *reality*:**

Example for a spin-1/2

$\Delta S_x \Delta S_y \geq \langle S_z \rangle / 2$

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If I tell you $\langle S_z \rangle = 1/2$, there's only one possible state: $|+z\rangle$.
$\Delta S_x = \Delta S_y = 1/2$
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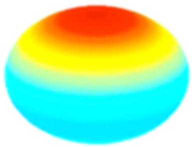

On the other hand, how precisely can I measure S_x? As precisely as I like. If by ΔS_x, we mean the uncertainty of the *measurement* (not of the *state*), it can be 0.

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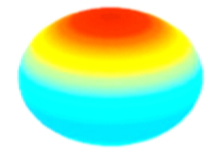

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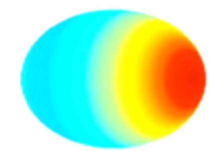

ΔS_y – the disturbance to S_y – may be as big as ±1 ... but it must be finite.
$\Delta S_x \Delta S_y = 0$, even though $\langle S_z \rangle = 1/2$, if what we mean by these symbols is measurement precision & disturbance.

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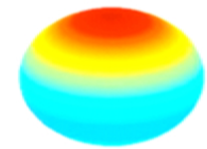

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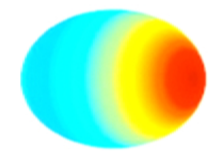

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Ozawa's relation

Heisenberg's uncertainty principle for *variances* is proved in every textbook, and we take no issue with it:

$$\Delta(A)\Delta(B) \geq \langle[A,B]\rangle / 2$$

A similar relation for measurement precision $\varepsilon(A)$ of the probe vs. disturbance to the system $\eta(B)$ is, however, false:

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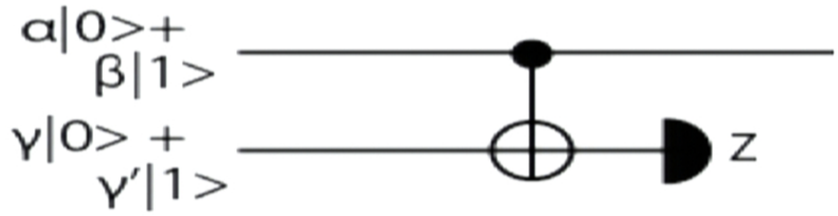
Ozawa, PRA 67, 042105 (2003):

$$\epsilon(A)\eta(B) + \epsilon(A)\Delta B + \eta(B)\Delta A \geq \frac{1}{2}\langle[A,B]\rangle$$

Use a C-NOT gate as a variable-precision interaction

How do you control the strength of a C-NOT?



- **If γ=1: α |00> + β |11>**
  - **Z_2 has complete information about Z_1**
- **If $\gamma = \gamma'$: (α|0> + β|1>) |+>**
  - **Z_2 has no information about Z_1**

Setting the probe state sets the effective measurement strength

(cf. Pryde et al. PRL **94** 220405 (2005))

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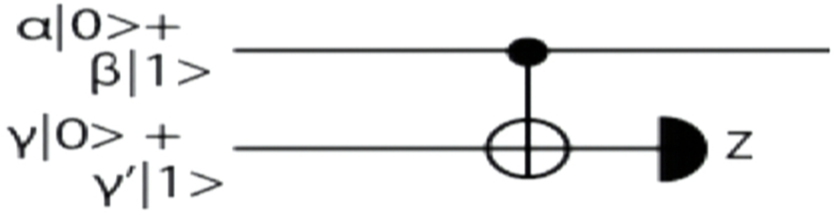

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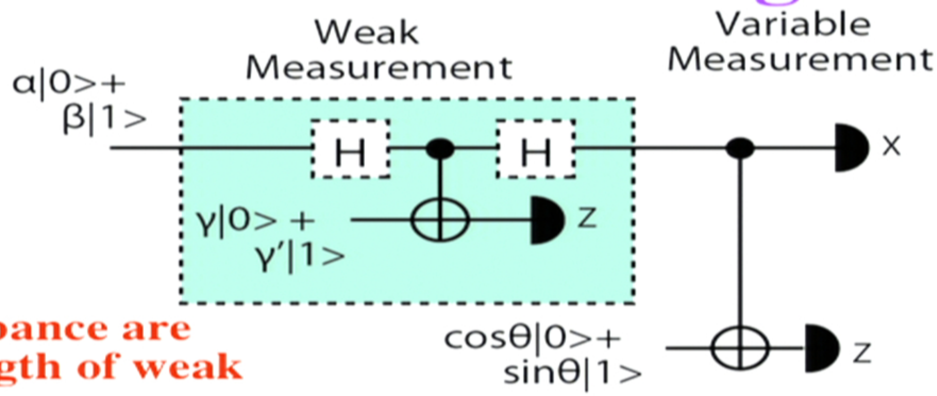
How weak is weak enough?

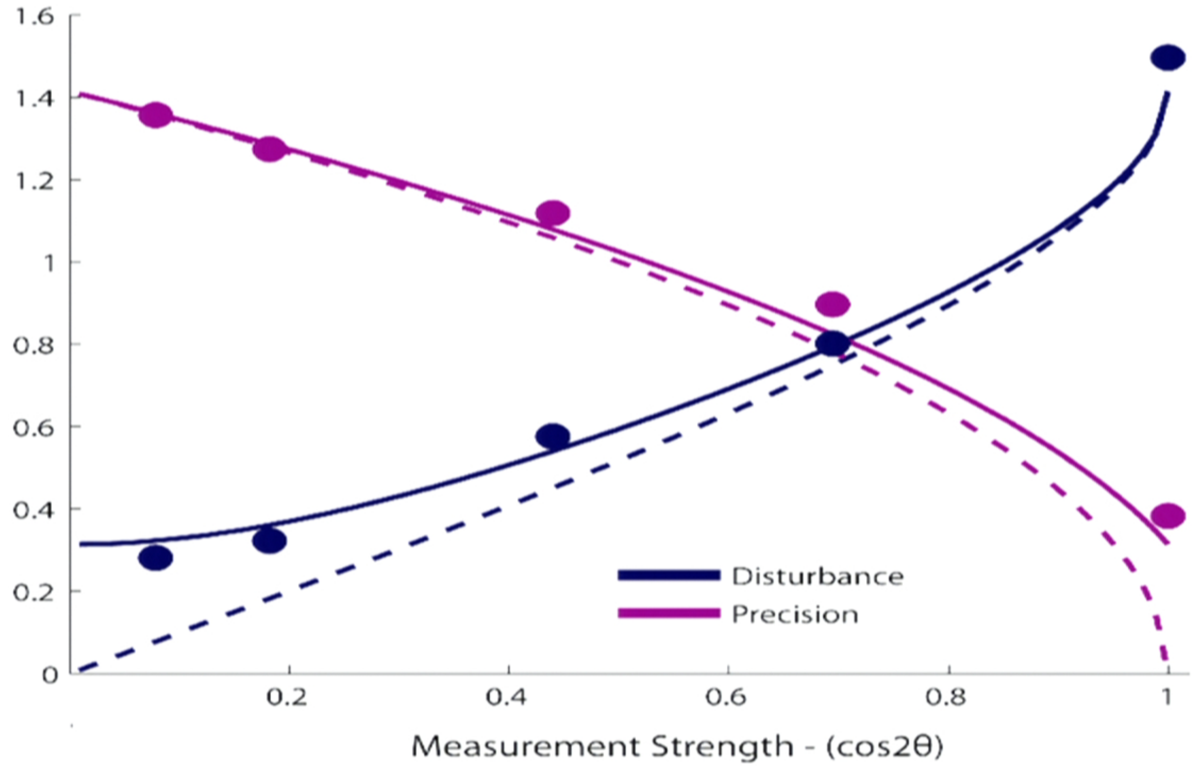


HEY! It turns out that the precision and disturbance are independent of the strength of weak measurement!

Results – Disturbance & Precision

Fix the strength of the weak probe, vary the strength of the von Neumann measurement and observe the precision and disturbance

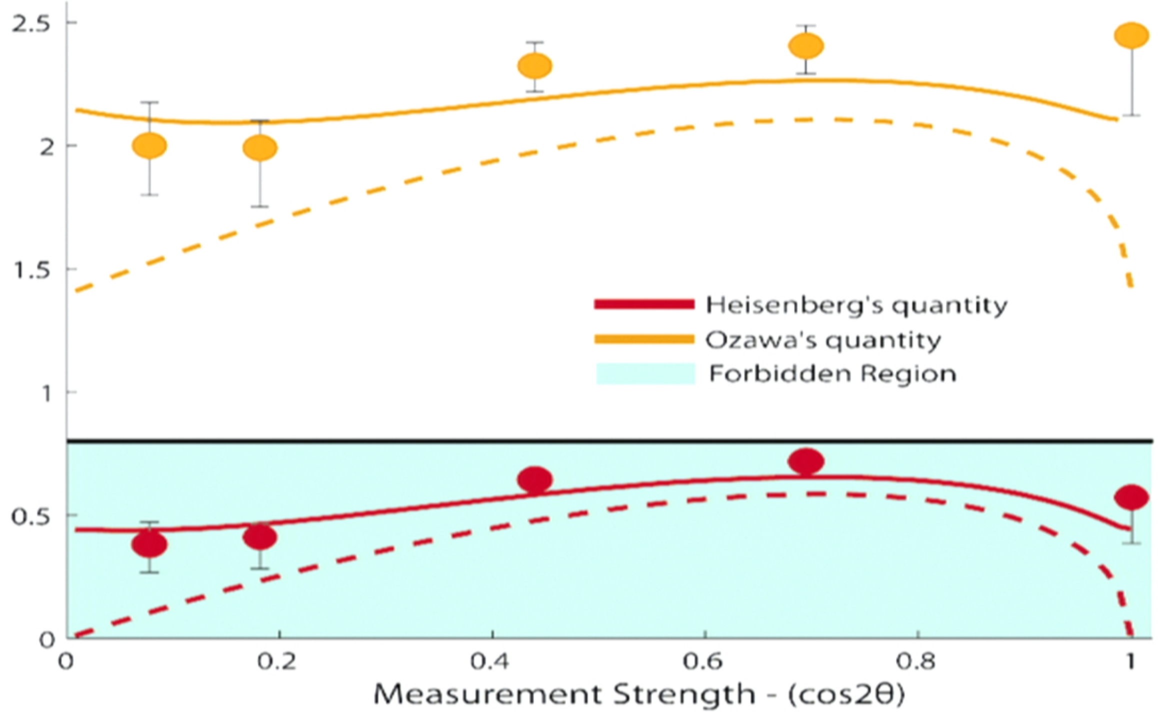
Dashed lines are theory, solid lines are simulations accounting only for imperfect entangled state preparation



Results – Ozawa & Heisenberg's Quantities

Forbidden region set by measuring of <Y> on the qubit after the weak measurement and teleportation

Dashed lines are theory, solid lines are simulations accounting only for imperfect entangled state preparation



Heisenberg's relation is clearly violated $\varepsilon(A)\eta(B) \geq 1/2\langle[A,B]\rangle$

Ozawa's remains valid $\epsilon(A)\eta(B) + \epsilon(A)\Delta B + \eta(B)\Delta A \geq \frac{1}{2}\langle[A, B]\rangle$

Is weak measurement good for anything *practical*?

$$A_w = \frac{\langle f|A|i\rangle}{\langle f|i\rangle}$$

may be very big if the postselection (<f|i>) is very unlikely...

Selected for a Viewpoint in *Physics*
RL **102,** 173601 (2009) PHYSICAL REVIEW LETTERS week ending 1 MAY 2009

Ultrasensitive Beam Deflection Measurement via Interferometric Weak Value Amplification

P. Ben Dixon, David J. Starling, Andrew N. Jordan, and John C. Howell
Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627, USA
(Received 12 January 2009; published 27 April 2009)

We report on the use of an interferometric weak value technique to amplify very small transverse deflections of an optical beam. By entangling the beam's transverse degrees of freedom with the which-path states of a Sagnac interferometer, it is possible to realize an optical amplifier for polarization independent deflections. The theory for the interferometric weak value amplification method is presented along with the experimental results, which are in good agreement. Of particular interest, we measured the angular deflection of a mirror down to 400 ± 200 frad and the linear travel of a piezo actuator down to 14 ± 7 fm.

DOI: 10.1103/PhysRevLett.102.173601 PACS numbers: 42.50.Xa, 03.65.Ta, 06.30.Bp, 07.60.Ly

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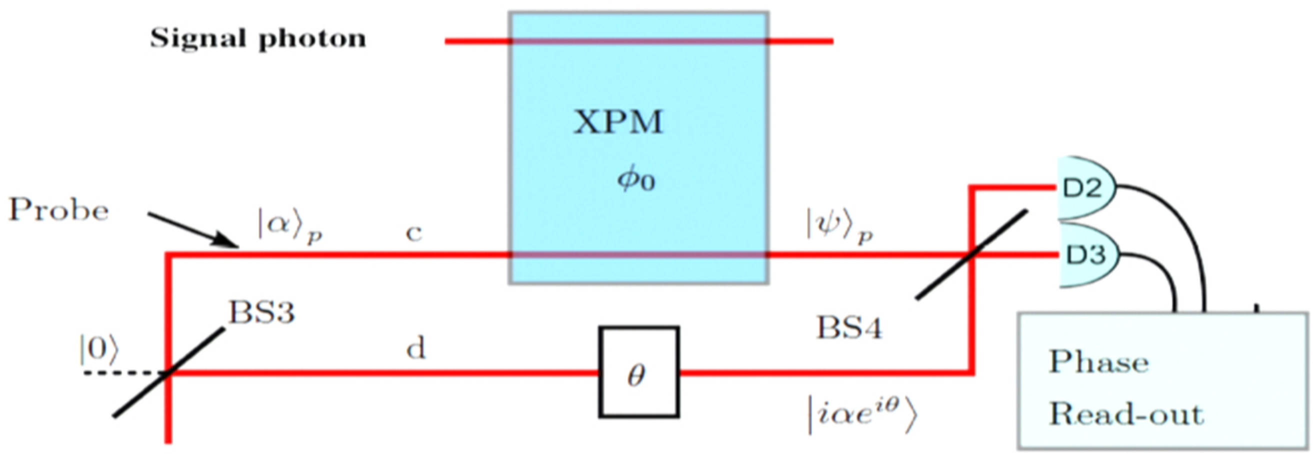
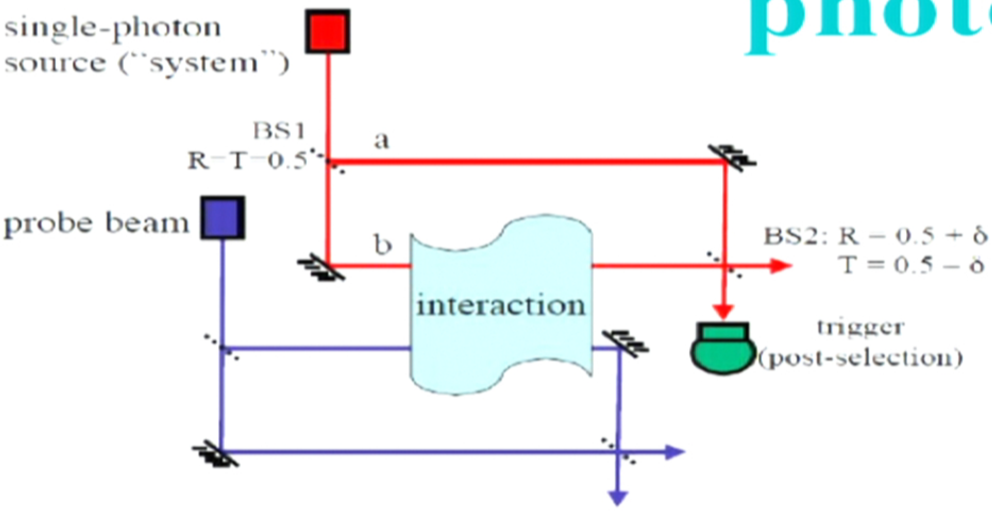
An example of a small quantity still hard to measure

"Giant" optical nonlinearities...
(a route to optical quantum computation;
and in general, to a new field of *quantum nonlinear optics*
– cf. Ray Chiao, Ivan Deutsch, John Garrison)



Can one photon act like many photons?



Weak Measurement Amplification of Single-Photon Nonlinearity,
Amir Feizpour, Xingxing Xing, and Aephraim M. Steinberg
Phys Rev Lett 107, 133603 (2011)