Title: Quantum paradoxes emerging in matter-wave interferometer experiments

Date: Jun 24, 2016 09:45 AM

URL: http://pirsa.org/16060071

Abstract: Peculiarities of quantum mechanical predictions on a fundamental level are investigated intensively in matter-wave optical setups; in particular, neutron interferometric strategy has been providing almost ideal experimental circumstances for experimental demonstrations of quantum effects. In this device quantum interference between beams spatially separated on a macroscopic scale is put on explicit view.
Recently, a new counter-intuitive phenomenon, called quantum Cheshire-cat, is observed in a neutron interferometer experiment. Weak measurement and weak values justify the access of the neutronsâ€™ dynamics in the interferometer. Moreover, another experiment reported full determination of weak-values of neutronâ€™s Â½-spin; this experiment is further applied to demonstrate quantum Pigeonhole effect and quantum contextual. In my talk, I am going to give an overview of neutron interferometry for investigation of quantum paradoxes.

Concept and paradoxes in a quantum universe @Perimeter Inst. Waterloo, CAN
24. July 2016

Quantum paradoxes
emerging in matter-wave interferometer experiments

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Chapman University

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Concept and paradoxes in a quantum universe @Perimeter Inst. Waterloo, CAN
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Quantum paradoxes emerging in matter-wave interferometer experiments

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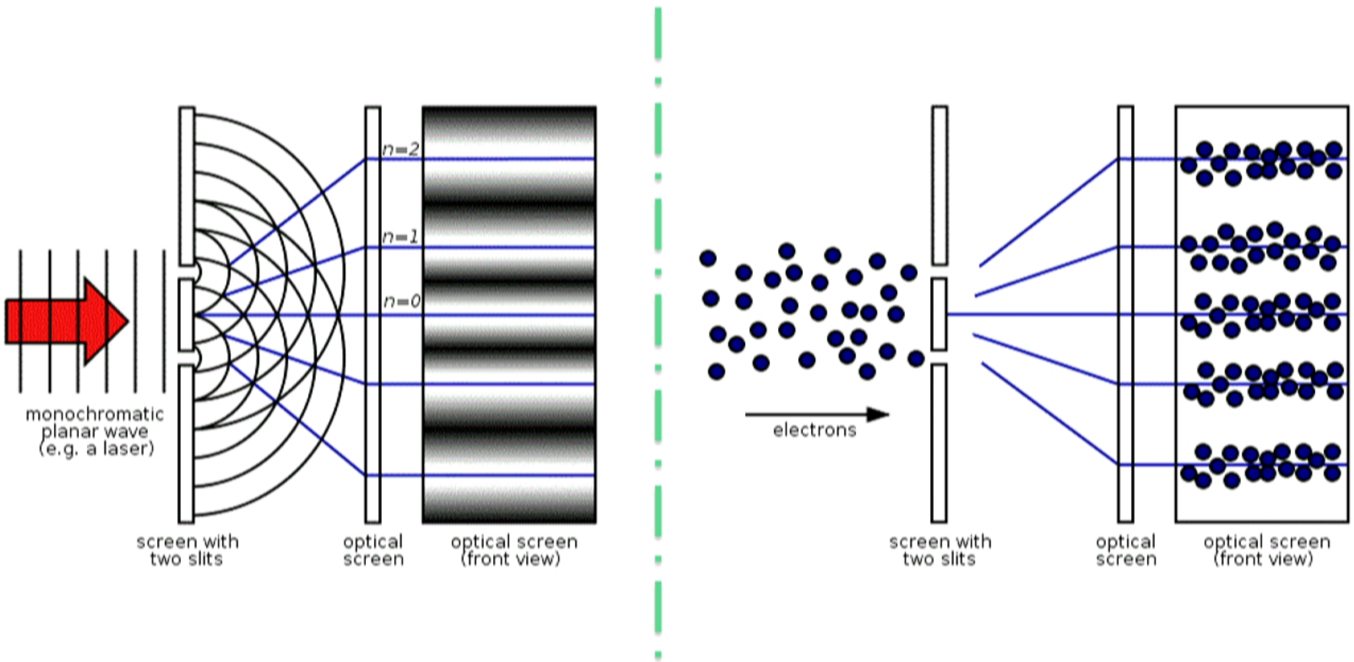
I. Introduction:
- **neutron interferometer**
- **entanglement between degrees of freedom**

II. Quantum Cheshire-Cat

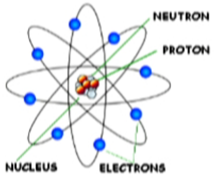
III. 1/2-spin weak-values:
- **quantum Pigeonhole effect**
- **quantum contextuality**

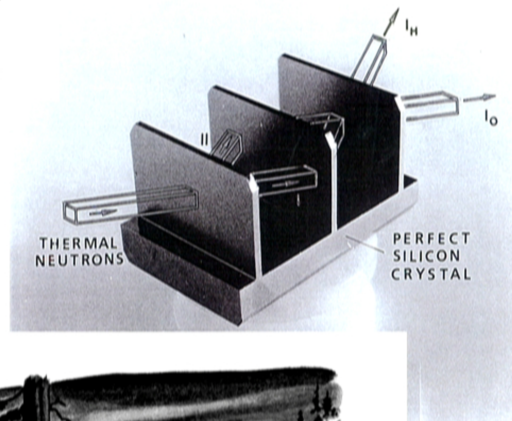
IV. Summary

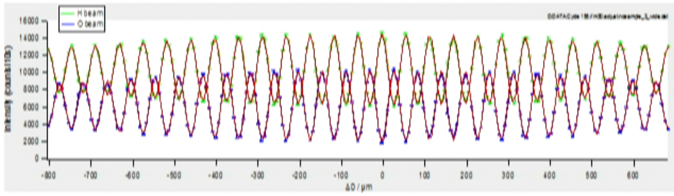
Waves in classical- and quantum-mechanics



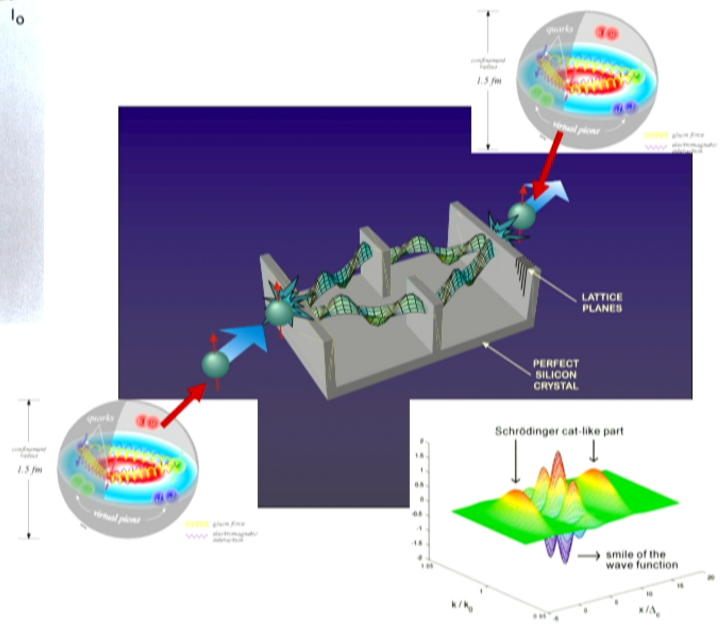
Neutronen interferometry: quantum skier



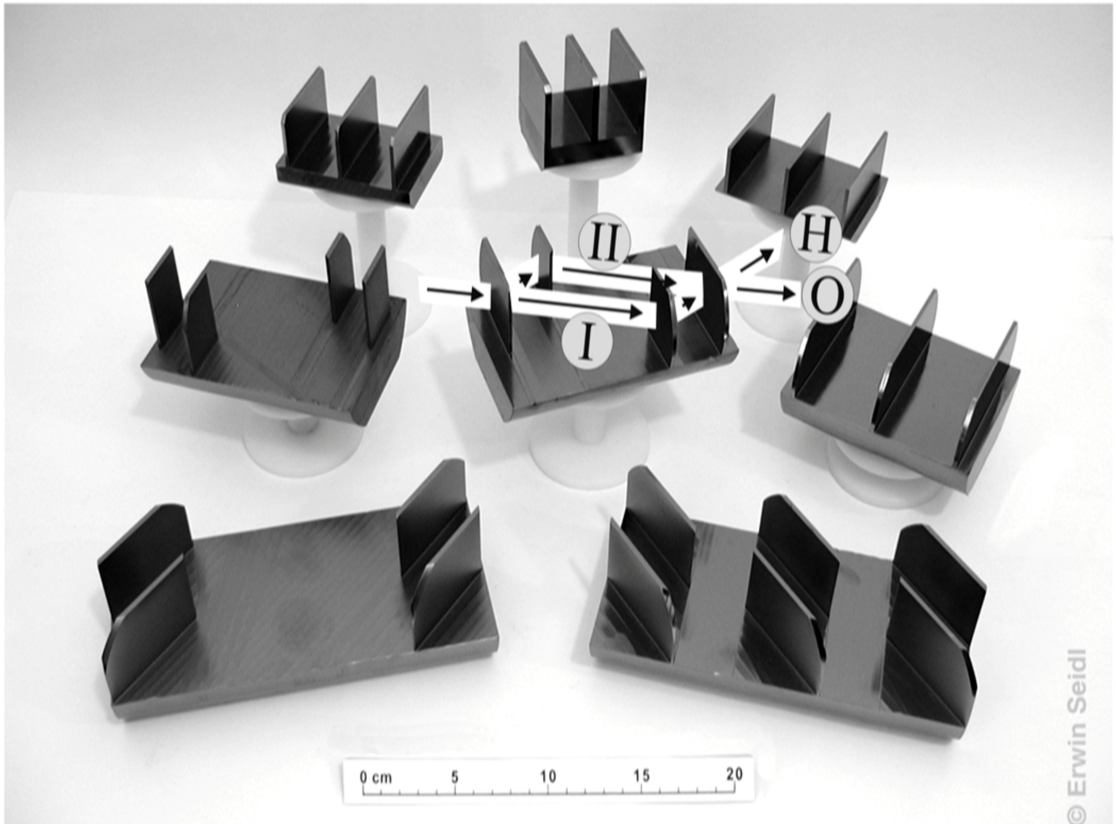




The New Yorker Collection, Ch.Adams 1940



Neutron interferometer family



The neutron

Particle	Feels four-forces	**Wave**

$m = 1.674928\,(1) \times 10^{-27}$ kg

$s = \frac{1}{2}\hbar$

$\mu = -9.6491783(18) \times 10^{-27}$ J/T

$\tau = 887(2)$ s

$R = 0.7$ fm

$\alpha = 12.0\,(2.5) \times 10^{-4}$ fm^3

u - d - d - quark structure

CONNECTION

de Broglie

$$\lambda_B = \frac{h}{m.v}$$

Schrödinger

$$H\psi(\vec{r},t) = i\hbar\frac{\delta\psi(\vec{r},t)}{\delta t}$$

&

boundary conditions

$$\lambda_c = \frac{h}{m.c} = 1.319695(20) \times 10^{-15}\ \text{m}$$

For thermal neutrons
$\lambda = 2$Å, $v = 2$km/s, $E_{kin} = 20$meV

$$\lambda_B = \frac{h}{m.v} = 1.8 \times 10^{-10}\ \text{m}$$

$$\Delta_c = \frac{1}{2\delta k} \cong 10^{-8}\ \text{m}$$

$$\Delta_p = v.\Delta t \cong 10^{-2}\ \text{m}$$

$$\Delta_d = v.\tau = 1.942(5) \times 10^{6}\ \text{m}$$

$$0 \leq \chi \leq 2\pi\ (4\pi)$$

m ... mass, s ... spin, μ ... magnetic moment, τ ... β-decay lifetime, R ... (magnetic) confinement radius, α ... electric polarizability; all other measured quantities like electric charge, magnetic monopole and electric dipole moment are compatible with zero

$-\mu B$

μB

two level system

λ_c ... Compton wavelength, λ_B ... deBroglie wavelength, Δ_c ... coherence length, Δ_p ... packet length, Δ_d ... decay length, δk.... momentum width, Δt ... chopper opening time, v ... group velocity, χ ... ... phase.

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Neutrons in quantum mechanics

Particle and wave properties

$$p = mv = h/\lambda$$

(L. De Broglie)

Schroedinger equation

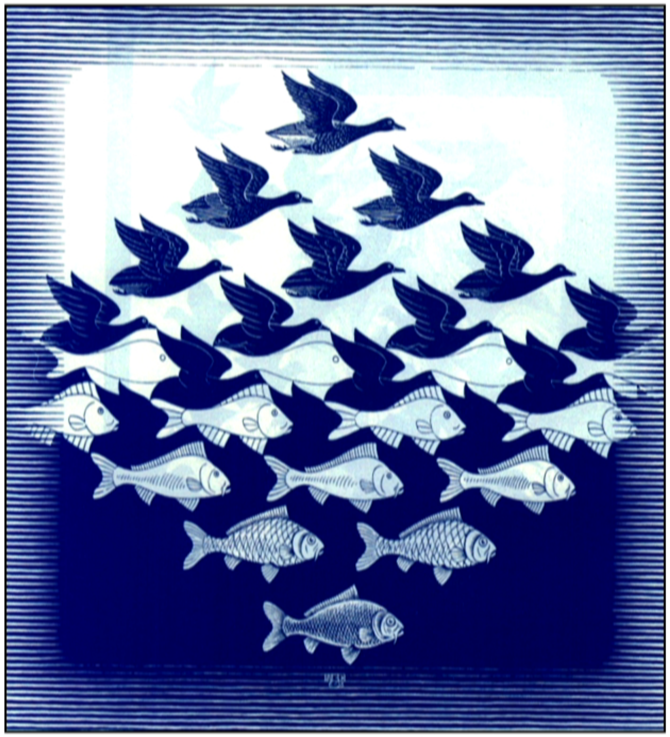
$$i\hbar \frac{\partial \Psi(\vec{r},t)}{\partial t} = H\Psi(\vec{r},t)$$

(E. Schrödinger)

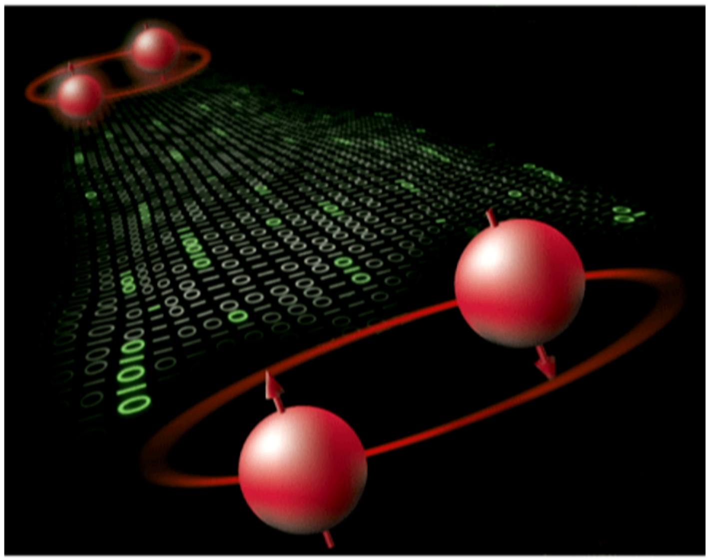
Uncertainity

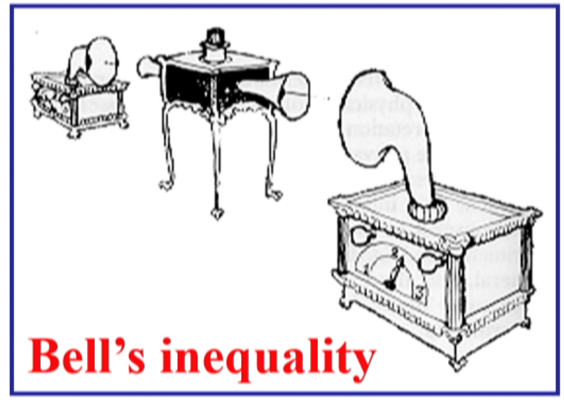
$$\Delta x \, \Delta p \geq \hbar/2$$

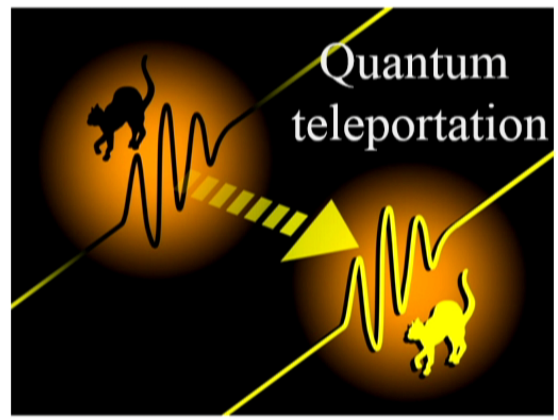
(W. Heisenberg)



Quantum information technology: entanglement







Bi-partite and tri-partite entanglements

2-Particle Bell-State

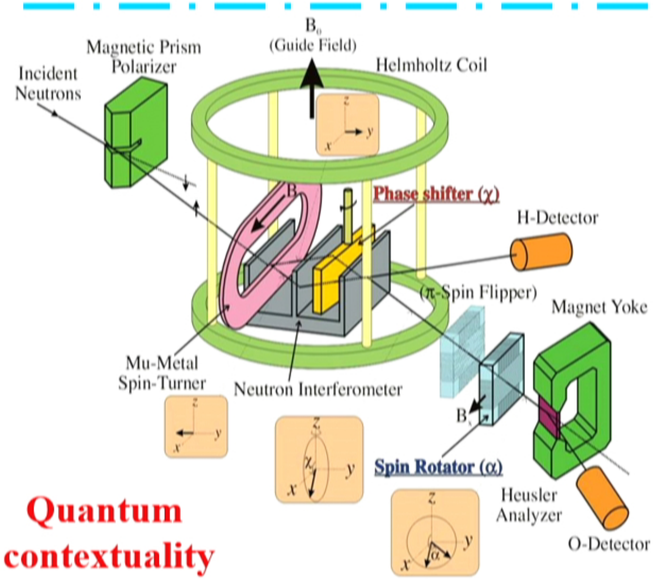
$$|\Psi\rangle = \frac{1}{\sqrt{2}}\{|\uparrow\rangle_{I} \otimes |\downarrow\rangle_{II} + |\downarrow\rangle_{I} \otimes |\uparrow\rangle_{II}\}$$

I, II represent 2-Particles

2-Space Bell-State

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\{|\uparrow\rangle_{s} \otimes |\mathrm{I}\rangle_{p} + |\downarrow\rangle_{s} \otimes |\mathrm{II}\rangle_{p}\}$$

s, p represent 2-Spaces, e.g., spin & path



Quantum contextuality

Violation of Bell-like inequality

$$S' \equiv E'(\alpha_1,\chi_1) + E'(\alpha_1,\chi_2) - E'(\alpha_2,\chi_1) + E'(\alpha_2,\chi_2)$$
$$= \mathbf{2.051} \pm \mathbf{0.019} \quad > \mathbf{2}$$

Nature2003, NJP2011

Kochen-Specker-like contradiction

$$E_x \cdot E_y = 0.407 \xleftrightarrow{63\%} E' \equiv \langle \hat{X}_1 \hat{Y}_2 \cdot \hat{Y}_1 \hat{X}_2 \rangle = -0.861$$

PRL2006/2009

Tri-partite entanglement (GHZ-state)

$$|\Psi_{\mathrm{Neutron}}\rangle = \{|\Psi_{I}\rangle \otimes |\uparrow\rangle \otimes |\Psi(E_0)\rangle + (e^{i\chi}|\Psi_{II}\rangle) \otimes (e^{i\alpha}|\downarrow\rangle) \otimes (e^{i\gamma}|\Psi(E_0 + \hbar\omega_r)\rangle)\}$$

$$M_{Measured} = 2.558 \pm 0.004 \quad > 2$$

PRA2010/NJP2013

nature physics

LETTERS

PUBLISHED ONLINE: 15 JANUARY 2012 | DOI: 10.1038/NPHYS2194

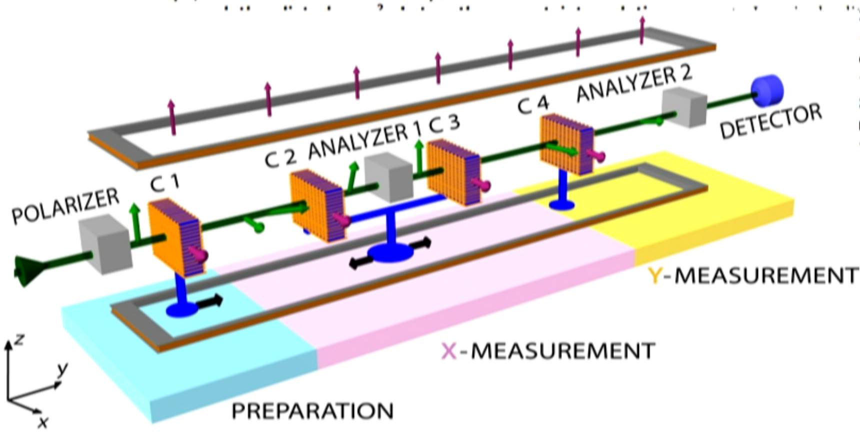
Experimental demonstration of a universally valid error–disturbance uncertainty relation in spin measurements

Jacqueline Erhart[1], Stephan Sponar[1], Georg Sulyok[1], Gerald Badurek[1], Masanao Ozawa[2] and Yuji Hasegawa[1]*

The uncertainty principle generally prohibits simultaneous measurements of certain pairs of observables and forms the basis of indeterminacy in quantum mechanics[1]. Heisenberg's original formulation, illustrated by the famous γ-ray microscope, sets a lower bound for the product of the measurement

as $\sigma(A)^2 = \langle\psi|A^2|\psi\rangle - \langle\psi|A|\psi\rangle^2$. Note that a positive definite covariance term can be added to the right-hand side of equation (2), if squared, as discussed by Schrödinger[5]. For our experimental setting, this term vanishes. Robertson's relation (equation (2)) for standard deviations has been confirmed by many different experi-

diffraction experiment[15] the uncertainty rela- equation (2), has been confirmed. A trade-off queezing coherent states of radiation fields[16], tal demonstrations have been carried out[17]. on (equation (2)) has a mathematical basis, but nplications for limitations on measurements. turally understood as limitations on state



Cheshire-cat

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Cheshire Cat

From Wikipedia, the free encyclopedia

This article is about a character in Alice's Adventures in Wonderland. For other uses, see Cheshire Cat (disambiguation).

The Cheshire Cat (/ˈtʃɛʃər/ or /ˈtʃɛʃɪər/) is a fictional cat popularised by Lewis Carroll in *Alice's Adventures in Wonderland* and known for its distinctive mischievous grin.

Contents [hide]

Cheshire Cat

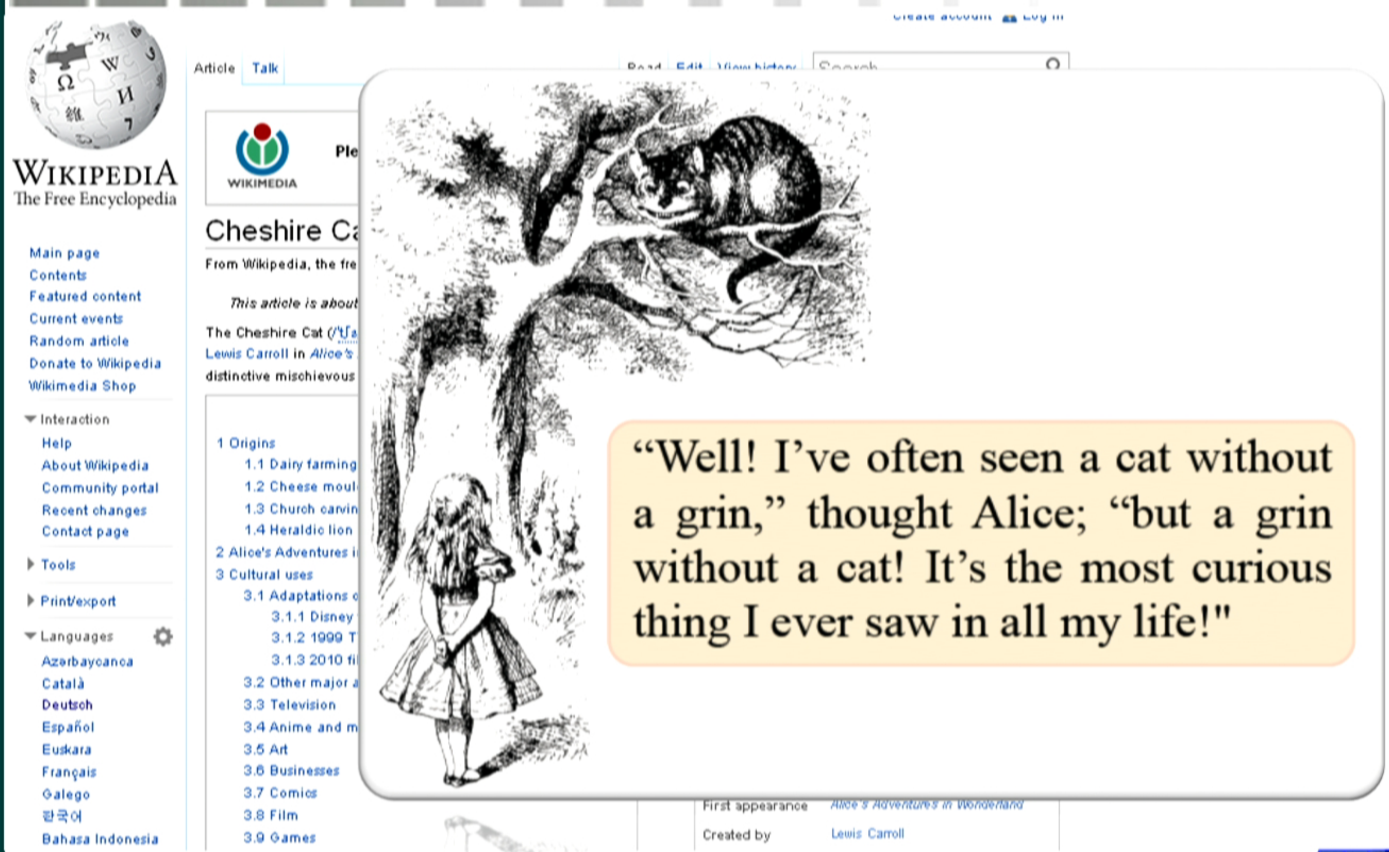
Alice character

The Cheshire cat as illustrator John Tenniel envisioned it in the 1866 publication

First appearance	*Alice's Adventures in Wonderland*
Created by	Lewis Carroll

FWF

Cheshire-cat



"Well! I've often seen a cat without a grin," thought Alice; "but a grin without a cat! It's the most curious thing I ever saw in all my life!"

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Quantum Cheshire-cat

PHYSICS TEXTBOOK

Yakir Aharonov
Daniel Rohrlich

Quantum Pa

Quantum Theory for the Perplexed

New Journal of Physics
The open access journal for physics

Quantum Cheshire Cats

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New Journal of Physics **15** (2013) 113015 (8pp)
Received 23 January 2013
Published 7 November 2013
Online at http://www.njp.org/
doi:10.1088/1367-2630/15/11/113015

Abstract. In this paper we present a quantum Cheshire Cat. In a pre- and post-selected experiment we find the Cat in one place, and its grin in another. The Cat is a photon, while the grin is its circular polarization.

Quantum Cheshire-cat

PHYSICS TEXTBOOK

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Quantum Cheshire Cats

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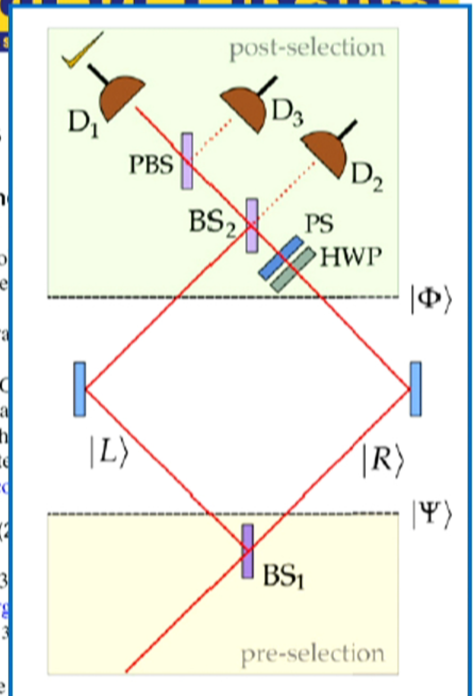

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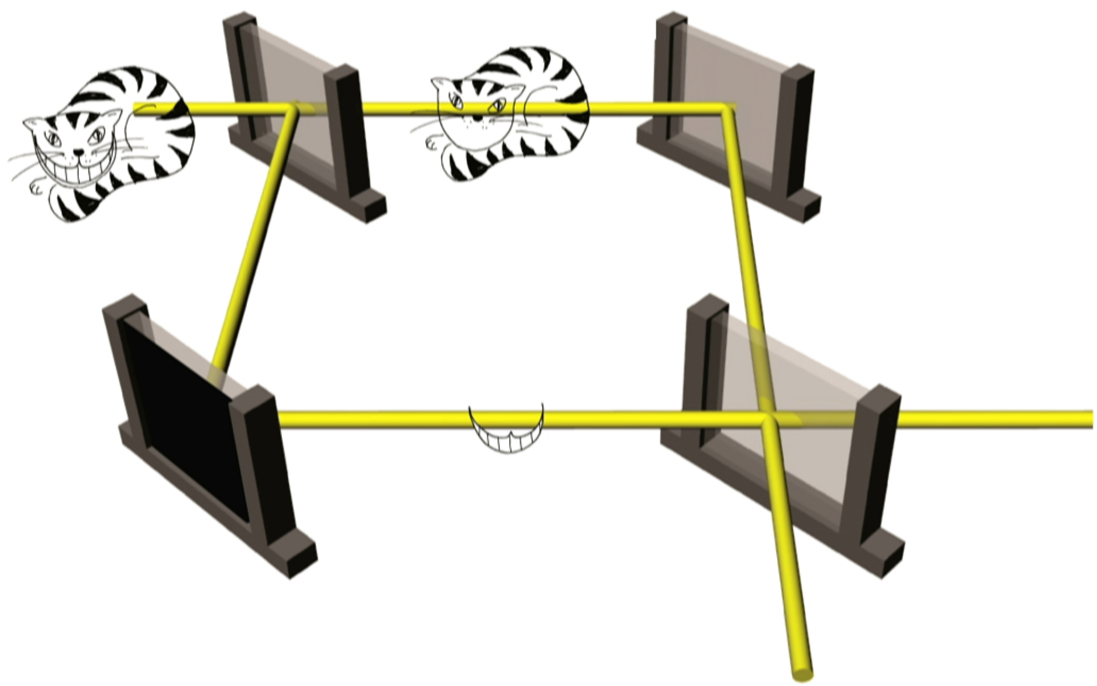
FWF

Quantum Cheshire-cat in neutron interferometer



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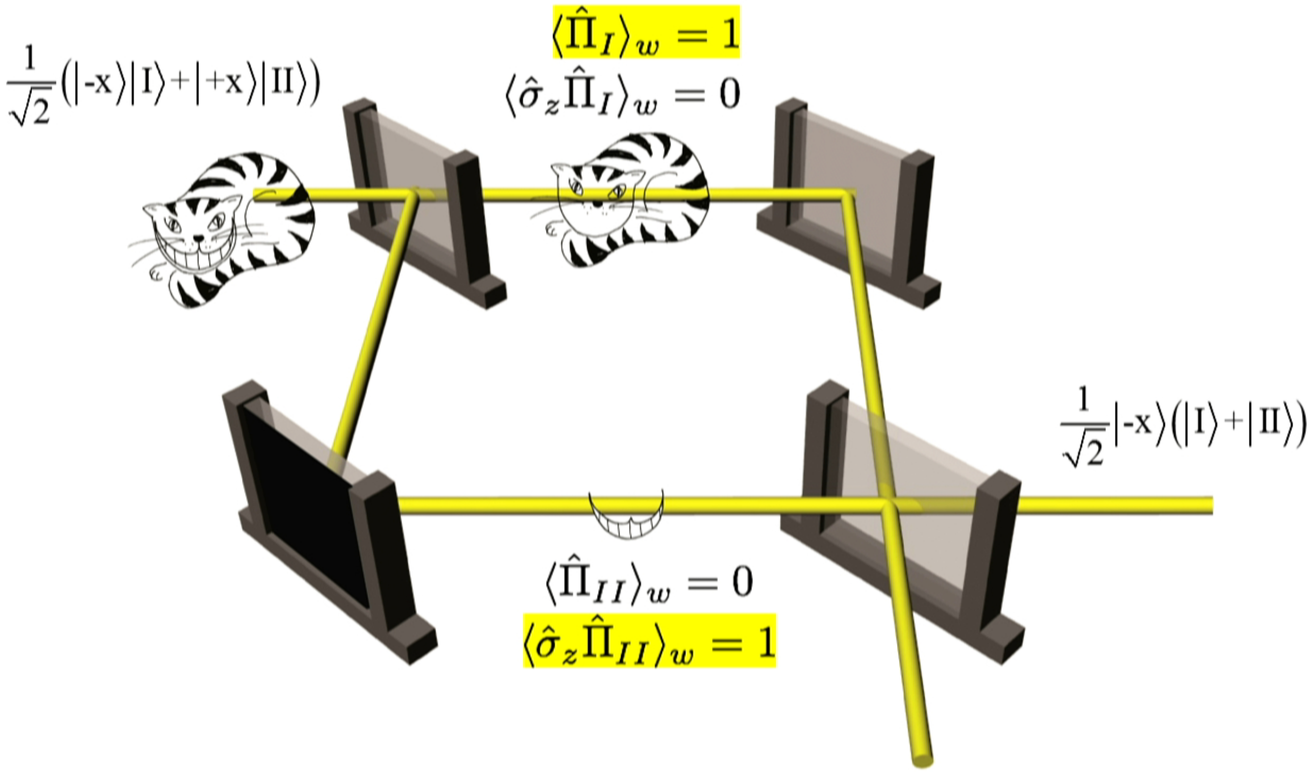
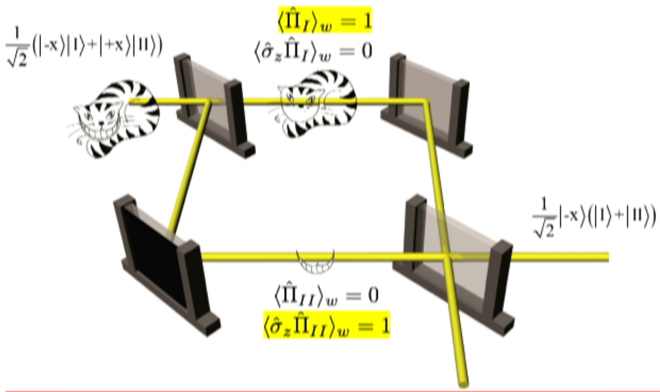
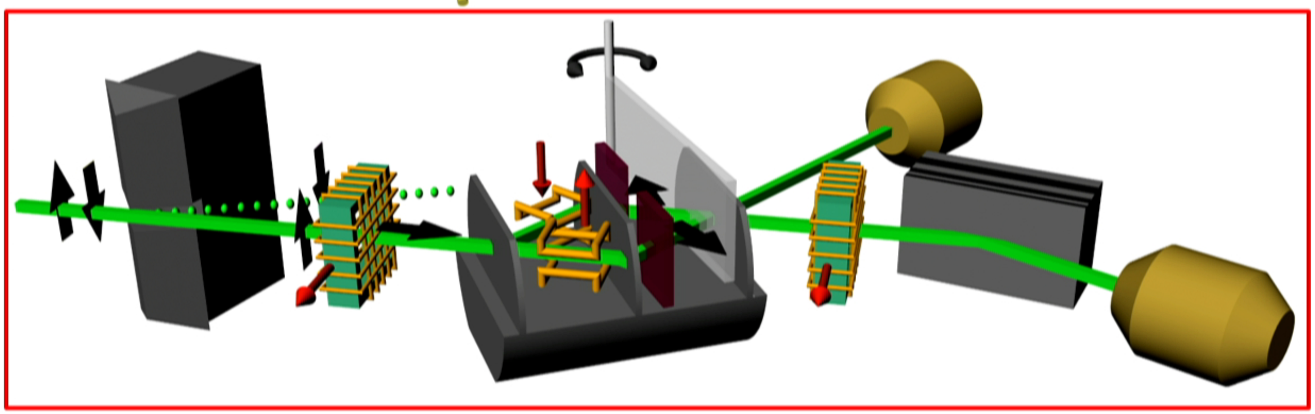
Quantum Cheshire-cat in neutron interferometer

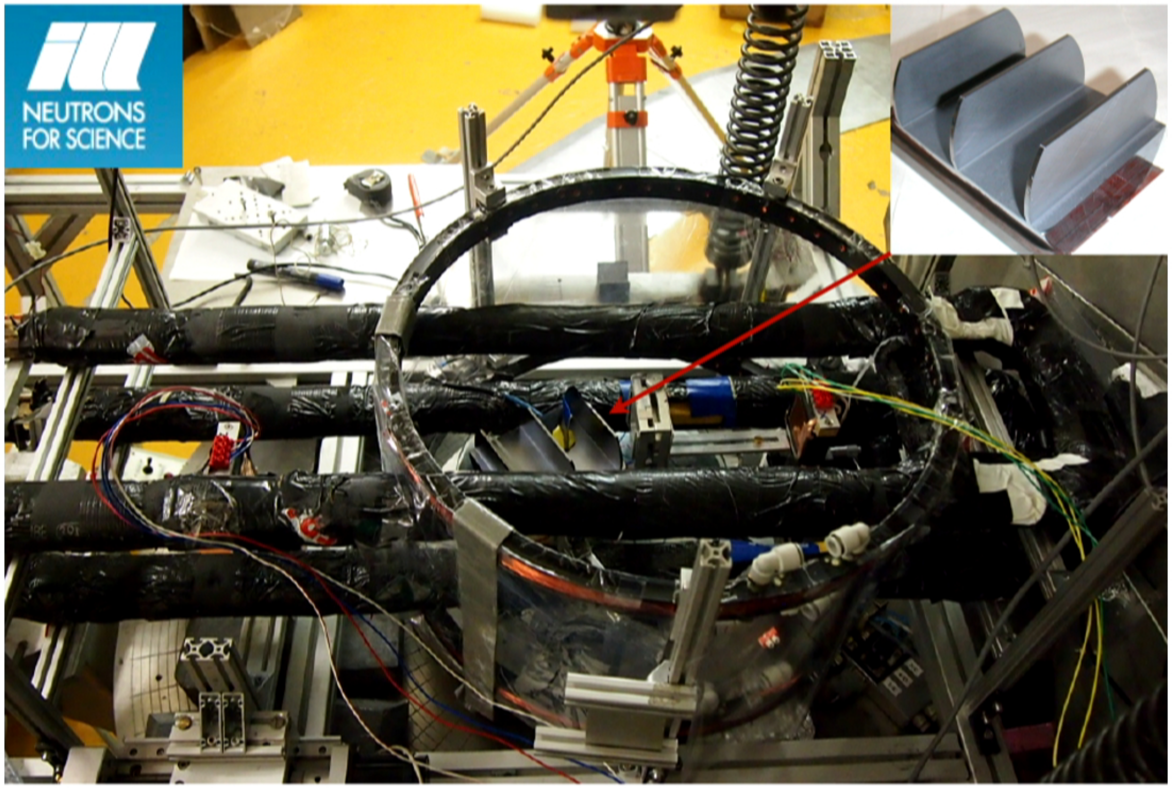


Quantum Cheshire-cat in neutron interferometer

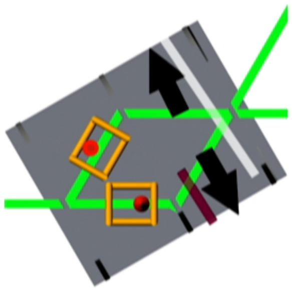


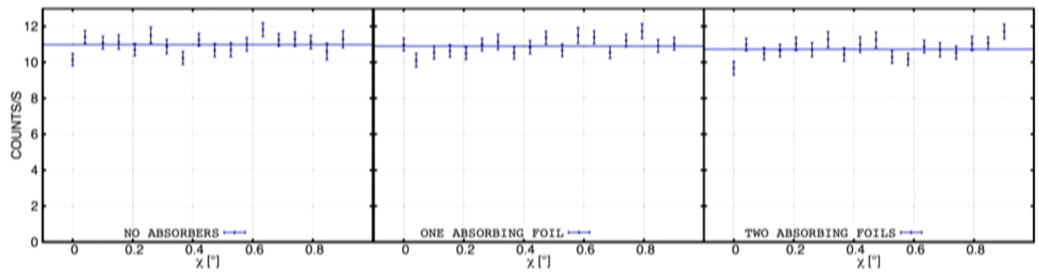


Quantum Cheshire-cat: experiment



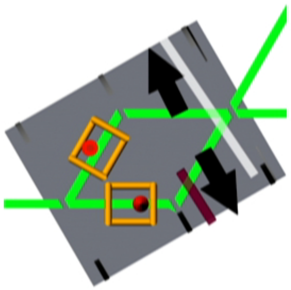
Quantum Cheshire-cat: neutron(cat) in upper path

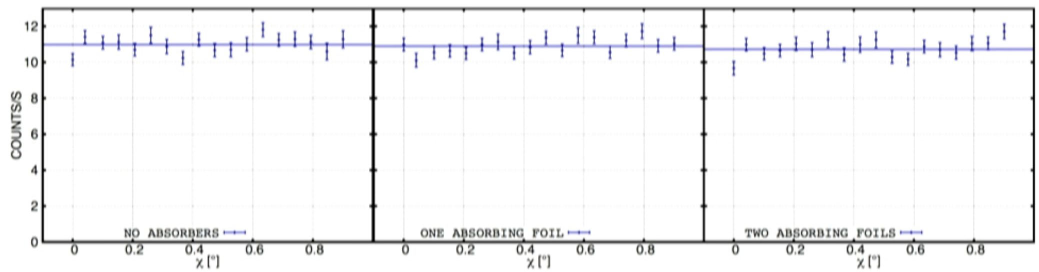




T=1 T=0.8 T=0.6

Quantum Cheshire-cat: neutron(cat) in upper path





T=1 T=0.8 T=0.6

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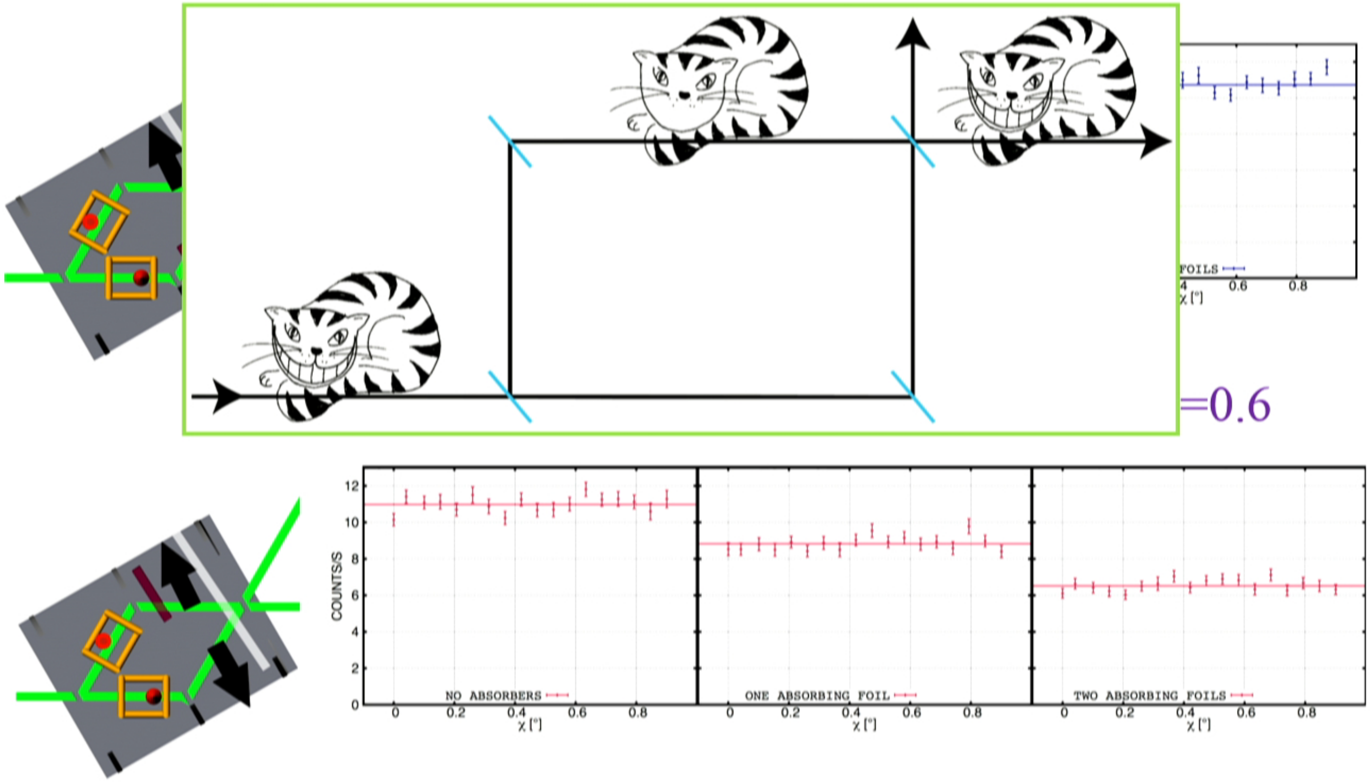
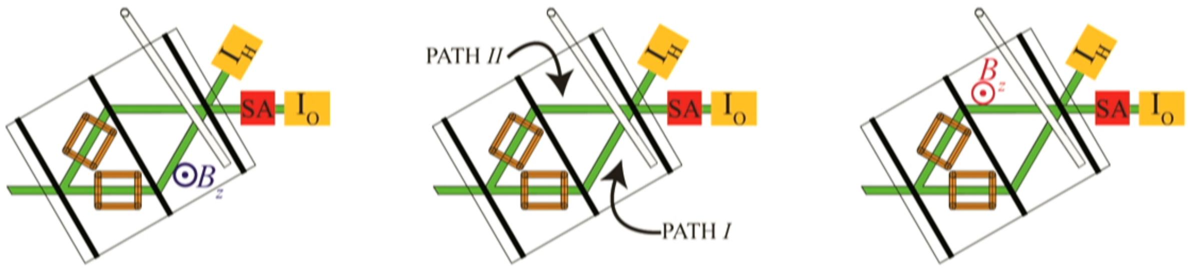
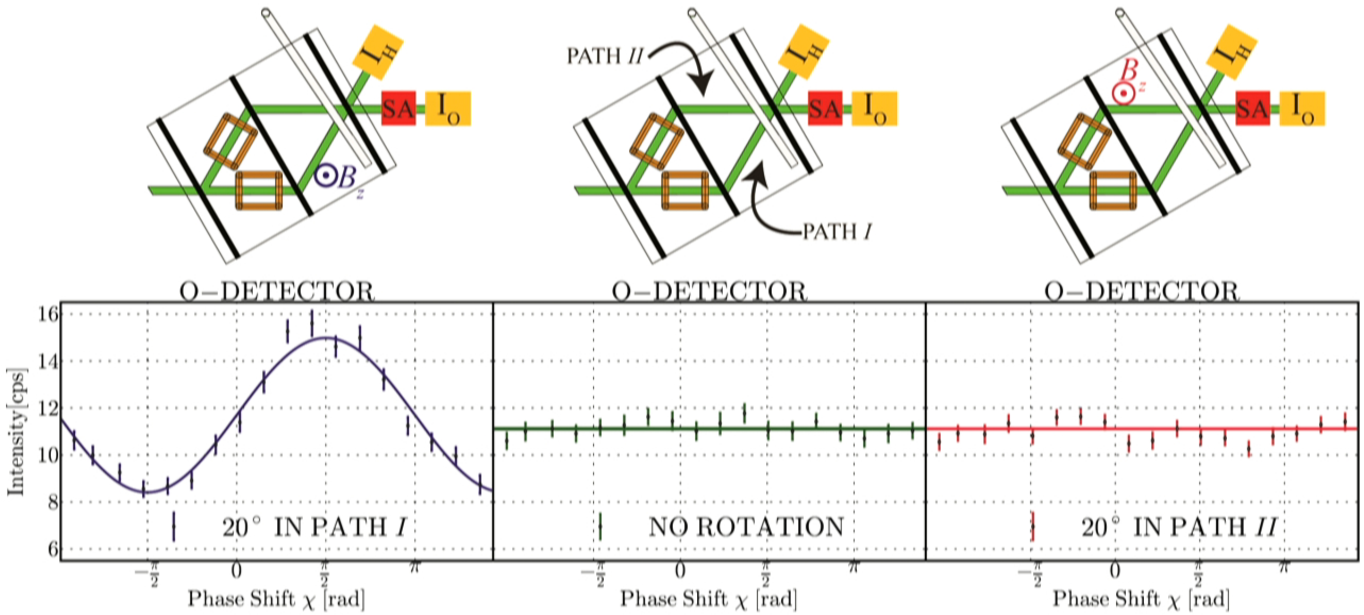
Quantum Cheshire-cat: neutron(cat) in upper path



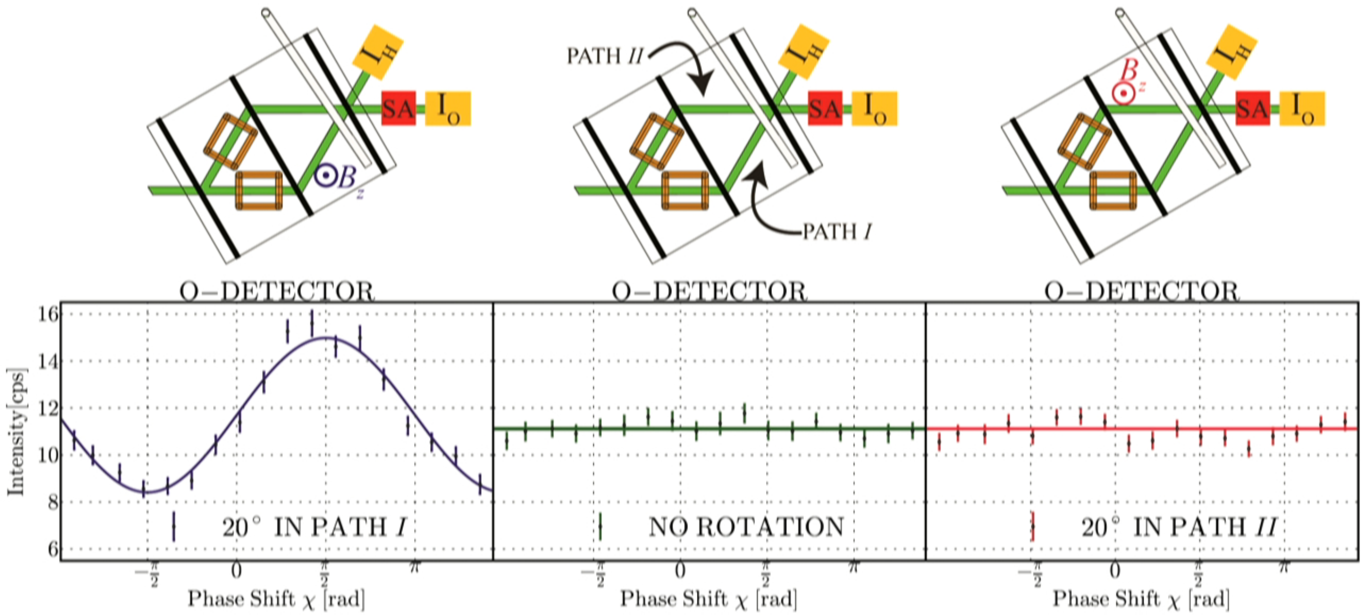
Quantum Cheshire-cat: spin(smile) in lower path



Quantum Cheshire-cat: spin(smile) in lower path



Quantum Cheshire-cat: spin(smile) in lower path



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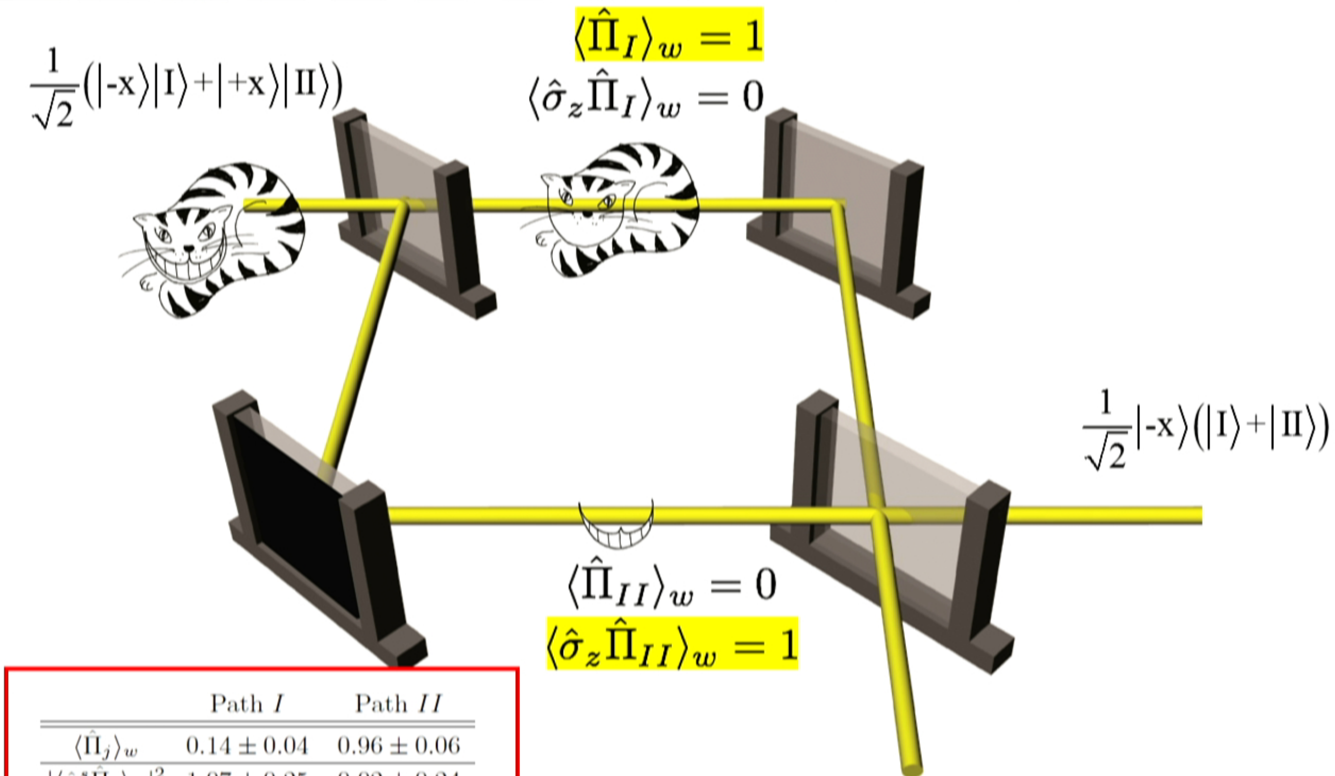
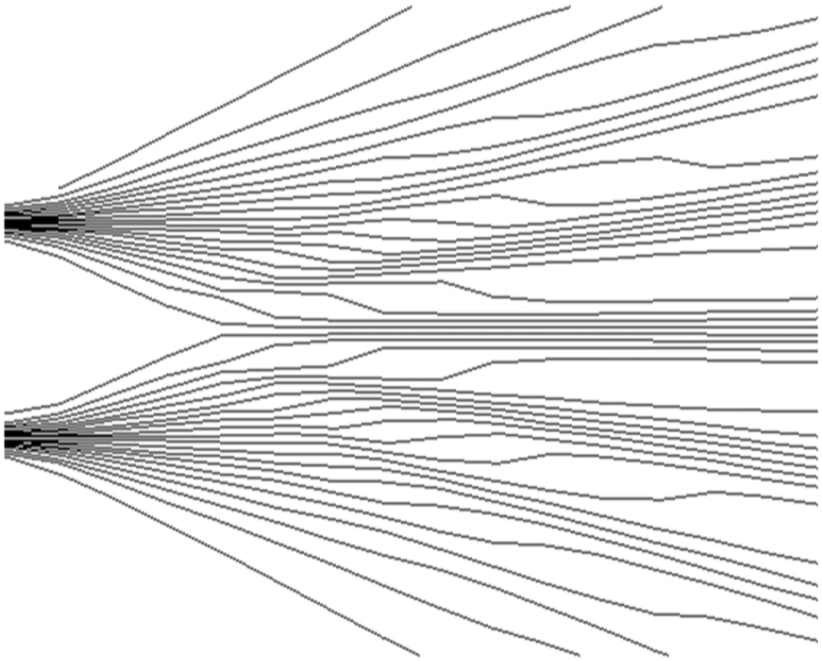
Quantum Cheshire-cat: final results



	Path I	Path II
$\langle\hat{\Pi}_j\rangle_w$	0.14 ± 0.04	0.96 ± 0.06
$\lvert\langle\hat{\sigma}_z^s\hat{\Pi}_j\rangle_w\rvert^2$	1.07 ± 0.25	0.02 ± 0.24

T. Denkmayr et al. Nature Comm. 5:4492 (2014).

Quantum Cheshire-cat: invisible cat/spin ???



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Weak measurement, weak value

VOLUME 60, NUMBER 14 PHYSICAL REVIEW LETTERS 4 APRIL 1988

How the Result of a Measurement of a Component of the Spin of a Spin-$\frac{1}{2}$ Particle Can Turn Out to be 100

Yakir Aharonov, David Z. Albert, and Lev Vaidman

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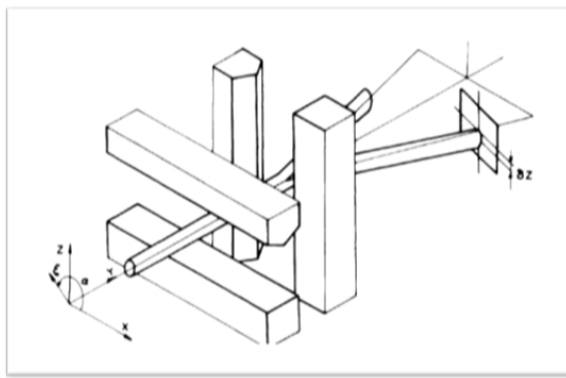
(Received 30 June 1987)

We have found that the usual measuring procedure for preselected and postselected ensembles of quantum systems gives unusual results. Under some natural conditions of weakness of the measurement, its result consistently defines a new kind of value for a quantum variable, which we call the weak value. A description of the measurement of the weak value of a component of a spin for an ensemble of preselected and postselected spin-$\frac{1}{2}$ particles is presented.



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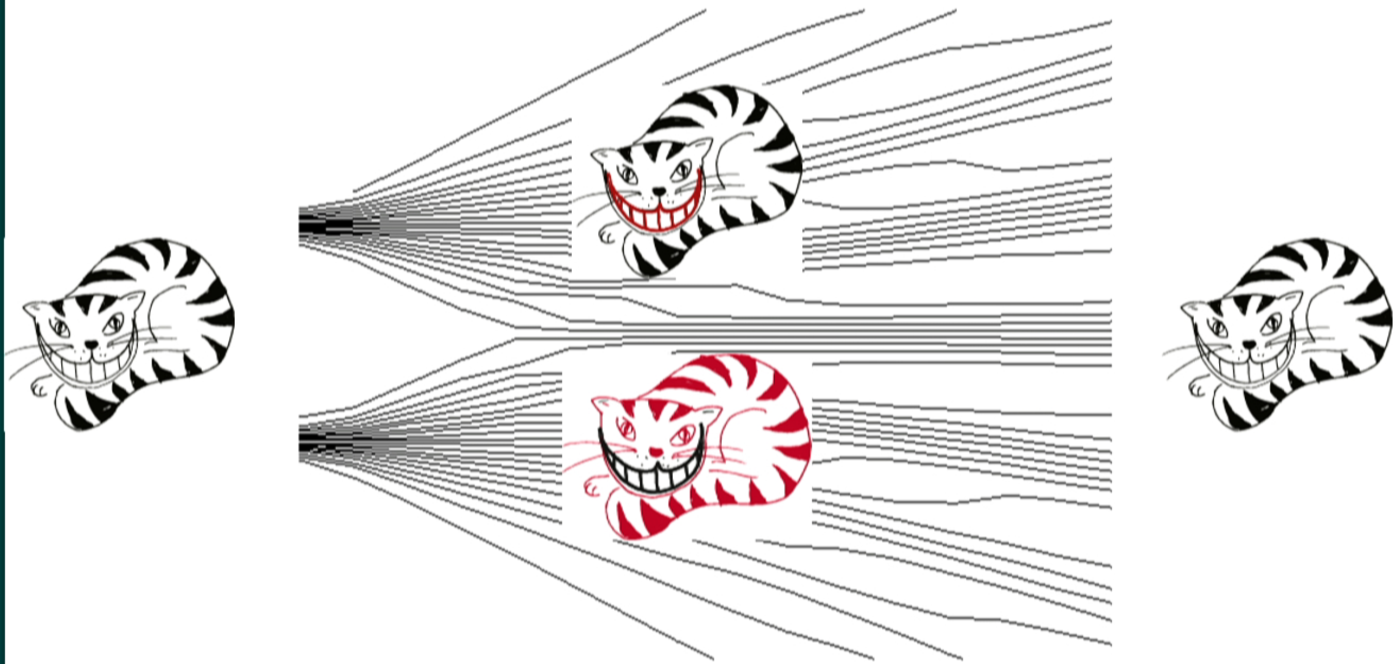

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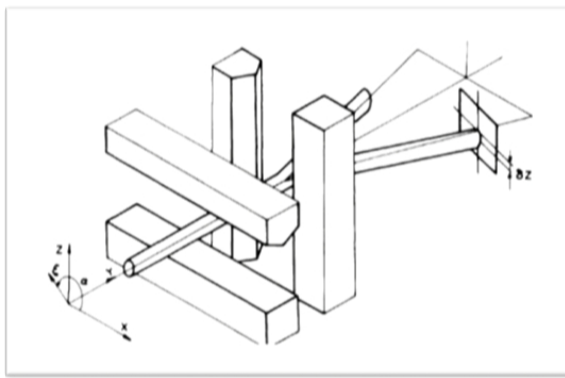
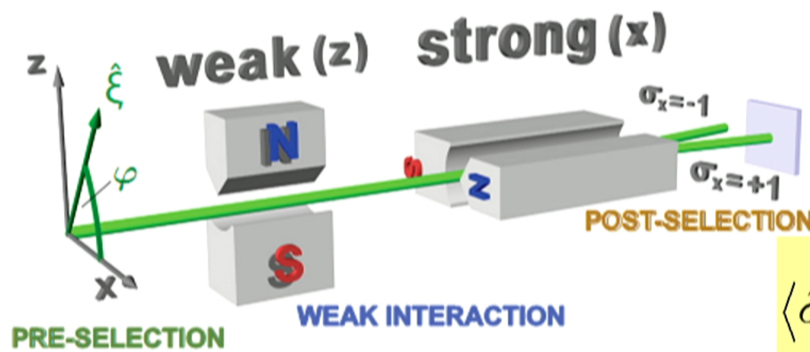


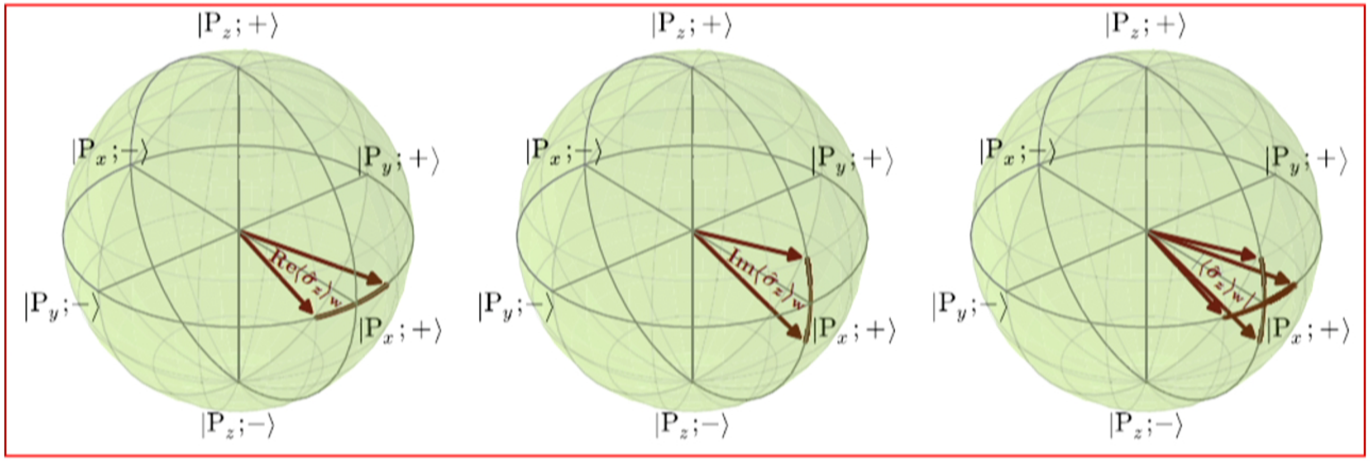
Weak measurement of neutron's ½-spin



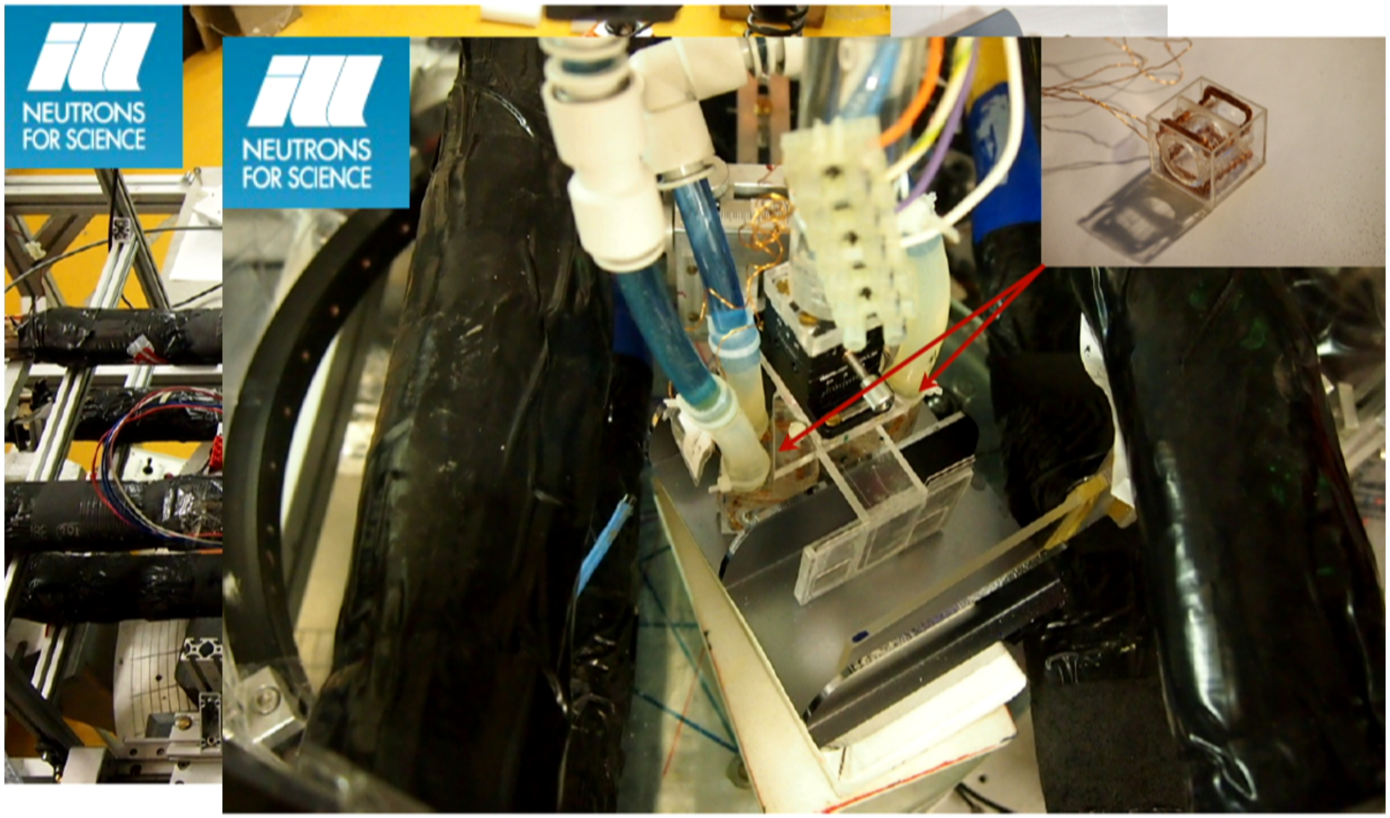
$$\left\langle \hat{\sigma}_z^s \right\rangle_w = \frac{\left\langle s_f \middle| \hat{\sigma}_z \middle| s_i \right\rangle}{\left\langle s_f \middle| s_i \right\rangle}$$

Weak measurement of ½-spin: real/imaginary/absolute

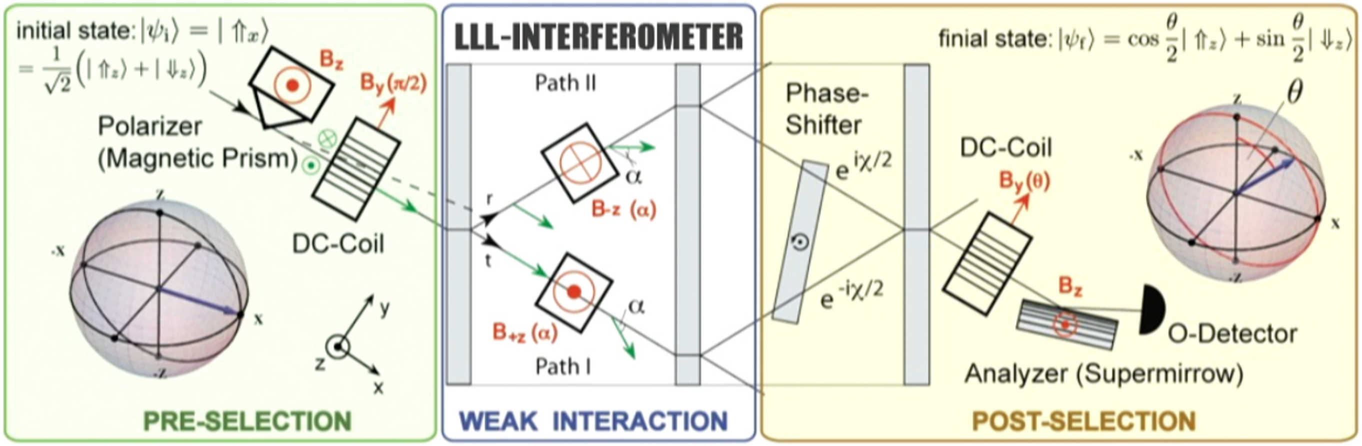
$$|\phi\rangle = \frac{\langle S_f|\, S_i\rangle}{\sqrt{2}} \left(\mathrm{e}^{-i\alpha\langle\hat{\sigma}_z^s\rangle_w/2}\,|I\rangle + \mathrm{e}^{i\alpha\langle\hat{\sigma}_z^s\rangle_w/2}\,|II\rangle \right)$$



Pictures of experimental setup

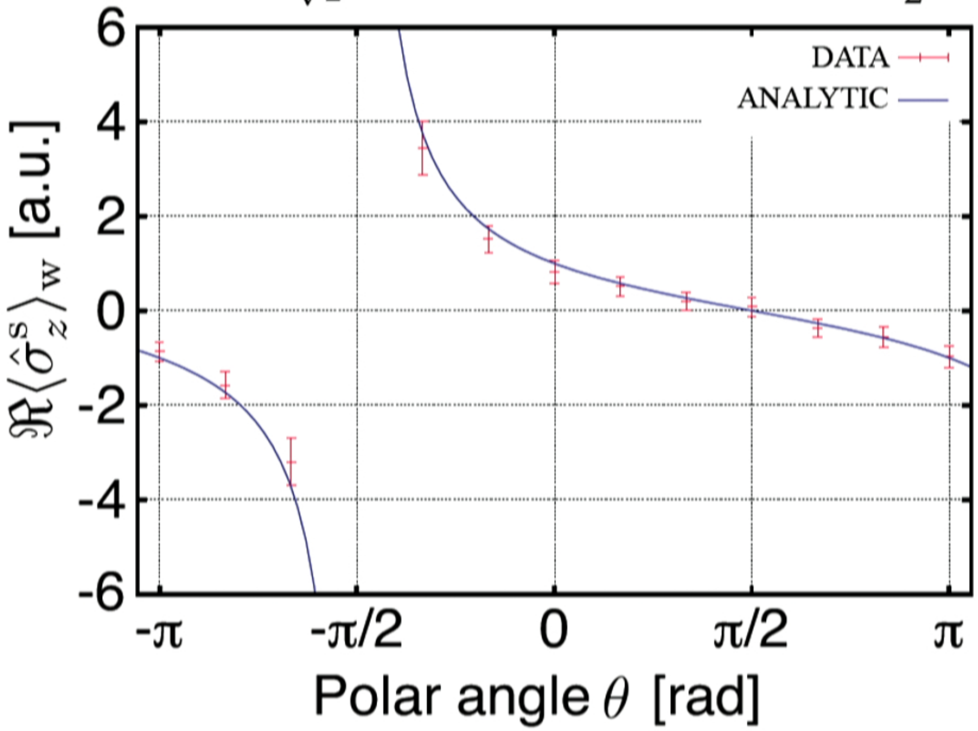


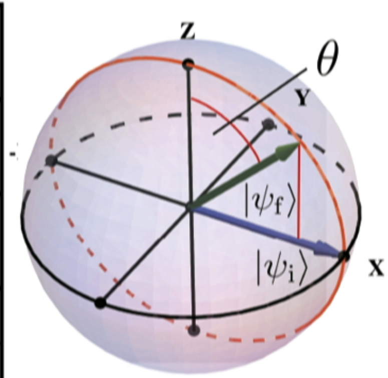
Experimental scheme



Weak measurement of ½-spin: real part

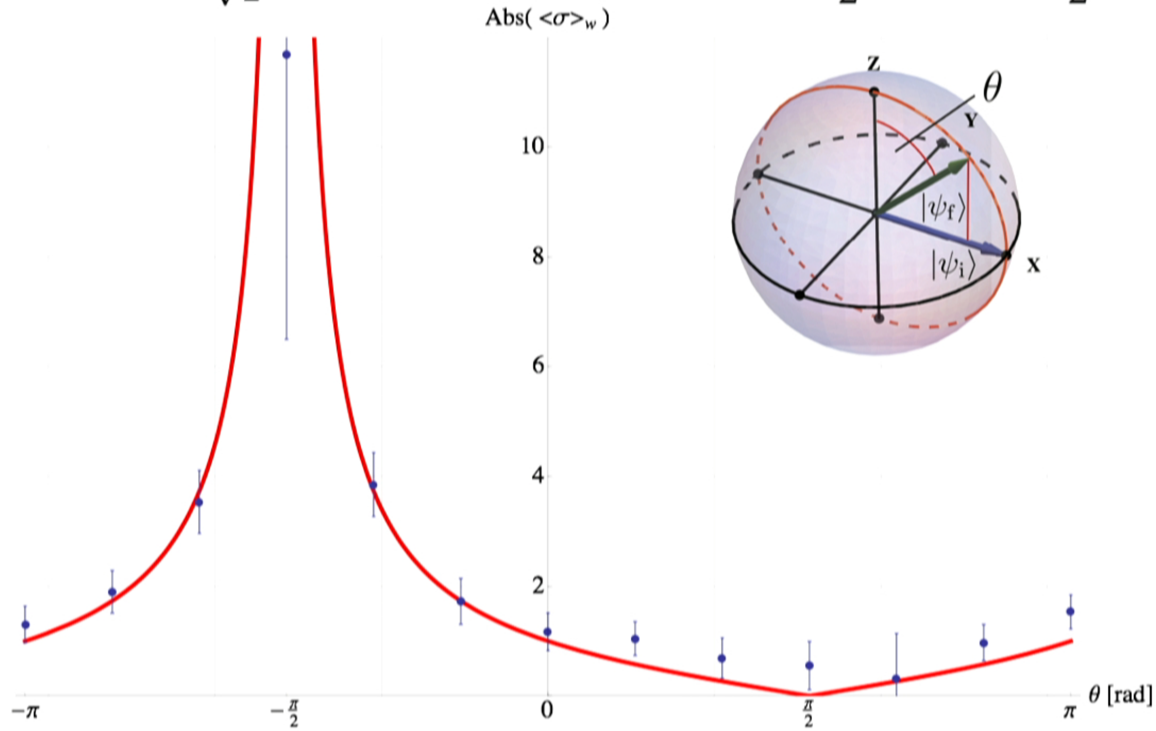
- $|\psi_\mathrm{i}\rangle = |\Uparrow_x\rangle = \frac{1}{\sqrt{2}}\left(|\Uparrow_z\rangle + |\Downarrow_z\rangle\right)$
- $|\psi_\mathrm{f}\rangle = \cos\frac{\theta}{2}|\Uparrow_z\rangle + \sin\frac{\theta}{2}|\Downarrow_z\rangle$





Weak measurement of ½-spin: absolute value

- $|\psi_\mathrm{i}\rangle = |\Uparrow_x\rangle = \frac{1}{\sqrt{2}}\left(|\Uparrow_z\rangle + |\Downarrow_z\rangle\right)$
- $|\psi_\mathrm{f}\rangle = \cos\frac{\theta}{2}|\Uparrow_z\rangle + \sin\frac{\theta}{2}|\Downarrow_z\rangle$



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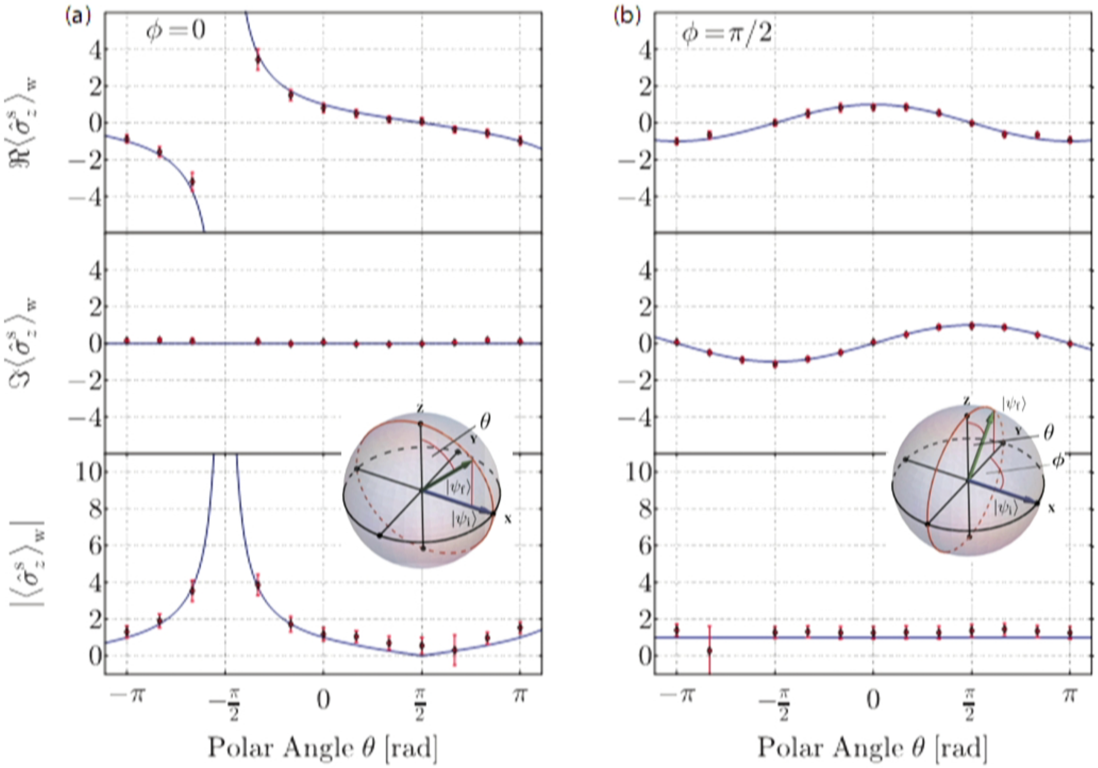
Weak measurement of ½-spin: final results



Quantum pigeonhole effect 1

Quantum violation of the pigeonhole principle and the nature of quantum correlations

Yakir Aharonov[a,b,c,1], Fabrizio Colombo[d], Sandu Popescu[c,e], Irene Sabadini[d], Daniele C. Struppa[b,c], and Jeff Tollaksen[b,c]

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Contributed by Yakir Aharonov, November 12, 2015 (sent for review April 3, 2015; reviewed by Charles H. Bennett and Lucien Hardy)

532–535 | PNAS | January 19, 2016 | vol. 113 | no. 3 www.pnas.org/cgi/doi/10.1073/pnas.1522411112

Quantum pigeonhole effect 1

PNAS

Quantum violation of the pigeonhole principle and the nature of quantum correlations

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[a]School of ... 92866; [c]Ins... and [e]H. H. ... Orange, CA ... lan, Italy;

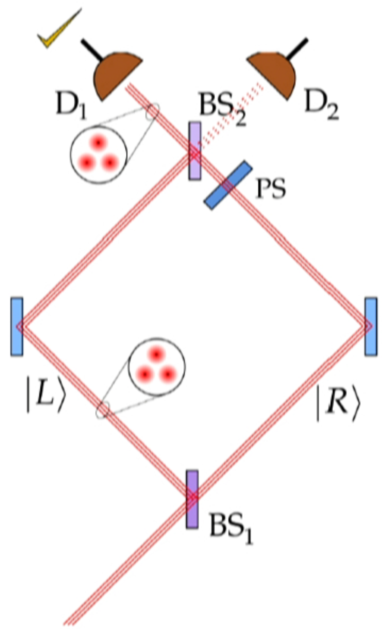
Contribute...

532–535 ... s.1522411112

The pigeonhole principle: "If you put three pigeons in two pigeon-holes, at least two of the pigeons end up in the same hole," is an obvious yet fundamental principle of nature as it captures the very essence of counting. Here however we show that in quantum mechanics this is not true! We find instances when three quantum particles are put in two boxes, yet no two particles are in the same box. Furthermore, we show that the above "quantum pigeonhole principle" is only one of a host of related quantum effects, and points to a very interesting structure of quantum mechanics that was hitherto unnoticed. Our results shed new light on the very notions of separability and correlations in quantum mechanics and on the nature of interactions. It also presents a new role for entanglement, complementary to the usual one. Finally, interferometric experiments that illustrate our effects are proposed.

FWF

Quantum pigeonhole effect 2



$$|\Psi\rangle = |+\rangle_1 |+\rangle_2 |+\rangle_3 \quad where \ |\pm\rangle \equiv \frac{1}{\sqrt{2}}\{|L\rangle \pm |R\rangle\}$$

Y. Aharonov et al. PNAS **113**, 532 (2016).

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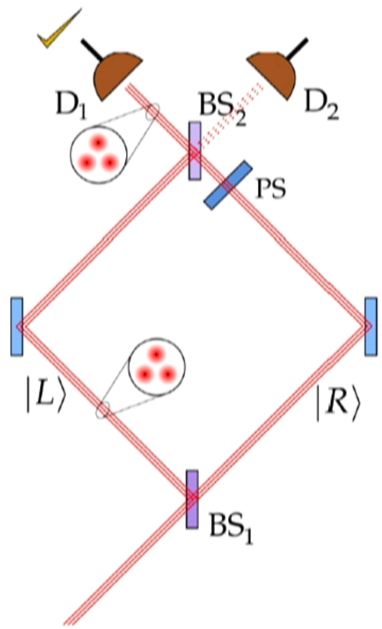
Quantum pigeonhole effect 2

$$|\Phi\rangle = |+i\rangle_1 |+i\rangle_2 |+i\rangle_3 \quad where \ |\pm i\rangle \equiv \frac{1}{\sqrt{2}}\{|L\rangle \pm i|R\rangle\}$$

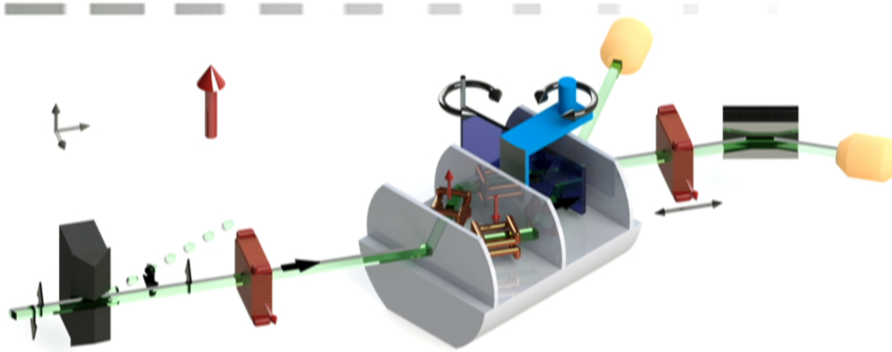


$$\begin{cases} \hat{\Pi}_{12}^{same} = \hat{\Pi}_{12}^{LL} + \hat{\Pi}_{12}^{RR} \\ \hat{\Pi}_{12}^{diff} = \hat{\Pi}_{12}^{LR} + \hat{\Pi}_{12}^{RL} \end{cases} \quad where \ \hat{\Pi}_{12}^{LL} \equiv |L\rangle\langle L| \ etc.$$

$$|\Psi\rangle = |+\rangle_1 |+\rangle_2 |+\rangle_3 \quad where \ |\pm\rangle \equiv \frac{1}{\sqrt{2}}\{|L\rangle \pm |R\rangle\}$$

Y. Aharonov et al. PNAS **113**, 532 (2016).

Quantum pigeonhole effect in neutron interferometer



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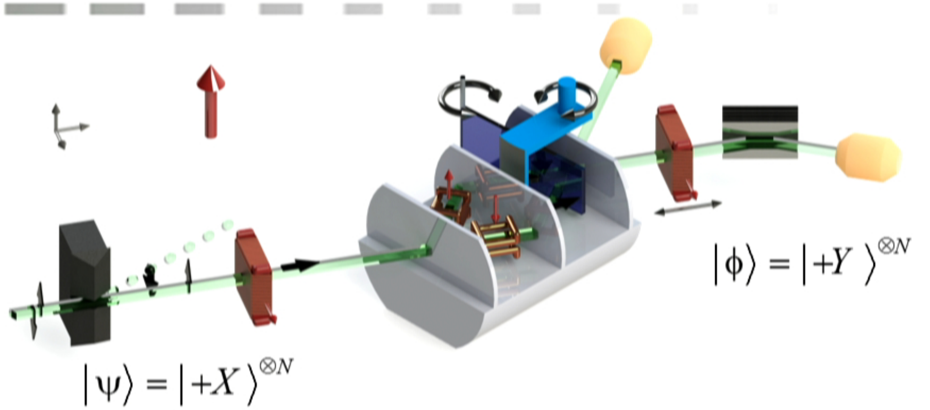
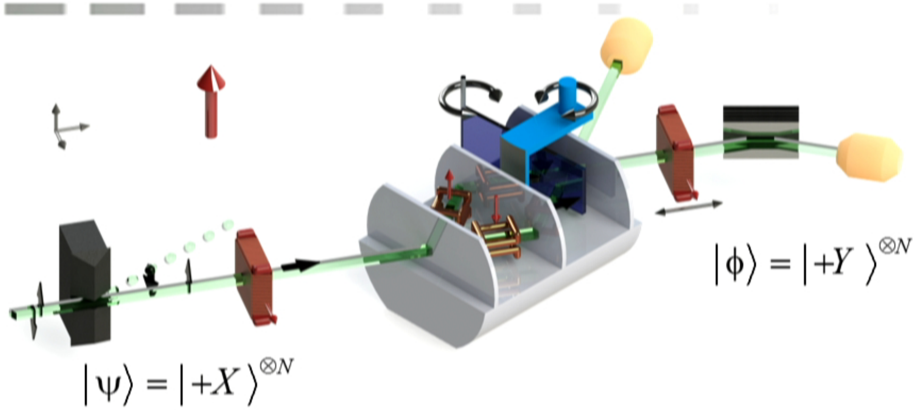
Quantum pigeonhole effect in neutron interferometer



$$\begin{cases} \hat{\Pi}^{even} = \hat{\Pi}_+\hat{\Pi}_+ + \hat{\Pi}_-\hat{\Pi}_- \\ \hat{\Pi}^{odd} = \hat{\Pi}_+\hat{\Pi}_- + \hat{\Pi}_-\hat{\Pi}_+ \end{cases} \quad where \ \hat{\Pi}_\pm \equiv |\pm Z\rangle\langle\pm Z|$$

Quantum pigeonhole effect in neutron interferometer



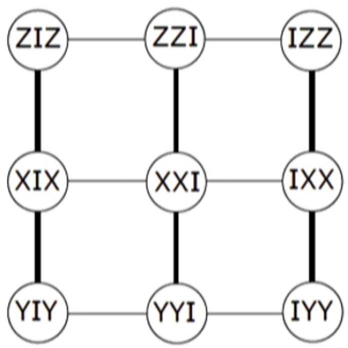
$$\begin{cases} \hat{\Pi}^{even} = \hat{\Pi}_+\hat{\Pi}_+ + \hat{\Pi}_-\hat{\Pi}_- \\ \hat{\Pi}^{odd} = \hat{\Pi}_+\hat{\Pi}_- + \hat{\Pi}_-\hat{\Pi}_+ \end{cases} \quad where\ \hat{\Pi}_\pm \equiv |\pm Z\rangle\langle \pm Z|$$

$$\boxed{\hat{\Pi}_w^{even} = 0\ \&\ \hat{\Pi}_w^{odd} = 1,\ then\ \left(\hat{\sigma}_z^{path} \bullet \hat{\sigma}_z^{path}\right)_w = -1}$$

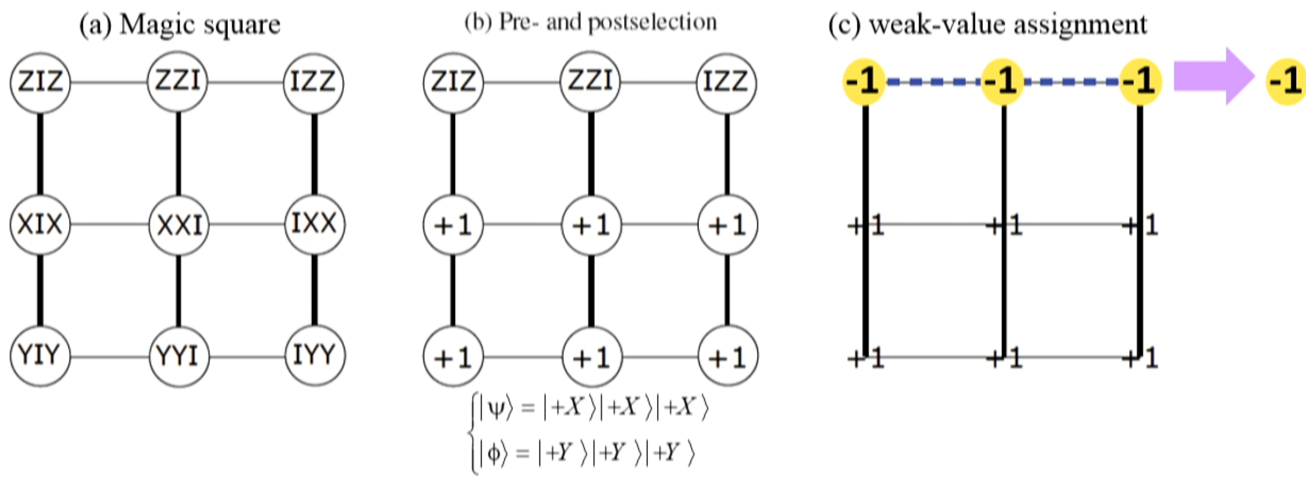
No two pigeons ever seem to be in the same box!!!

Quantum contextuality in neutron interferometer

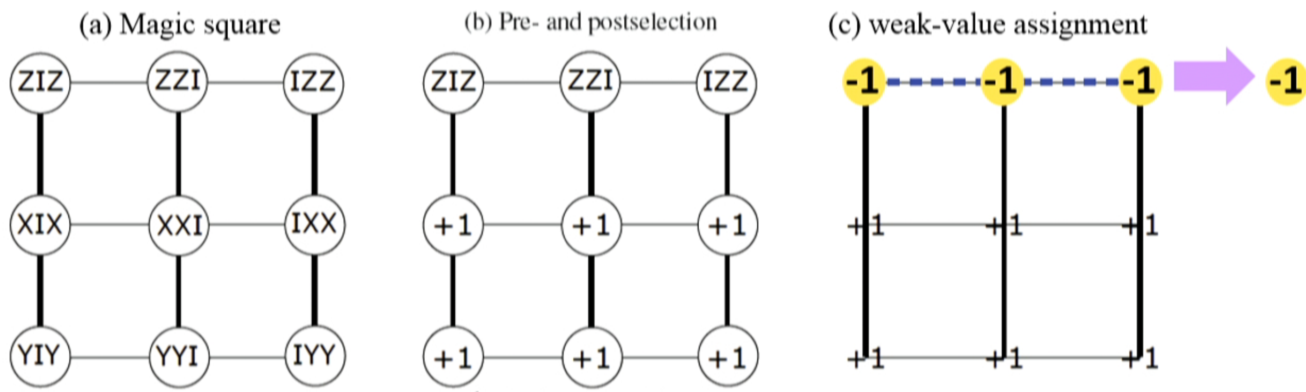
(a) Magic square



Quantum contextuality in neutron interferometer



Quantum contextuality in neutron interferometer



$$\begin{cases} |\Psi\rangle = |+X\rangle|+X\rangle|+X\rangle \\ |\phi\rangle = |+Y\rangle|+Y\rangle|+Y\rangle \end{cases}$$

$$\Pi_1^{(3)} = |+Z,+Z,+Z\rangle\langle +Z,+Z,+Z| + |-Z,-Z,-Z\rangle\langle -Z,-Z,-Z|,$$

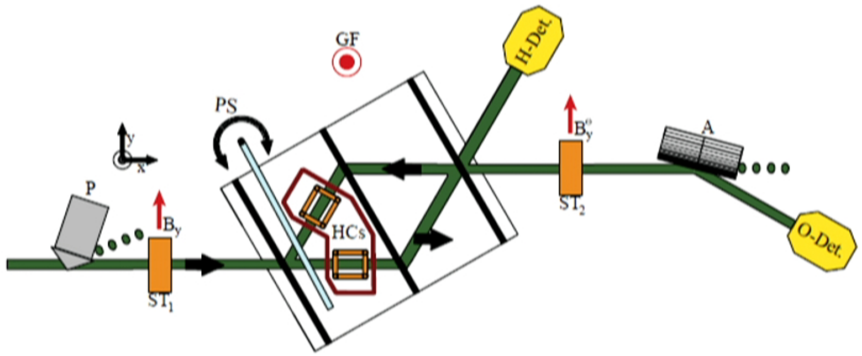
$$\Pi_2^{(3)} = |+Z,-Z,+Z\rangle\langle +Z,-Z,+Z| + |-Z,+Z,-Z\rangle\langle -Z,+Z,-Z|,$$

$$\Pi_3^{(3)} = |-Z,+Z,+Z\rangle\langle -Z,+Z,+Z| + |+Z,-Z,-Z\rangle\langle +Z,-Z,-Z|,$$

$$\Pi_4^{(3)} = |-Z,-Z,+Z\rangle\langle -Z,-Z,+Z| + |+Z,+Z,-Z\rangle\langle +Z,+Z,-Z|,$$

$$(\Pi_1^{(3)})_w = \prod_{n=1}^{3} \frac{1+Z_w}{2} + \prod_{n=1}^{3} \frac{1-Z_w}{2} = -\frac{1}{2} \boxed{\notin [0,1]}$$

WV via weak/strong measurements: experiment



Concluding remarks

Neutron interferometer is effective tool for studies of quantum paradoxes

- Quantum Cheshire-Cat was observed in neutron interferometer.

- Weak-values of ½-spin allow to demonstrate quantum pigeonhole effect and contextuality

➔ ***further development & applications***